Executive Summary

Massive MIMO was proposed in 2010, suggesting that basestations (BS) could be equipped with a large-scale antenna array to efficiently increase the system throughput and improve the energy efficiency. Large-scale antenna arrays could be centralized or distributed. In both cases, the BS can form much narrower beams to serve more MSs simultaneously. Consequently, the channel between each pair of users tends to be orthogonal (in spatial domain), each user can benefit from the huge array gain, and more users can be scheduled using the same time frequency resources with much lower energy consumption.

The initial version of the massive MIMO scheme in 3GPP, i.e., full dimension MIMO (FD-MIMO), is being standardized in Rel-13. It’s expected that even greater prominence of MIMO technology will take place in 5G era. Results from early research and evaluations have shown great potential of massive MIMO in boosting spectrum efficiency. However, major challenges still exist before its standardization and practical applications can be realized:

1. **Accurate modeling of massive MIMO channel and deployment scenarios**: Achievable gain of massive MIMO depends on the channel condition and deployment scenario. Channel and scenario modeling are preconditions for design, evaluation and standardization of MIMO schemes. Due to the large number of antenna elements, the channel model is more complicated to reflect the realistic properties of antenna arrangements and antenna correlation.

2. **Highly efficient physical layer design**: Huge amount of antennas and large scale of potential users to be scheduled make it challenging to design cost/spectral/energy-efficient physical layer architectures and algorithms. MIMO schemes and detection algorithms have direct impact on complexity, energy efficiency and system performance. Tradeoffs between those criteria are critical to the successful application of massive MIMO and highly accurate and efficient CSI measurement and feedback are of key importance.

3. **Reliable and feasible active antenna array design**: Both the active antenna modules and the resultant massive array must be cost effective and environmentally friendly. The associated architecture optimization, miniaturization, reliability assurance, calibration, transmission/reception (T/R) chain design, and interface design would be important in research and development of massive MIMO.

This Topical Whitepaper covers key issues of massive MIMO, including channel measurement and modeling, transmission and reception algorithms, reference signal design, CSI acquisition schemes, large-scale active antenna array designs, massive MIMO in high-frequency band, as well as deployment of massive MIMO in heterogeneous and dense networks. Initial evaluation results and prototype designs are also presented as starting points and references for continuous evaluation, prototyping, and standardization of massive MIMO technologies in the future.
1. Introduction

In order to support the rapid increase of high speed traffic and subscriber number, radio link with much higher data rate and capacity is desired to the next generation system. As shown by multi-antenna theory, the capacity of a radio link with multiple antennas at both ends is much higher than traditional single-antenna link. Research on multi-antenna system in recent years provides profound theoretical basis and reveals its promising future. Nowadays, MIMO has been widely adopted throughout all the 4G standardizations. For the LTE system based on OFDM+MIMO, MIMO played important roles in data rate and reliability enhancements, coverage extension, interference suppression and capacity improvement.

Massive MIMO theory proposed in 2010 suggested that BS could be equipped with a large-scale antenna array to efficiently increase the system throughput and improve the energy efficiency. Consequently, the channel between each pair of users tends to be orthogonal, each user can benefit from the huge array gain, and more users can be scheduled using the same time frequency resource with much lower energy consumption. As shown in Fig.1, with the increase of antenna number, both cell average and edge user throughput can be improved drastically.

![Figure1: Performance of massive MIMO](image)

Even though results from early researches and evaluations have shown great potential of massive MIMO in boosting spectrum efficiency for the 5G system, there are still several challenges that need to be settled before its standardization and practical application. In this report, with the considerations on future trends and possible deployment scenarios of 5G system, potential massive MIMO schemes are discussed.

2. Key Technologies

2.1 Channel measurement and modeling

The basic idea of 5G Massive MIMO channel measurement is utilizing practical Massive MIMO antenna array and sounder system to launch the channel measurements under various 5G typical scenarios to obtain the measurement samples which contain the 5G channel characteristic. These obtained samples will serve for 5G Massive MIMO channel parameter extraction and model development in order to enhance the scientific understanding of 5G propagation channel and eventually build the channel model library for the communication system design.
2.1.1 The platform and principle of Massive MIMO channel measurement

The channel measurement platform is based on the RS vector signal generator (VSG) SMW200A+AFQ100B and the Agilent vector signal analyzer (VSA) M9703 to support the carrier frequency range from 0.1GHz to 26 GHz and the bandwidth of 200 MHz. VSG and VSA are shown in figure 2 as the transmitter and receiver below.

![Figure 2: The transmitter (left) and receiver (right) of the measurement platform](image)

The platform applies Multi-Carrier Spread Spectrum technique to design the sounding signal. The merit of this design is that a low Peak to Average Power Ratio (PAPR) and a constant channel frequency domain response can be achieved in the observed bandwidth. By capturing the channel frequency domain complex transfer function and utilizing the reference check measurement, the extraction of various characteristic parameters such as loss, fading, delay, angle, and correlation can be achieved for different Massive MIMO transmission links to eventually aid the development of Massive MIMO channel model.

The measurement is based on a three-dimensional mechanical turntable to establish a virtual Massive MIMO array with the half-wavelength antenna spacing. This turntable supports horizontal x-axis movement (with maximal range of 3m), vertical z-axis movement (with maximal range of 3m), and horizontal y-axis rotation (with 360 degrees). This turntable has the highest speed of 10 cm/s, the minimal distance precision of 0.01 mm and the minimal angle precision of 0.01 degree. Figure 3 below shows the three-dimensional turntable.

![Figure 3: Three-dimensional turntable](image)

In order to increase the number of statistical samples and decrease the noise perturbation and signal temperature drift, measurement is repeated for 5 times for each Massive MIMO link in each path of static measurement.
2.1.2 Massive MIMO channel measurement

The detailed Massive MIMO measurement parameters are shown below:

- **Carrier Frequencies**: 1.4 GHz, 2 GHz, 3.3 GHz, 4 GHz, 4.4 GHz, 4.9 GHz, 6 GHz, 11 GHz, 15 GHz, 22 GHz, 26 GHz
- **Bandwidths**: 100 MHz, 200 MHz
- **Scenarios**: Indoor LOS, Outdoor NLOS, Outdoor LOS, Outdoor NLOS
- **Antenna Array Types**: Linear Array, Planar Array
- **Array Sizes**: 64x4, 128x1, 256x256

1) **Indoor channel measurement**

The LOS and NLOS indoor channel measurement for Massive MIMO are launched inside a large conference room. The measurement scenario is shown below:

![Indoor measurement scenario](image)

**Figure 4: Massive MIMO indoor measurement scenario**

![Transmitter and receiver for Massive MIMO indoor measurement](image)

**Figure 5: Transmitter and receiver for Massive MIMO indoor measurement**

For the indoor LOS scenario measurement with 64x4 linear array and 6 GHz carrier frequency, Figure 6 shows the Power Delay Profile (PDP) of the 1st array element (left) and the Root Mean Square (RMS) delay spread of all the 64...
array elements (right). It is observed that the RMS delay spread is range from 40 to 80 ns. Also it is worth noting that there has a large difference of delay spread between different array elements. So the spatial non-stationarity of this array is significant.

![Figure 6: Analysis of delay characteristic for Massive MIMO indoor LOS scenario](image)

For the indoor NLOS scenario measurement with 64x4 linear array and 6 GHz carrier frequency, figure 7 shows the PDP of the 1st array element (left) and the RMS delay spread of all the 64 array elements (right). It is observed that the RMS delay spread is range from 100 to 300 ns, which is about 100-200 ns longer than the LOS scenario. Also, there has a large difference of delay spread between different array elements, which indicates that the spatial non-stationarity of this array is significant.

![Figure 7: Analysis of delay characteristic for Massive MIMO indoor NLOS scenario](image)

2) Outdoor channel measurement

The outdoor LOS channel measurement for Massive MIMO is launched at the campus scenario, which is shown below:

![Figure 8: Massive MIMO outdoor measurement scenario](image)
For the outdoor LOS scenario measurement with 64x1 linear array and 3.33 GHz carrier frequency, Figure 8 shows the PDPs of the 1st (left) and the 42nd (right) array elements. It is observed that for a large size array, there has a change of the multi-path distribution structures at the both end elements of the Massive MIMO array.

![Figure 8: Analysis of PDPs for Massive MIMO outdoor LOS scenario](image)

For the outdoor LOS scenario measurement with 64x1 linear array and 3.33 GHz carrier frequency, Figure 9 shows the RMS delay spread in different array elements. It is observed that there exists a large difference of the RMS delay spread between different array elements. So the spatial non-stationarity of this array is significant.

![Figure 9: Analysis of RMS delay spread for Massive MIMO outdoor LOS scenario](image)

### 2.1.3 Massive MIMO channel modeling

In Massive MIMO Channel Modeling, cluster based channel model will be built for the non-stationarity characteristic of Massive MIMO.

- At first, for the practical measured data, the adaptive clustering algorithm is conduct at the scatter clusters in typical scenarios to achieve the multi-path signal clustering. In the meanwhile, the research and modeling work of the signal statistical distribution characteristic inside a cluster can be accomplished.

- Next, modeling research is developed on the space consistency (correlation) of the scatter clusters between different moments (or different antenna array positions). Also, statistical modeling for birth-and-death process of the scatter clusters at different moments (or different antenna array positions) can be achieved.

- Finally, cluster based Massive MIMO channel model are built and various Massive MIMO channel model libraries are formed for different carrier frequencies, array types and scenarios.
2.2 Transmission and reception

Huge amount of antennas and large scale of potential users to be scheduled make it challenging to design cost/spectral/energy-efficient physical layer architectures and algorithms. Beamforming schemes and detection algorithms have direct impacts on complexity, energy efficiency and system performance. It might be even more complicated, if inter-cell coordination is also considered with large-scale antenna arrays. In both cases, the tradeoff between those criteria is critical to the application of massive beamforming in commercial networks. Similar to beamforming schemes discussed above, highly accurate and efficient CSI measurement and feedback are still very important.

The performance gain of massive MIMO comes from the near-orthogonal of multi-user channel vectors. However, with multiple non-ideal factors in practical devices and propagation environments, carefully designed transmission and detection algorithms are still essential to ensure efficient inter-user interference suppression and multi-user schedule gain. Transmission and detection algorithms have direct impacts on complexity, energy efficiency and system performance. It might be even more complicated, if inter-cell coordination is also considered with large-scale antenna arrays. In both cases, the tradeoff between those criterions is critical to the application of massive beamforming in commercial networks.

For Tx-Rx schemes with massive MIMO, there are three technical challenges should be considered, i.e., spectrum efficiency, signalling overhead, and implementation complexity. To address the above challenges, three different Tx-Rx schemes and/or their combinations are proposed.

- **Wideband high-order MU-MIMO transmission**

  With massive antenna elements mounted on the base station, the characteristics of the system become different from the small scale MIMO system, which motivates us to design a new transmission mode for massive MIMO systems. Strong ability of high-order multi-user transmission is the key feature of massive MIMO. Due the DoF provided by massive antennas and the asymptotic orthogonal property of user channels, large number of users can be co-scheduled and then spatially multiplexed on the same time and frequency resources for downlink transmission. The number of co-scheduled users can be comparable with that of active users in the cell. Therefore, most of active users in the network can be co-scheduled on each TTI and each subband even with the common scheduler used by current networks. Besides, the channel quality of individual UEs varies slowly with both time and frequency due to the channel hardening effect of massive MIMO channels. Thus little diversity gain can be obtained by user scheduling. Considering these properties, we introduce a wide band and high order MU-MIMO transmission mode for massive MIMO systems. To support wideband high-order MU-MIMO transmission, DMRS enhancement and some necessary signaling should be defined.

- **Separate horizontal and vertical beamforming**

  With 2D AAS, it is possible to steer the beams in both horizontal and vertical dimensions. One promising scheme is beam selection based on cell-specific beamformed CSI-RS. In this scheme, CSI is acquired using multiple beamformed CSI-RSs in two steps: 1) eNB transmits multiple beamformed CSI-RSs with different beam direction; 2) UE selects preferred beamformed CSI-RS and feeds back its index and CSI, i.e., beam index (BI), RI, PMI and CQI(s). Considering that the current codebooks are designed for horizontal precoding, it is straightforward that beam index (BI) and PMI represent vertical and horizontal precoding, respectively, i.e., multiple beamformed CSI-RSs are transmitted with different vertical tilting angles. This scheme has several advantages, including smaller specification impact, beamforming gain for CSI-RS, and higher forward compatibility to future systems.
using larger number of antennas and higher frequency. To reduce CSI-RS overhead, UE-specific beamformed CSI-RS based approach may also be considered. Or some CSI-RS enhancement could be designed.

Figure 11: Channel measurement and beamforming

- Hybrid beamforming

Massive MIMO can realize beamforming in different ways, i.e., digital beamforming and analog beamforming. The former is performed in the digital baseband back-end, while the latter in the analog radio frequency (RF) front-end. Each approach has its own pros and cons. For digital beamforming, it can provide better beam steering precision, but it is more complex and expensive, since it requires separate baseband processing modules and power-hungry ADC/DAC converters for each antenna element (AE). On the other hand, analog beamforming is simpler and inexpensive, but less flexible. A reasonable compromise, known as hybrid beamforming, is to move some processing from digital baseband to analog RF at the cost of some flexibility loss in beam steering. For the transmission of user data channels and signals, user-specific beamforming can be designed to steer beams pointing to the expected user(s) and consequently the offered beamforming gain can compensate the severe propagation loss. But this is not the case for common channels and signals, e.g. discovery signals of small cells and phantom cells, due to the fact that user-specific beamforming cannot be applied to common channels and signals. Therefore, how to guarantee an effective and robust coverage is critical for common channels and signals. To solve this problem, we propose a novel hybrid beamforming transmission scheme, in which multiple analog beams are transmitted simultaneously via analog beamforming at the radio frequency (RF) frontend and cyclic shift (CS)-based beamforming is utilized in the digital back-end. With a proper CS setting, the received channel impulse responses (CIRs) from different beams can always be combined orthogonally (to avoid destructive combination). Therefore, a more stable and robust coverage of common channels and signals can be guaranteed.

Figure 12: Hybrid beamforming based on cyclic shift operation
2.2.1 Centralized massive MIMO

1) A 3-D beamforming scheme

In the traditional 2D beamforming system, the users can be just served simultaneously in horizontal directions and can not be distinguished in the vertical domain. Relative to the 2D beamforming, 3D beamforming can exploit the elevation dimension as well as the azimuth dimension in MIMO system. It can improve the coverage area of the cell in the vertical domain and reduce the interferences among the terminals. Also it can form beams to the terminals in elevation adaptively and decrease the interferences between the users located in the same azimuth angels but not the same downtilts. Here in 3D-UMa and 3D-UMi scenarios, the performance of 3D beamforming is evaluated.

The users can be just served simultaneously in different horizontal directions. However users located in the same azimuth angel can not be served at the same time because all beams in vertical domain have the same downtilt.

![Figure 13: The structure of 2D antenna array](image)

Assume that the BS adopts 2D antenna array. The configuration of antenna array is presented in Figure 13. The number of antenna elements in horizontal direction and vertical direction is \( N_h \) and \( N_v \) respectively. And the total number of antennas is \( N = N_h \times N_v \). Each UE is equipped with \( N_r \) antennas. The scheme of 3D beamforming is described below.

**Step 1:** Assuming that the channel vector between UE \( k \) and the respective BS is:
\[
\mathbf{h}_k = [\mathbf{h}_{k1}, \mathbf{h}_{k2}, \ldots, \mathbf{h}_{kN_v}] \in \mathbb{C}^{N_v \times (N_h \times N_v)}, \quad \mathbf{h}_{ki} \in \mathbb{C}^{N_v \times N_h} \quad (i = 1, 2, \ldots, N_v)
\]

is the channel matrix between the \( i \)-th row transmitting antenna elements and user \( k \). Calculate the average correlation matrix \( \mathbf{R} \in \mathbb{C}^{N_h \times N_h} \) for the \( N_h \) horizontal channels. Then get the horizontal beamforming vector through eigenvalue decomposition. This can be expressed as:
\[
\mathbf{R} = \frac{1}{N_v} \sum_{i=1}^{N_v} (\mathbf{h}_{ki})^H \mathbf{h}_{ki}
\]

\[
[w^h_k, \lambda^h_k] = \text{eig}(\mathbf{R})
\]

where eig() denotes the eigenvalue decomposition. \( \lambda^h_k \) and \( w^h_k \) are the largest eigenvalue and the corresponding eigenvector, respectively.

**Step 2:** Assume that the antenna elements in the BS are column-wise indexed and the channel matrix between UE \( k \) and the BS \( j \) is
\[
\mathbf{h}^T_j = [\mathbf{h}_{j1}^T, \mathbf{h}_{j2}^T, \ldots, \mathbf{h}_{jN_h}^T] \in \mathbb{C}^{N_h \times (N_v \times N_h)}, \quad \mathbf{h}_{ji}^T \in \mathbb{C}^{N_v \times N_h}, \quad i = 1, 2, \ldots, N_h
\]

is the channel matrix from the \( i \)-th column of antenna elements to UE \( k \). The vertical beamforming vector is achieved as below:
\[
R_v = \frac{1}{N_h} \sum_{i=1}^{N_v} (h_{ki}^*)^H h_{ki}^* \\
[w_v^k, \lambda_v^k] = \text{eig}(R_v)
\]

where \( R_v \) is the average correlation matrix for the vertical domain. \( w_v^k \in \mathbb{C}^{N_v \times 1} \) is the vertical beamforming vector.

Step 3: In FDD system, each UE will feedback the horizontal and vertical beamforming vectors to its respective BS. Here we will not consider the codebook to quantize the beamforming vector and assume that the UE feedback the non-quantized beamforming vectors to the BS. The 3D beamforming vector \( w_k \in \mathbb{C}^{(N_h \times N_v) \times 1} \) of UE \( k \) based on channel matrix \( h_k^{\text{sc}} \) is calculated as follows:

Step 3: The 3D beamforming vector \( w_k \in \mathbb{C}^{(N_h \times N_v) \times 1} \) is calculated as follows:

\[
w_k = w_v^k \otimes w_h^k
\]

Where \( \otimes \) denotes the Kronecker product.

Table 1 lists the parameters of the system-level simulation. And the maximal number of co-scheduled users is 8.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>settings</th>
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</thead>
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<tr>
<td>Scenario</td>
<td>3D-UMa/3D-UMi</td>
</tr>
<tr>
<td>UE antenna</td>
<td>2Rx X-pol (0/+90)</td>
</tr>
<tr>
<td>configuration</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
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<tr>
<td>Antenna element</td>
<td>0.5 carrier wave length both in</td>
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<td>interval</td>
<td>horizontal and vertical direction</td>
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<tr>
<td>Carrier frequency</td>
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</tr>
<tr>
<td>the number of</td>
<td>10</td>
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<tr>
<td>UEs per cell</td>
<td></td>
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<tr>
<td>UE distribution</td>
<td>Referred to 36.873</td>
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<tr>
<td>UE speed</td>
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<td>Traffic model</td>
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<td>HARQ</td>
<td>The maximal number of retransmission</td>
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<td>feedback</td>
<td>PMI/CQI feedback granularity: 50PRB</td>
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<td>feedback</td>
<td>RI feedback period: 100ms</td>
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<tr>
<td>overhead</td>
<td>CQI/PMI feedback period 5ms</td>
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<tr>
<td></td>
<td>3 symbols for DL CCHs, 4 CRS ports</td>
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</tbody>
</table>
and DM-RS with 12 REs per PRB

Wrapping method | Geographical distance based

Figure 14: cell average spectrum efficiency of 3D beamforming

Figure 15: Cell edge spectrum efficiency of 3D beamforming

In the simulation, xHyV means that the numbers of antennas in the horizontal direction and vertical direction are x and y, respectively. In the 2D beamforming, the vertical domain adopts 102 degree for all the users.

The performance of the 3D beamforming improve as the number of antennas increases while there is something wrong with the 2D beamforming. The number of the configuration 8H16V increased relative to the configuration 8H10V. However the performance of 8H16V is inferior slightly to that of 8H10V. This is can be explained that in 2D beamforming, the beam width becomes narrower and the power is concentrated on the direction of 102 degree. And the users located out of the range of 102 degree will obtain the lower performance gain. So as the number of antennas in vertical direction increases to some extent, the performance of 2D beamforming will decline.
To verify the impact of the antenna array on the system performance, here we consider an extreme case where the number of antennas is increased in the horizontal direction and the number of antennas in vertical direction is 1. In 3D beamforming, from Figure 16 and 17, we can see that when the total number of the antennas is fixed, the more the number of antennas in the horizontal direction, the better the performance. Though the antenna number of the configuration 40H1V is smaller than the number of the configuration 8H10V, the performance of the 40H1V is still better the performance the 8H10V.

Figure 16: Cell average spectrum efficiency for different antennas array

Figure 17: Cell edge spectrum efficiency for different antennas array
In the simulations above, the feedback granularity is assigned to 50. Here we assign the feedback granularity to 6. Through the simulation results above of the 3D beamforming and 2D beamforming, we can conclude that, 3D beamforming makes full use of the degree of freedom in the 3D space and it improves the cell average spectrum efficiency and the cell edge spectrum efficiency. Also we can see that the more the antennas in horizontal direction, the better the performance, because angle spread (AS) in the horizontal direction is larger than that in the vertical domain.

2) A joint port virtualization and 3D MIMO transmission method

We consider a massive MIMO system where both BS and user equipment (UE) are equipped with a two dimensional uniform rectangular array (URA). In the BS side, there are $M$ antenna elements (AEs) in each column and $N$ AEs in each row. In the UE side, there are $M_u$ AEs in each column and $N_u$ AEs in each row. The array configuration of the BS and the UE can be co-polarized or cross-polarized. The distance between adjacent AEs in the horizontal and vertical direction are $d_h$ and $d_v$, respectively.
The signal received at the UE side can be represented as, \( y = \mathbf{H}_{3D} \mathbf{W}_{3D} \mathbf{x} + \mathbf{n} \), where \( \mathbf{H}_{3D} \) is the whole 3D channel information with the dimension of \( MN \times MN \). \( \mathbf{W}_{3D} \) is the corresponding 3D precoder with the dimension of \( MN \times MN \). \( N_s \) is the number of the data streams. \( \mathbf{n} \) is noise vector which follows complex Gaussian distribution. It is also assumed that \( \mathbf{W}_h \) and \( \mathbf{W}_v \) are precoding matrices of the horizontal and vertical directions, respectively. In a separated horizontal and vertical transmission scheme is given, \( \mathbf{W}_{3D} = \mathbf{W}_h \otimes \mathbf{w}_v \), where \( \mathbf{w}_v \) is a vector, which means that the vertical direction supports only one data stream. In the codebook based CSI feedback, the UE is able to select the azimuth PMI and elevation PMI based on the estimated horizontal channel \( \hat{\mathbf{H}}_h \) and vertical channel \( \hat{\mathbf{H}}_v \), respectively,

\[
\mathbf{W}_h = \arg \max_{\mathbf{w}_h \in C_h} \text{Cap}(\hat{\mathbf{H}}_h, \mathbf{W})
\]

\[
\mathbf{w}_v = \arg \max_{\mathbf{w}_v \in C_v} \text{Cap}(\hat{\mathbf{H}}_v, \mathbf{w})
\]

Here \( \text{Cap}(\cdot) \) is the operation of capacity calculation. \( C_h \) and \( C_v \) are horizontal and vertical codebooks. Usually, \( \mathbf{w}_v \) can be expressed as,

\[
\mathbf{w}_v = [w_1 \, \ldots \, w_m \, \ldots \, w_N]^T
\]

\[
w_m = \frac{1}{\sqrt{M}} \exp \left[ -j \frac{2\pi}{\lambda} (m-1) d_v \cos \theta_{\text{eilt}} \right]
\]

where \( \theta_{\text{eilt}} \) is the electrical downtilt. Furthermore, \( \cos \theta_{\text{eilt}} \) can also be quantized and \( \mathbf{w}_v \) is in the form of DFT vectors.

Based on this scheme, [1] gave an improved transmission scheme, where beamforming is adopted by the vertical direction and the horizontal CSI-RS is also weighted by vertical beamforming vector. In this case, the channel information estimated by the horizontal direction includes both horizontal and vertical channel information. It means that the antenna elements of one column are virtualized as one antenna port in this scheme. Then the two dimensional URA is degraded to one dimensional uniform linear array, and the transmission schemes of previous LTE version can be reused. Meanwhile, all the antenna ports are used to estimate the equivalent channel information, which makes the measurement results accurate.

However, the system performance is limited by the vertical direction, in which only one data stream is transmitted. In the following subsection, we will give an improved transmission scheme considering both the number of the data streams of the vertical direction and the accuracy of the vertical beamforming. Basically, the improved scheme is implemented based on the adaptive port virtualization of the vertical direction.

(1) Proposed transmission scheme

To support multi-stream transmission in the vertical direction, the AEs in one column can be virtualized as more than one logical ports. It is assumed that \( K \) vertical AEs form a logical antenna, and the value of \( K \) can be varied in the transmission. At this time, the number of the antenna ports in the vertical direction is \( M/K \). The AEs weighting in each antenna port is expressed as,

\[
\mathbf{w}_{\text{AE}} = [w_1 \, \ldots \, w_i \, \ldots \, w_K]^T
\]

\[
w_i = \frac{1}{\sqrt{K}} \exp \left[ -j \frac{2\pi}{\lambda} (k-1) d_v \cos \theta_{\text{eilt}} \right]
\]

where the superscript of \( \mathbf{w}_{\text{AE}} \) is used to indicate its dimension.

Considering port virtualization scheme, the equivalent 3D channel can be represented by,
\[
H_{eq} = H_{3D}W_{AE} = \begin{bmatrix}
w_{AE}^1 & \cdots & w_{AE}^K \\
\vdots & \ddots & \vdots \\
0 & \cdots & w_{AE}^K
\end{bmatrix}
\]

It is assumed that \( H_{3D} = \begin{bmatrix} H_1 & H_2 & \cdots & H_{MN/K} \end{bmatrix} \), and \( H_p (p = 1, 2, \cdots, MN/K) \) represents the channel between the UE and the AEs in logical antenna port \( p \). Thus, the above equation can be rewritten as,

\[
H_{eq} = H_{3D} \times W_{AE} = \begin{bmatrix} H_1w_{AE}^1 & H_2w_{AE}^2 & \cdots & H_{MN/K}w_{AE}^{MN/K} \end{bmatrix}
\]

where \( h_{eq}^p (p = 1, 2, \cdots, MN/K) \) represents the equivalent channel between the UE and the antenna port \( p \) after the port virtualization scheme. It can be seen that the selection of \( K \) will affect the number of the logical antenna ports. Besides, the selection of \( K \) will also affect the width of the formed beams. Figure 20 shows the normalized array factor formed by 10, 20 and 40 AEs. Larger \( K \) can acquire narrower beamwidth and direct the main lobe to the users more accurately.

![Figure 20: Normalized array patterns with different \( K \) values in the vertical direction](image_url)
To achieve a better tradeoff between beamwidth and the number of simultaneously supported streams, we propose to select a smaller $K_0$ to do port virtualization, and then the adequate value of $K$ can be calculated to make maximize the system performance. This smaller $K_0$ should also guarantee the vertical beamforming. For example,

$$ \begin{cases} \text{mod}(M, K_0) = 0 \\ K_0 \geq b \end{cases} $$

Here, $b$ equals to 8 or 10, or other classic values of $K$ used in vertical beamforming. After $K_0$ is determined, BS acquires $\theta_{aoa}$ either from angle of arrival (AOA) estimation or the UE feedback through transmitting a new type of CSI-RS. And then the BS transmits two sets of CSI-RS. One set is corresponding to one row of the logical antenna ports. The other set is weighted by $w_{\text{AE}}$ for each logical port and corresponding to one column of the logical antenna ports. By these two CSI-RS sets, the UE can estimate the horizontal and vertical equivalent channel $\hat{h}_H$ and $\hat{h}_V$, respectively. Note that, if channel estimation is accurate, $\hat{h}_H$ and $\hat{h}_V$ are columns of $H_{eq}$.

Furthermore, the adequate value of $K$, the horizontal and vertical precoder and the number of their supported data streams $N_H$ and $N_V$ can also be estimated. The detailed procedure is summarized as follows (algorithm 1).

**Step 1:** Calculate horizontal precoder and the number of the supported streams utilizing horizontal equivalent channel information $\hat{h}_H$,

$$ W_H = \arg \max_{W \in C_{\text{eq}}} \text{Cap}(\hat{h}_H, W) $$

$$ N_H = L(W_H) $$

where $L(A)$ represents the number of the columns of matrix $A$.

**Step 2:** Calculate vertical precoder and the number of the supported streams. At the beginning, it is assumed that the number of the antenna ports in the vertical direction is $i = 1$. In this case, the vertical equivalent channel is $\hat{h}_V$.

Check whether $\text{mod}(M, iK_0)$ is equal to 0 or not. If $\text{mod}(M, iK_0) = 0$, then $i = i + 1$, until $\text{mod}(M, iK_0) = 0$ and...
do the following operations to estimate current vertical precoder $W_v$ and the number of the supported streams $N_v'$,

$$\hat{H}_v \leftarrow \hat{H}_v W_p$$

$$W_v = \arg\max_{W_v \in C} \text{Cap}\left(\hat{H}_v, W\right)$$

$$N_v' = L(W_v)$$

Check all possible values of $i$ within the condition of $i \leq M/K_0$ and select best $W_v$ and $N_v'$ which can maximize the capacity.

Step 3: Calculate 3D precoder $W_{3D}$ with the Kronecker product operation, i.e.,

$$W_{3D} = W_H \otimes W_v$$

$W_p$ used in algorithm 1 is defined as,

$$W_p = \text{diag}\left\{\frac{M/K_0}{M}, \ldots, \frac{M/K_0}{M}\right\} \in \mathbb{C}^{M \times M}$$

$$w_p^i = \left[1 \ w_{K_0+1} \ \cdots \ w_{(i-1)K_0+1}\right]^\top \in \mathbb{C}^{1 \times 1}$$

The function of $W_p$ is to further perform port virtualization, from $M/K_0$ ports to $M/iK_0$ ports. It is noted that $W_p$ is important. Without $W_p$, the weighting in an logical port with $iK_0$ AEs is,

$$\begin{bmatrix} (w_{AE}^{K_0})^\top & (w_{AE}^{K_0})^\top & \cdots & (w_{AE}^{K_0})^\top \end{bmatrix}^\top = \begin{bmatrix} w_1 & \cdots & w_{K_0} & \cdots & w_1 & \cdots & w_{K_0} \end{bmatrix}^\top$$

The normalized array pattern formed by this weighting is shown in Figure 21 with the parameter of $K_0 = 10$, $i = 2$, $\theta_{oe} = 45^\circ$. It can be seen that the level of the sidelobe can not be neglected and the mainlobe is not appeared at $45^\circ$. While with $W_p$, the weighting in an logical port with $iK_0$ AEs is,

$$\text{diag}\left\{w_{AE}^{K_0}, \ldots, w_{AE}^{K_0}\right\} W_p^i = \begin{bmatrix} w_{AE}^{K_0} \\ w_{AE}^{K_0} \\ \vdots \\ w_{AE}^{K_0} \\ w_{AE}^{K_0} \end{bmatrix}$$

It can be easily derived that the weighting is equivalent to $w_{AE}^{K_0} = \begin{bmatrix} w_1 & w_2 & \cdots & w_{K_0} \end{bmatrix}^\top$.

With the same parameter of $K_0$, $i$ and $\theta_{oe}$, the normalized array factor is also shown in Figure 1. It can be seen that the mainlobe is appeared at the direction of $\theta = 45^\circ$.

After the port virtualization and precoder selection, $W_H$ and $W_v$ have $N_H$ and $N_v$ orthogonal vectors, respectively. The whole 3D precoder can be derived from $W_{3D} = W_H \otimes W_v$ and $N_HN_v$ data streams are supported in the transmission.

However, in algorithm 1, $W_H$ and $W_v$ are selected independently and the 3D precoder is simply acquired through the Kronecker product of them without a further check.

Therefore, algorithm 2 is proposed to further check the transmission capability of the 3D channel.
Step 1: Calculate horizontal precoder and the number of the supported streams utilizing horizontal equivalent channel information \( \hat{\mathbf{H}}_h \),

\[
W_H = \arg \max_{\mathbf{W} \in \mathbb{C}^{H \times W}} \text{Cap}(\hat{\mathbf{H}}_h, \mathbf{W})
\]

\[
N_H = L(W_H)
\]

Step 2: Calculate vertical precoder and the number of the supported streams. At the beginning, it is assumed that the number of the antenna ports in the vertical direction is \( i = 1 \). In this case, the vertical equivalent channel is \( \hat{\mathbf{H}}_v \).

Check whether \( \text{mod}(M, iK_a) \) is equal to 0 or not. If \( \text{mod}(M, iK_a) = 0 \), then \( i = i+1 \), until \( \text{mod}(M, iK_a) = 0 \) and do the following operations to estimate current vertical precoder \( W_v \) and the number of the supported streams \( N_v \),

\[
\hat{\mathbf{H}}_v \leftarrow \mathbf{H}_v \mathbf{W}_v
\]

\[
W_v = \arg \max_{\mathbf{W} \in \mathbb{C}^{V \times W}} \text{Cap}(\hat{\mathbf{H}}_v, \mathbf{W})
\]

\[
N_v = L(W_v)
\]

Calculate \( W_{3D}^i \) with Kronecker product operation, i.e., \( W_{3D}^i = W_H \otimes W_v = [z_1 \ z_2 \ \cdots \ z_{N_HN_V}] \). It is assumed that \( \hat{\mathbf{H}}_{eq} = f(\hat{\mathbf{H}}_h, \hat{\mathbf{H}}_v) \), and the function \( f(\hat{\mathbf{H}}_h, \hat{\mathbf{H}}_v) \) represents that the Kronecker product is performed to each row of \( \hat{\mathbf{H}}_h \) and \( \hat{\mathbf{H}}_v \). Then utilize all columns of \( W_{3D}^i \) and \( \hat{\mathbf{H}}_{eq} \) to perform the norm operation \( \| \hat{\mathbf{H}}_{eq} z_r \| \) and reorder \( r(1, 2, \cdots, N_HN_V) \) and the columns of \( W_{3D}^i \) in the descending order of \( \| \hat{\mathbf{H}}_{eq} z_r \| \). Next, check the capacity of the channel with \( \hat{\mathbf{H}}_{eq} \) and the newly arranged \( W_{3D}^i \), and then select the best number of the total streams of the 3D channel under current value of \( i \) (i.e., the proper number of the columns of \( W_{3D}^i \) to perform precoding).

Check all possible values of \( i \) within the condition of \( i \leq M/K_a \) and select best \( W_{3D}^i \) which can maximize the capacity.

In algorithm 2, \( f(\hat{\mathbf{H}}_h, \hat{\mathbf{H}}_v) \) expresses that the Kronecker product is performed in each row of \( \hat{\mathbf{H}}_h \) and \( \hat{\mathbf{H}}_v \). Each row of \( \hat{\mathbf{H}}_h \) (\( \hat{\mathbf{H}}_v \)) corresponds to the channel between one AE of the UE and one row (column) antennas of the BS. Although the equivalent 3D channel cannot be acquired by the UE due to limit of the RS resource, it can be estimated by \( \hat{\mathbf{H}}_h \) and \( \hat{\mathbf{H}}_v \) to assist the rank selection. The case that aggressive rank selection in algorithm 1 by simply multiplying \( N_H \) and \( N_V \) can be avoided.

In the following subsection, we will introduce a RI feedback scheme to assist the proposed transmission scheme.

(2) RI feedback scheme

In conventional MIMO systems, with certain number of the antennas, the BS usually has several codebooks, each rank indication is corresponding to one codebook. Therefore, the exact precoder is determined by both RI and PMI. In massive MIMO systems, when both horizontal and vertical direction support multiple data streams, the RI feedback becomes complicated.

If only the total rank is reported by the UE, and horizontal and vertical PMI are feedback separately, it is hard for the BS to derive the exact value of \( N_H \) and \( N_V \), therefore the exact precoders of the two directions cannot be derived. If horizontal and vertical ranks are both feedback, the total rank of the channel can be \( N_HN_V \). However, the case that...
the total rank is a prime number (such as 3 or 5) can not be indicated well. Thus, we propose to feedback the total rank $N_H$ and $N_V$ simultaneously.

Numerical simulations are conducted to compare the performance of the proposed separated horizontal and vertical multi-stream transmission and conventional methods. 3D-UMi channel model studied by 3GPP is used in the simulation. Single cell and single user are considered. The user is uniformly dropped in the horizontal plane and has a probability of 80% to be dropped in the indoor environment. If the UE is dropped in the outdoor, the height of it is 1 meter. Otherwise, the height of it is $h_{UE} = 3(n_H - 1) + 1.5$, in which $n_H$ meets the following distribution,

$$n_H \sim \text{uniform}(1, N_H). N_H \sim \text{uniform}(4,8)$$

We average over 1000 user drops of the simulation. In each drop, we evaluate the capacity performance with 50 channel realizations.

2D planar co-polarized URAs are equipped at the BS and the UE. The number of the AEs at the UE side is $M_u = 1, N_u = 4$. The number of the AEs at the BS side is varied in the simulation. $(M, N, K_u)$ is used to describe the antenna configuration for simplicity. Other parameters used in the simulation is shown in Table 2. To acquire better performance, horizontal and vertical precoders are from the singular value decomposition of the horizontal and vertical channels.

<table>
<thead>
<tr>
<th>Table 2: Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Carrier frequency</td>
</tr>
<tr>
<td>Channel model</td>
</tr>
<tr>
<td>BS antenna height</td>
</tr>
<tr>
<td>$d_H, d_V$</td>
</tr>
<tr>
<td>AEs weighting</td>
</tr>
</tbody>
</table>

Figure shows the capacity comparison of the proposed multi-stream transmission scheme in algorithm 1 and the conventional scheme with different antenna configurations. The number of AEs at the BS side is 40 and the number of the antenna ports in the horizontal direction is not large. It can be seen that in high SNR region, algorithm 1 outperforms conventional method which always transmits single stream in the vertical direction. Especially when $(M, N, K_u) = (40,1,10)$. SNR = 35dB, the gain is over 100%. When the value of $M/K_u$ is small, the gain of algorithm 1 is small. That is because the effect of adaptive adjustment of port number in algorithm 1 is little in this case.

In Figure, the number of AEs at the BS side is 160 and the number of the horizontal antenna ports is further increased. The phenomenon is similar to Figure 22. The algorithm 1 outperforms the conventional method in high SNR region and is worse than the conventional method in low SNR region. Compared with the configurations of $N = 1$ and $N = 2$ in Figure, the gain of algorithm 1 is less or even negative. It means that the deviation between the precoder and the eigenvectors of the 3D channel is magnified by the larger number of the horizontal antenna ports.

Figure gives the comparison of algorithm 1, algorithm 2 and the conventional method with the configuration of $(M, N, K_u) = (20,4,5)$. After the further rank selection, algorithm 2 outperforms algorithm 1 and the conventional method within the whole range of SNR. Note that the equivalent 3D channel $\tilde{H}_{eq}$ in algorithm 2 is derived from the kronecker product of the horizontal and vertical channel. When $\tilde{H}_{eq}$ is replaced by the ideal equivalent 3D channel, the capacity is improved further, which is indicated by the black curve.
Figure 22: The comparison of algorithm 1 and the conventional scheme with small number of horizontal antenna ports configuration

Figure 23: The comparison of algorithm 1 and the conventional scheme with larger number of horizontal antenna ports configuration
In this work, we have proposed two joint port virtualization and multi-stream transmission methods in massive MIMO systems. With the proposed transmission algorithms, the port virtualization is flexible and the number of the supported data streams can be selected adaptively. Moreover, a RI feedback scheme is also proposed to assist the proposed transmission algorithms. Numerical simulation results show that our proposed algorithms provide better performance than the scheme in the existing 3D MIMO systems.

3) Two-stage beamforming based on hybrid array

To address the cost and complexity issues with massive MIMO, hybrid beamforming is proposed in recent years. Based on hybrid analog and digital array structure, two-stage beamforming scheme performs an analog phase shift at the frontend with much lower complexity to coarsely match the spatial characteristic of channel. While at baseband, the inter-user interference can be further suppressed with the second-stage of beamforming. Due to the controllable complexity and cost, hybrid beamforming is considered to be a promising solution of massive MIMO, especially for higher-frequency and larger bandwidth.

In this section, a two-stage beamforming scheme based on hybrid array is presented. The algorithm can be summarized as follows.

<table>
<thead>
<tr>
<th>Analog beam selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. BS: analog beam scan</td>
</tr>
<tr>
<td>2. User: analog beam search and report</td>
</tr>
</tbody>
</table>

Baseband CSI feedback and hybrid beamforming

| 1. User: analog beamformed equivalent baseband channel estimation and CSI reporting |
| 2. BS: hybrid beamforming |

For the step of analog beam selection, two schemes are considered. In algorithm 2, each user only reports a bitmap of 0 and 1 reflecting the suggestion on M analog beams, where M is the number of Tx/RU. While in algorithm 1, totally M beams are suggested by each user as well. Furthermore, an achievable capacity is reported for each selected beam. As shown in the example in Table 3, the BS chooses the M (Tx/RU number) analog beams with highest weight in algorithm 2. The M beams with highest sum rate are chosen in algorithm 1 (see Table 4 for an example).
Table 3: An example of algorithm 2

<table>
<thead>
<tr>
<th>index</th>
<th>v1</th>
<th>v2</th>
<th>v3</th>
<th>v4</th>
<th>v5</th>
<th>v6</th>
<th>v7</th>
<th>v8</th>
<th>v9</th>
<th>v10</th>
</tr>
</thead>
<tbody>
<tr>
<td>User1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>User2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>User3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>User4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>User5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>weight</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: An example of algorithm 1

<table>
<thead>
<tr>
<th>index</th>
<th>v1</th>
<th>v2</th>
<th>v3</th>
<th>v4</th>
<th>v5</th>
<th>v6</th>
<th>v7</th>
<th>v8</th>
<th>v9</th>
<th>v10</th>
</tr>
</thead>
<tbody>
<tr>
<td>User1</td>
<td>51</td>
<td>67</td>
<td>15</td>
<td>72</td>
<td>0</td>
<td>92</td>
<td>78</td>
<td>0</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>User2</td>
<td>15</td>
<td>40</td>
<td>57</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>25</td>
<td>36</td>
</tr>
<tr>
<td>User3</td>
<td>0</td>
<td>2</td>
<td>65</td>
<td>95</td>
<td>77</td>
<td>60</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>69</td>
</tr>
<tr>
<td>User4</td>
<td>0</td>
<td>26</td>
<td>10</td>
<td>88</td>
<td>0</td>
<td>38</td>
<td>60</td>
<td>2</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>User5</td>
<td>16</td>
<td>0</td>
<td>56</td>
<td>0</td>
<td>54</td>
<td>0</td>
<td>11</td>
<td>58</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>Sum rate</td>
<td>82</td>
<td>135</td>
<td>203</td>
<td>260</td>
<td>131</td>
<td>190</td>
<td>154</td>
<td>60</td>
<td>152</td>
<td>125</td>
</tr>
</tbody>
</table>

The performance results of above two algorithms are shown in Figure 25. Where K=20 users and Nt=100 antennas are assumed in the simulation. It’s noticed that, with the increase of Tx/RU number, the proposed two-stage algorithms can be improved. The performance gaps between algorithm 1 and optimal full digital ZF tend vanish as M increases.
2.2.2 Distributed massive MIMO

Massive MIMO (M-MIMO) is defined that a base station installs hundreds of antennas centrally, and provides larger array gain and space freedom to mitigate intra & inter cell interference. Therefore, M-MIMO can improve wireless communication performance by multiplexing more users on the same time-frequency resource than LTE.

Distribute MIMO (D-MIMO) is similar with M-MIMO except that hundreds of antennas distribute in different geographical position, as well as these antenna of D-MIMO are connected by optical fibers. The obvious advantage is saving transmitting power and reducing interference, because the distance both antennas and UEs is closer, meanwhile a cooperation be seen an action between antennas of D-MIMO in a cell, which inter-interference signals transformed into useful signals.

1) Deployment scenario

With the number of antennas increasing, the signal processing and antenna shape will be different in the massive MIMO systems. For example, when the carrier frequency is 2GHz, the wavelength is 15cm, considering that the array gain is not large enough until the antenna distance is larger than half of a wavelength, the size of an 8-by-8 antenna array with 128 cross polarization antenna elements will achieve at least 60-by-60 cm. Taking the antenna shape of massive MIMO into account, the distributed massive MIMO gains many advantages over the centralized manner. Firstly, it is easier to deploy. The distributed structure supports a more flexible design on the antenna shape, which contributes to overcome the challenge that site selection for the massive MIMO deployment. Moreover, distributed massive MIMO provides better coverage. The distributed massive MIMO provides a larger coverage, this will reduce the co-channel interference and the handoff probability.

From the deployment perspective, we consider several application scenarios of distributed massive MIMO as the follows.

（1）Outdoor deployment

For the outdoor deployment, the main advantage of distributed massive MIMO is easy to deploy. The outdoor deployment can be classified into two types. (i) Large distribution: Several antenna arrays are under centralized processing, and the total antenna arrays make up the massive MIMO. This type can be combined with the deployment of the ultra-dense network, and the inter-cell interference can then be cancelled effectively by centralized resource management and as a result, the cell throughput will be improved. The large distribution type is illustrated in Fig. 26. (ii) Small distribution: The massive MIMO consists of the modularized antenna subarrays. The deployment is illustrated in Fig. 27.

Figure 26: Large distributed massive MIMO deployment
By separating the large antenna array into multiple smaller subarrays, locating each of the subarrays at different site locations and controlling the subarrays in a centered manner, the goal of using this modularized antenna subarray is to ease the difficulties of deploying the massive MIMO system in the practical. On one hand, the smaller antenna size will bring significant flexibility and convenience to the deployment and maintenance, which will turn into financial benefits as the operation cost can be reduced; on the other hand, the modularized antenna subarray can be used in both large distribution and small distribution cases, as a result, the modularized antenna subarray could be taken as a common design for the distributed massive MIMO.

(2) Indoor deployment

For the indoor deployment, the main advantage of distributed massive MIMO lies in the flexible networking. Using the modularized antenna subarrays, three examples are shown in Fig. 28. (a) Office case: antenna subarrays are located at the corners, and those antenna subarrays deployed in the same room is under centralized processing to form the massive MIMO. It is an alternative to process the antenna subarrays across the rooms. (b) Shopping mall case: there are shops or rooms located along the hallway in both sides, so the antenna subarrays can be deployed along the hallway. (c) Stadium case: The antenna subarrays can be deployed on the central display screens.

In addition, distributed massive MIMO has some particular superiority in certain deployment scenarios. For example, the antenna can be made to the shape of characters, mural and branch. Moreover, this kind of antenna can adapt to more situations without the hard restriction on the physical size. Thus, it is a promising technology to deploy the distributed massive MIMO in practice. Nevertheless, it faces some challenges, such as the difficulties in the physical design, the performance degeneration, the compensation and calibration of digital baseband signal processing, and the protection in practical scenarios.

To achieve the performance gain, the distributed massive MIMO with modularized antenna subarrays can be combined with virtual sectorization, as shown in Fig. 29.
Figure 29: Modularized distributed massive MIMO with virtual sectorization

2) Performance analysis

The performance of distributed massive MIMO is affected by multiple factors, the causality may be very complicated. However, with a case-by-case manner, some observations can be made from the simulation results.

Use case 1: Small-Distributed Massive MIMO with Modularized Antenna Subarray

Only the TDD system is considered in the simulation and the reciprocal of the UL/DL channel is assumed. The antenna array is configured as (8, 4, 2, 64), the other topology parameters and user distribution are as same as those in the 3D-UMa ISD200 scenario in 3GPP TR36.873. The antenna subarray and the separation of subarrays are defined as in Figure 30 and the rest of the simulation parameters are shown in Table 5.

![Antenna Subarray Configuration](image)

Figure 30: Antenna Subarray Configuration

(Left: centralized; Middle: horizontal modularized; Right: vertical modularized)

Table 5: Simulation Parameters
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS Tx Power</td>
<td>41dBm</td>
</tr>
<tr>
<td>Duplex Mode</td>
<td>TDD</td>
</tr>
<tr>
<td>Antenna Separation</td>
<td>0.5λ H/0.8V</td>
</tr>
<tr>
<td>Traffic Mode</td>
<td>Full buffer model</td>
</tr>
<tr>
<td>Topology</td>
<td>7 cells, 3 physic sectors/cell</td>
</tr>
<tr>
<td>User Number Per Sector</td>
<td>10</td>
</tr>
<tr>
<td>UE antenna</td>
<td>2 (XPL 0/+90)</td>
</tr>
<tr>
<td>Transmission Mode</td>
<td>TM9</td>
</tr>
<tr>
<td>Overhead</td>
<td>3 DL CCHs symbols, 2 CRS port, 12DMRS/PRB</td>
</tr>
<tr>
<td>CSI-RS Period</td>
<td>5ms</td>
</tr>
</tbody>
</table>

Table 6: Simulation Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SE (bps/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized massive MIMO: 8x8x2</td>
<td>4.77 (100%)</td>
</tr>
<tr>
<td>Horizontal modularization: 8x4x2+8x4x2 (2 sector)</td>
<td>5.51 (115.5%)</td>
</tr>
<tr>
<td>Vertical modularization: 4x8x2+4x8x2/2 sector</td>
<td>5.65 (118.4%)</td>
</tr>
</tbody>
</table>

The simulation results are shown in Table 6. When the horizontal modularization is applied, the 2 antenna subarrays form 2 horizontal sectors; when the vertical modularization is applied, 2 vertical sectors are formed. Comparing to the centralized manner, the proposed modularization schemes show 11.5% and 18.4% gain, respectively. This gain mainly comes from the increasing of MU-number, which is increased from 4 (the maximum MU-number allowed in LTE Rel-12) to 8. Since the space between antenna subarrays can be adjusted accordingly, the interference between different sectors as well as the interference caused by the side slop can be further mitigated.

Use case 2: Large-Distributed Massive MIMO

In this case, a based FDD LTE is considered as simulation evaluation system. It is assumed that there are total 192 transmitting antenna and 192 UEs in each of the hexagonal region. In order to decrease complexity of simulation, the results only focus on center cell in green, while other cells in red are seen as interference cells. Figure31 shows the network topology of M-MIMO, there are total has 19 hexagonal region, and each hexagonal region has 3 cells. Figure32 shows the network topology of D-MIMO, there are total has 7 hexagonal region; because transmitted power of each antenna is extremely lower, only 2-layer network topology structure is considered in our evaluation. It is noteworthy that some details about simulation assumption can be found in appendix.

Figure31: Massive MIMO network topology

Figure32: Distribution MIMO network topology
Figure 33 gives the UE & Small hexagonal region distribution model in each big hexagonal region for D-MIMO, which Small hexagonal region represents coverage area of a single antenna in D-MIMO system. The coverage of a small hexagonal has only one user. However, all transmitting antennas, in M-MIMO, are installed in the center of the big hexagonal region. In D-MIMO, each center of the small hexagonal region has only one transmitting antenna. Moreover, the distribution of UE is the same in both M-MIMO and D-MIMO.

![UE & Small hexagonal region distribution model](image)

Figure 33: UE & Small hexagonal region distribution model

Both Figure 34-(a) and Figure 34-(b) shows results of average and 5% user spectral efficiency of M-MIMO and D-MIMO; as well as we can see that D-MIMO shows better performance than M-MIMO in the two figures. From Figure 34-(a), M-MIMO shows the best performance when multiplexing 96 users, which means multiplexing 32 users each sector; and D-MIMO shows the best performance when multiplexing 150 users. Then, in Figure 34-(b), it is clearly seen that, when 5% user spectral efficiency climbs to the highest point, M-MIMO can multiplex 16 user each sector; but multiplexing 100 users are found in the D-MIMO’s results.

![User spectral efficiency](image)

(a)average spectral efficiency
Figure 34: A comparing between Massive MIMO and Distribution MIMO

With aforementioned simulation parameter assumptions, D-MIMO shows better performance than M-MIMO, which reasons are that:

- Spatial degrees of freedom of M-MIMO is only 64 in each sector, so when growth multiplexing multiuser leads a increase about channel correlation, the system performance will have a obvious decrease, coming from intra-cell interference. Meanwhile, inter-cell interference in M-MIMO system also become more serious.

- Spatial degrees of freedom of D-MIMO increase to 192, and, because of antenna distribution on different location, channel correlation is very low. Hence, the D-MIMO has more freedom to suppress interference. Distance between antenna from different small cell in D-MIMO is long (>30m), so users’ wireless channel in D-MIMO is more independent than users in M-MIMO, which is helpful to multiplex more users in D-MIMO.

In general, D-MIMO’s performance is better than M-MIMO with ideal simulation parameter assumptions. However, ideal backhaul link and perfect channel state information are not available in real scenario, so performance of D-MIMO will degrade, we will study this field in future.

Table 7: Distribution MIMO simulation assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Channel Model</td>
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<td>D-MIMO: UMI</td>
</tr>
<tr>
<td>Total Tx Power</td>
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<tr>
<td>Total number of UE</td>
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</tr>
<tr>
<td>Total number of antenna</td>
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<td>Down tilt angle</td>
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<tr>
<td>UE Speed</td>
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<td>Scheduler</td>
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<tr>
<td>Algorithm for Tx precoding</td>
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<td>Feedback scheme</td>
<td>ideal channel covariance R</td>
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<td>Handover margin</td>
<td>3dB</td>
</tr>
<tr>
<td>Wrapping method</td>
<td>Geographical distance based</td>
</tr>
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</table>
### 2.2.3 Massive MIMO Based Wireless Backhaul

The main part of the construction and operation cost of the wireless network is the construction cost and the network operating and maintaining cost. From the perspective of the operation, the massive MIMO scheme with less cost in its deployment, operation and maintenance is more in line with the operators’ requirements.

In the 5G communication system, the number of the base station (BS) will increase significantly. Managing the site-construction cost gets more important with the number of BS increasing. On the other hand, the site selection will face serious challenges due to the need of the flexibility in the site selection in the future ultra dense network deployment.

The wired (fiber) backhaul and point-to-point microwave wireless backhaul used for the traditional BS is not suitable for these new challenges. The wired backhaul requires high construction cost. Moreover, the connected BS should be located near the backhaul access point. When the macro BS are deployed for the wide coverage, the aforesaid aspects of wired backhaul will not bring significant negative impacts on the construction, operation and maintenance of the network. However, with a denser of large amount of low-cost and small-coverage BS and the denser deployment, wired backhaul is not the optimal. As the ultra dense network and small cell on/off are candidate promising technology in the future network, it is necessary to propose a backhaul solution to balance the construction cost, network performance and networking flexibility.

The network construction and operation are continuous and sustainable progress. And for the different technologies, they may have different deployment road maps and life cycles. The coexistence and coordination of different technologies is expected. The massive MIMO will be combined with micro BS deployment inevitably. Fig. 35 illustrated the scene that the BS provides macro coverage as well as wireless backhaul for small cells with the help of the massive MIMO.

![Wireless backhaul with massive MIMO](image)

**Figure 35: Wireless backhaul with massive MIMO**

For the macro BS using the massive MIMO, from the transmission perspective, there is no difference between the users and the micro BS accessed via the backhaul link. Therefore, by using the spatial degree of freedom provided by the massive MIMO, the macro BS can provide wireless backhaul for multiple small cells located in the different positions simultaneously. On the other hand, with dynamic beamforming, the massive MIMO based wireless backhaul supports the flexible adjustment of the small cell BS deployment position. Compared to the traditional backhaul, this scheme can reduce the cost of site selection and backhaul link construction significantly.

However, on the channel modeling aspect, using massive MIMO to provide wireless backhaul needs some different concerns with traditional channel models (such as 3GPP TR36.873). Firstly, since the small cell can be deployed either indoor or outdoor, the channel modeling should not only take the impacts of small cells’ elevation into account, but also the indoor and outdoor environments, which have different penetration factors. Secondly, the operators could optimize...
the site locations for the small cell base stations during the deployment, which turns into a higher chance for the line-of-sight (LoS) channel between macro BS and small cell BS. The channel modeling for the wireless backhaul should show this feature as well. Moreover, the small cell BS doesn’t move as neither frequently nor fast as an UE does, so the channel between the macro BS and small cell BS is slow-variant in time. This new feature can be modeled by the Doppler frequency shift under the traditional channel modeling framework or by the new methods for better accuracy.

The new features bring new challenges for the channel modeling, but at the same time, they bring more chances in the research and optimization of the channel estimation and channel state information feedback. With the new schemes, the massive MIMO can effectively work with higher performance and a simpler transmission mode in this wireless backhaul scenario. And as a result, the difficulty and cost of the network operation could be reduced significantly.

2.2.4 Co-design of Energy Efficiency and Spectrum Efficiency in Massive MIMO

Two hybrid BF structures that have drawn much attention of researchers are shown in Fig.36, with $N$ being the transceiver number and $NM$ being the antenna number. In structure 1 each transceiver is connected with all antennas, such that the transmitted signal on each of the $N$ digital transceivers goes through $NM$ RF paths (mixer, power amplifier and phase shifter, etc) and summed up before being connected with each antenna element, as shown in Fig.36 (a). Analog BF is performed over $NM$ RF paths per transceiver and digital BF can then be performed over $N$ transceivers. This structure is a natural combination of analog BF and digital BF, and achieves full BF gain for each transceiver. However, the complexity of this structure is rather high, e.g. the total number of RF paths is $N^2M$.

An $N$ by $M$ hybrid BF structure is shown in Fig.36 (b), where each of the $N$ transceivers is connected with $M$ antennas. Analog BF is performed over only $M$ RF paths in each transceiver and digital BF is performed over $N$ transceivers. This structure is more practical for base station antenna deployment in the current cellular systems, where each transceiver is generally connected to a column of antennas. Compared with structure 1, the BF gain per transceiver is $1/N$ the gain in structure 1, but with a much reduced complexity, the total number of RF paths being $NM$.

![Fig.36 Hybrid BF Structures](image)

EE-SE Relationship
Consider the $N$ by $M$ BF structure: perfect analog BF is assumed within $M$ antennas per transceiver for one user (in total there are $N$ users). There is zero inter-user interference with the assumption of a large enough $M$ or via proper user scheduling even when $M$ is not so large. The $N$ user sum capacity of this structure is derived as $C=W\log_2(1+MP\eta_{\text{SE}}/WN_0)$, where $W$ is the system bandwidth, $P$ is the total power of $M$ power amplifiers (PA) per transceiver, $\eta_{\text{PA}}$ is the PA efficiency, and $N_0$ is the thermal noise density. Channel gain is assumed to be 1. The SE of this structure is written as $\eta_{\text{SE}}=C/W$.

In this section, the following simple power model is used, i.e., $P_{\text{total}}=NP+P_{\text{static}}=NP+NP_0+P_{\text{common}}+NMP_{\text{rf\_circuit}}$, where $P_{\text{total}}$ is the total power, $NP$ is the RF power of total $N$ transceivers, $P_{\text{static}}$ is the static power of the base station, including the part of power $NP_0$ which scales with the number of transceiver $N$, $P_{\text{common}}$ which is common for any transceiver number, and $NMP_{\text{rf\_circuit}}$ which scales with total antenna number $NM$. The EE-SE relationship [9-11] can be written as,

$$\eta_{\text{EE}} = \frac{C}{P_{\text{total}}} = \frac{\eta_{\text{SE}}}{\frac{N}{2^N-1} M N \eta_{\text{PA}} + NP_0 + P_{\text{common}} + NMP_{\text{rf\_circuit}}/W}$$

EE-SE Relationship at the Green Points

It can be derived based on Eq.1 that there exists only one green point on EE-SE curve for each case, i.e., there exists only one $\eta^*_{\text{EE}}$ which maximizes the EE performance. The relationship between $\eta^*_{\text{EE}}$ and $\eta^*_{\text{SE}}$ is further given as $\lg(\eta^*_{\text{EE}})=\eta^*_{\text{SE}} \frac{\lg 2/N}{N \ln 2}$, i.e., $\eta^*_{\text{EE}}$ scales with $\eta^*_{\text{SE}}$ linearly with a slope of $-\lg 2/N$. Similar to the EE-SE relationship with classic Shannon theory, a higher $\eta^*_{\text{SE}}$ will always lead to a lower $\eta^*_{\text{EE}}$.

Assume $W=2\times10^7$Hz, $N_0=10^{-17}$dBm/Hz and a channel gain of -100dB. The EE-SE relationship is depicted for two scenarios, the scenario with $N=4$ and $M=100$, and the scenario with $N=8$ and $M=50$. For each scenario, four $(P_{\text{rf\_circuit}}, P_{\text{common}}, P_0)$ combinations are simulated, including (1W, 50W, 1W), (5W, 100W, 5W), (5W, 100W, 2W) and (1W, 50W, 3W). EE (bits/Joule) is depicted in log-scale and SE (bits/s/Hz) is depicted in linear scale. As shown in Fig.37, the EE-SE curve is different with different $(P_{\text{rf\_circuit}}, P_{\text{common}}, P_0)$ combinations. On each curve, there exists only one green point. Also, the green points are actually in a straight line for both scenarios, with a large slope in the first scenario. This indicates that in the EE optimal design, a smaller transceiver number $N$ brings more EE performance improvement with a given SE reduction.
How does $N$ affect EE-SE?

When the required SE is pre-determined, it is desirable that the transceiver number $N$ is optimized, yielding the highest EE performance with the minimum transceiver number. Based on Eq.1, it’s found that in the cases $NM=L$ and independent $N$ and $M$, for any given SE, there exists only one optimal $N$ to yield the best EE. The practical meaning of the existence of the optimal $N$ is that with a given SE, a system designer doesn’t need to implement too many transceivers to achieve the best EE performance.

Assume $P_{\text{if,circuit}}=1\,\text{W}$, $P_{\text{common}}=50\,\text{W}$, $P_0=1\,\text{W}$, $\eta_{\text{PA}}=0.375$, $W=2\times10^7\,\text{Hz}$, $N_0=10^{-17}\,\text{dBm/Hz}$, and a channel gain of -100dB. Considering the $NM=500$ case, the impact of $N$ (from 1 to 10) on EE performance is shown in subplot 1 of Fig.38, where five SE values are simulated. Note that since $N$ and $M$ are integers, there are only 5 valid $(N,M)$ combinations for $NM=500$, that is, $(1,500)$, $(2,250)$, $(4,125)$, $(5,100)$ and $(10,50)$. It can be observed that on each curve there exists one optimal $N$ that yields the highest EE. For example, when SE is 20bps/Hz, the optimal $N$ is 4. When SE is 8bps/Hz, the optimal $N$ is just 1. The case when $N$ is larger than 10 is not shown in the figure, since it may be difficult to schedule users with negligible inter user interference when $M$ is very small.
When $N$ and $M$ are independent, the impact of $N$ on EE performance is shown in subplot 2 in Fig.3, where $M=50$ and other parameters are same with that in subplot 1. Similar to the fixed NM case, on each curve there exists one optimal $N$. For example, when SE is 40bps/Hz, the optimal $N$ is 6. Different from the fixed NM case, the EE performance is very sensitive to $N$, because the total antenna number scales with $N$.

### 2.3 Reference signal design and enhancement

In massive MIMO system a large number of beams should be generated to realize multi-user MIMO multiplexing. If we simply follow the traditional design philosophy in current LTE system, i.e., channel state information acquisition consisting of channel measurement based on downlink CSI-RS and limited feedback in uplink, the reference signal overhead will be increased significantly. In order to ensure an enough feedback accuracy of CSI, the uplink feedback overhead will also be increased significantly. The two factors will devour a large portion of performance gain provided by massive MIMO. Therefore, it is necessary to reconsider reference signal design and enhancement for massive MIMO system. This topic has always been the key part of MIMO standardization. For massive MIMO deployment, it is very important to investigate, evaluate and design the standardization schemes for RS design and enhancement.

#### 2.3.1 Overall enhancement scheme

To support the aforementioned Tx-Rx schemes, RS should be enhanced for massive MIMO, including

- **SRS**: To boost the system capacity of channel reciprocity based transmission, it is necessary to enhance the sounding capacity or increase the SRS orthogonality. Promising solutions include increased comb number with CS constraint, increased symbol number in UpPTS with OCC across SRS symbols, precoded SRS, etc. The introduction of OCC is beneficial to enhance SRS coverage and reduce the negative impact to channel estimation caused by random interference. Precoded SRS can effectively reduce the requirement of SRS resources by multi-antenna UEs.
DMRS: To support high-order MU-MIMO transmission. Promising solutions include lower density DMRS, increased OCC length, etc.

- Beamformed CSI-RS or some newly defined beamformed RS: To support flexible beam selection. In addition to FDM, TDM, and CDM, CS domain multiplexing is also possible to reduce the overhead. Meanwhile, CS domain multiplexing enables parallel beam measurement and selection in the transform domain.

### 2.3.2 Beamformed reference signal

Instead of measuring CSI based on reference signal from each antenna directly, beamformed reference beams can be used by user to choose the preferred beams in this scheme. In most cases, the number of discernable beams is less than the number of antenna. Therefore the reference signal overhead can be reduced. With beamformed reference signal, the user can report CQI, rank and desired combination of beams.
2.3.3 Reference Signal Design based on Hybrid Beamforming

Consider the $N$ by $M$ hybrid BF structure with a linear array of $NM$ antennas. Assume the main beam direction of ABF on each transceiver is $\phi_0$ and the feed coefficient on each antenna is 1. The corresponding array factor (AF) of the $i$-th transceiver ABF can be written as

$$ AF(\phi) = \sum_{m=0}^{M-1} e^{j2\pi n m \left( \frac{\cos \phi - \cos \phi_0}{\lambda} \right)} $$

where $d$ is the antenna spacing and $\lambda$ is the wave length.

Let $D_i = \text{diag}(e^{j\alpha_0}, e^{j\alpha_1}, \ldots, e^{j\alpha_{N-1}})$, where $\alpha_i$ ($i=1, \ldots, N-1$) is the phase shift on the $i$-th transceiver in digital domain.

The total AF can be summed up to be

$$ AF_{\text{total}}(\phi) = \left[ \begin{array}{c} 1 \\ \vdots \\ \sum_{j=0}^{N-1} e^{j2\pi d m \left( \frac{\cos \phi - \cos \phi_0}{\lambda} \right)} \end{array} \right] \cdot \left[ \begin{array}{c} \sum_{m=0}^{M-1} e^{j2\pi n m \left( \frac{\cos \phi - \cos \phi_0}{\lambda} \right)} \end{array} \right]. $$

We observe that when

$$ \alpha_i = -2i\pi d M \left( \frac{\cos \phi - \cos \phi_0}{\lambda} \right), i = 0, \ldots, N - 1, $$

$AF$ in the direction $\phi$ is maximized, with the corresponding maximum value

$$ \max \left( AF_{\text{total}}(\phi) \right) = N \left| \sum_{m=0}^{M-1} e^{j2\pi n m \left( \frac{\cos \phi - \cos \phi_0}{\lambda} \right)} \right|. $$

Therefore, for given ABF, the main beam direction of the hybrid BF is determined by the DBF weights. This feature can be conveniently utilized in frequency domain, e.g. different DBF weights are applied on different subcarriers in OFDM system to generate beams with different main beam directions. This leads to the following beam domain RS design.

The RS will occupy part of the frequency band, e.g. $2K+1$ consecutive subcarriers, which are assumed to be well within the channel’s coherent bandwidth. In the $s$-th OFDM symbol, the main beam direction of ABF is set to be $\phi_{0,s}$ for all transceivers. While the main beam direction of hybrid ABF and DBF on the $k$-th ($k=0,1,\ldots,2K$) subcarrier is $\phi_{0,s} + (K-k) \Delta$, with $\Delta$ being the beam spacing on the consecutive subcarriers. This is also shown in Fig.1.

With the hybrid BF design in Section II.A, the DBF weight on the $i$-th transceiver on the $k$-th subcarrier in the $s$-th OFDM symbol is given by

$$ D_k(i,i) = e^{-j2\pi d M \left( \frac{\cos \phi_{0,s} + (K-k) \Delta - \cos \phi_{0,s}}{\lambda} \right)} $$

$$ = e^{j2\pi i d M \left( \frac{\cos \phi_{0,s} + (K-k) \Delta - \cos \phi_{0,s}}{\lambda} \right)} $$

$$ = e^{j2\pi i \Delta d M \left( \frac{K-k}{\lambda} \right)} $$

36
The mobile user measures the RS power and feedback the best subcarrier index to base station. The base station then knows the best DBF precoder for each mobile user. [12]

2.4 Channel state information acquisition

CSI (channel state information) acquisition plays an important role in implementation of MIMO, especially for downlink multi-user transmission, where system performance highly relies on the inter-user interference suppression level of the beamformed signals. Eventually, the accuracy of multi-user scheduling and beamforming are determined by the precision of CSI obtained at transmitter side. For TDD (Time Division Duplex) system, the reciprocity between UL (Uplink) and DL (Downlink) can be utilized for channel estimation. However, issues like antenna array calibration and pilot contamination need to be settled. For FDD (Frequency Division Duplex) system, both traditional codebook based implicit feedback and long-term reciprocity based feedback schemes and new mechanisms, such as compressed sensing and pre-tasting based feedback, could be considered as well. The challenge for CSI design in FDD is the tradeoff between performance and overheads with reference signal, especially when more and more antenna arrays are used.

2.4.1 New subframe and reference signal design

5G network is expected to support multi-connectivity across bands and technologies, including 4G, 5G, and WiFi. Multi-connectivity ensures seamless coverage and allows phased 5G rollout leveraging operators’ available 4G assets. Figure 4 illustrated a scenario where simultaneous 4G, 5G (both below and above 6GHz bands including mmWave), and WiFi connectivity from both macro and small cells can be offered to a multi-mode device.

![Simultaneous 4G+5G connectivity](image)

**Figure 43: Simultaneous 4G+5G connectivity**

Massive MIMO, as one of key 5G technology enablers, facilitates coverage improvement and power consumption reduction for both sub-6GHz and mmWave. Specifically, massive MIMO enables coverage layer using higher bands, e.g. 3.8-4.2 GHz band for coverage layer in macro deployment. There exist some challenges to achieve this, e.g.

- Higher carrier frequency: increasing from 2 GHz band to 4 GHz band requires 6 dB increase in receive power;
- Larger bandwidth: 4x increase envisioned from 20 MHz to 80 MHz requires 6 dB increase of receive power. As a solution, massive MIMO offers large beamforming gains, which enable significant coverage enhancement. This allows reuse of legacy cell tower. To achieve large beamforming gain, timely and accurate channel state information is required. One example design of enhanced TDD subframe is illustrated in Figure 4. The additional headers could be inserted to support massive MIMO requirements such as downlink transmit beamforming training and uplink channel estimation for demodulation. Such subframe structure enables fast turnaround for uplink sounding to reciprocal downlink transmission. It provides sufficient channel estimation due to minimal channel de-correlation, as well as mobility support.

![Basic TDD subframe](image)

**Figure 44: Enhanced TDD sub-frame**

Evaluation results are provided to demonstrate benefits of massive MIMO with enhanced TDD subframe design. Figure 45 shows downlink throughput gains of massive MIMO with 24-Tx over 80 MHz bandwidth at 4 GHz band compared to 2-Tx over 20 MHz at 2 GHz band. ISD of 1.7km is assumed, and 46 dBm total transmission power for both cases. It can be observed that cell edge users of 1 km cell radius are still able to scale up throughput with bandwidth. This means same cell tower locations can be leveraged, without new cell planning.

![Figure 45: Coverage layer (1.7km ISD) improvements with 4GHz massive MIMO and new TDD subframe design](image)

Figure 46 illustrates coverage layer (1.7km ISD) improvements with massive MIMO and new subframe under high mobility. It can be observed that cell edge throughput requirements are still met for outdoor mobility, i.e. short 5G subframe is beneficial for reciprocity at high Doppler. We note performance loss of legacy timeline results from channel de-correlation, and beamforming de-correlation can range from 2-5ms.
Figure 46: Coverage layer (1.7km ISD) improvements with 4GHz massive MIMO and new TDD subframe design under high mobility

Figure 47 shows small cell (500m ISD) performance improvements. It can be observed that with massive MIMO and new subframe design, cell edge user at 500m ISD can still scale up throughput with bandwidth.

Figure 47: Small cell (500m ISD) performance improvements with 4GHz massive MIMO and new TDD subframe design

2.4.2 Virtual sectorization

The key point in virtual sectorization scheme is the beamforming of CSI-RS. Multiple sectors in horizontal and/or elevation domains can be formed based on large-scale antenna array. With identical cell ID in each virtual sector, traditional channel estimation and feedback schemes can still be used. The DOF of multi-antenna channel in both horizontal and elevation domains are fully utilized, while the effective antenna ports number is reduced in each virtual sector. As a consequent, in FDD system, the overhead is reduced efficiently. Furthermore, the required modification to the standard is limited.
As the generation and selection of virtual sector are essential to this scheme, they are discussed and evaluated below.

- Beamformed CSI-RS based virtual sectorization
  To implement the virtual sectorization, multiple CSI-RS resources should be configured for channel estimation, each corresponds to a virtual sector. In each virtual sector, the port number of received CSI-RS for each UE is at most 8 (LTE Rel-12 support at most 8 antenna ports).

  The antenna elements are first mapped to the TXRU, and then multiple TXRUs can generate virtual sectors in different directions. In this scheme, the downtilt angle and horizontal angle have great impact on the system performance.

- Virtual sector selection
  In order to access the optimal virtual sector, the BS and UE need to perform sector selection. There are mainly two ways to select the beam in FDD systems.

---

**Figure 48: virtual sectorization**

**Figure 49: Antenna port virtualization**

Figure 49 illustrates the mapping from the antenna elements to the antenna ports with 4 vertical virtual sectors, with the antenna configuration \((M,N,P,Q) = (32,4,2,32)\). The 8 adjacent elements with the same polarization in a column are mapped to one TXRU, so there are 4 TXRUs with the same polarization in a column. Each TXRU corresponds to a virtual sector, of which the downtilt angle can be set to different value in various scenarios. In the horizontal direction, there are 8 TXRUs, and each of them is mapped to an antenna port. Thus, each virtual sector has 8 antenna ports, which is the same as in LTE Rel-12.
The first way is based on the FDD channel reciprocity. The BS uses the DFT precoder to generate the downlink CSI-RS beam, and the channel correlation matrix $R$ can be calculated based on the uplink SRS. Thus, the beam selection is given by:

$$W = \arg \max_{W \in C}(W_{i}^{H}RW_{i})$$

where $W_{i}$ is the precode vector, $C$ is the DFT codebook of all virtual sector. It is assume that the correlation matrix is reciprocal between uplink and downlink in FDD systems. The premise of this assumption is that the antenna are well calibrated, and the calibration of antenna in FDD system needs further research.

The second way is based on the CSI-RS based RSRP measurement. This scheme requires that the users feedback the RSRP measurement of all virtual sectors in multiple CSI process. After that, the BS can select the best beam based on the feedback. Note that the CSI-RS based RSRP measurement was introduced in Rel-12, which is supported only by the Rel-12 UEs, and the current standard support at most 4 CSI-RS processes.

- **Performance evaluation**

  The performance evaluation of the virtual sectoreization in FDD massive MIMO systems is conducted in this section, where the vertical and horizontal sectorization are considered. The simulation scenario is 3D-UMa, ISD is 200m. The other parameters are listed in Table 8.

<table>
<thead>
<tr>
<th>Table 8: Simulation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
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<tr>
<td>BS Tx power</td>
</tr>
<tr>
<td>Duplex mode</td>
</tr>
<tr>
<td>Antenna configuration</td>
</tr>
<tr>
<td>Traffic model</td>
</tr>
<tr>
<td>Number of cell</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>User number per cell</td>
</tr>
<tr>
<td>Antenna number of UE</td>
</tr>
<tr>
<td>Feedback mode</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<td>Transmission mode</td>
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<td>Overhead</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>CSI-RS period</td>
</tr>
</tbody>
</table>

- **Vertical sectorization**

  The two kinds of antenna configuration in vertical sectorization are $(M, N, P, Q) = (16, 4, 2, 16)$ and $(M, N, P, Q) = (32, 4, 2, 32)$, corresponding to 2 and 4 vertical sectors, respectively.
Figure 50: Vertical sectorization

As shown Table 9, compared with the performance of single sector, the cell average throughput is improved by 51%, and the cell edge throughput is improved by 22% in the 2 vertical sectors case. While in the 4 vertical sectors case, the cell average throughput can achieve 101% gains, and the cell edge throughput can achieve 16% gains.

Table 9: Performance of vertical sectorization

<table>
<thead>
<tr>
<th>3D-UMA 200m ISD Vertical sectorization</th>
<th>Antenna downtilt angle</th>
<th>Cell average throughput (bps/Hz)</th>
<th>Cell edge throughput (bps/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sector</td>
<td>[104]</td>
<td>2.6949 (100%)</td>
<td>0.0910 (100%)</td>
</tr>
<tr>
<td>2 sectors</td>
<td>[114, 85]</td>
<td>4.0722 (151%)</td>
<td>0.1113 (122%)</td>
</tr>
<tr>
<td>4 sectors</td>
<td>[114, 104, 94, 84]</td>
<td>5.4185 (201%)</td>
<td>0.1052 (116%)</td>
</tr>
</tbody>
</table>

- Horizontal sectorization

Figure 51: Horizontal sectorization

The two kinds of antenna configuration in horizontal sectorization are \((M,N,P,Q) = (8,8,2,16)\) and \((M,N,P,Q) = (8,16,2,32)\), corresponding to 2 and 4 horizontal sectors, respectively.

As shown in Table 10, compared with the performance of single sector, the cell average throughput is improved by 42% in the 2 horizontal sectors case and 78% in the 4 horizontal sectors case. The cell edge throughput has no obvious improvement.
### Table 10: Performance of horizontal sectorization

<table>
<thead>
<tr>
<th>Antenna horizontal angle</th>
<th>Cell average throughput (bps/Hz)</th>
<th>Cell edge throughput (bps/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sector</td>
<td>[104]</td>
<td>2.6949 (100%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0910 (100%)</td>
</tr>
<tr>
<td>2 sectors</td>
<td>[30, -30]</td>
<td>3.8229 (142%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0893 (98%)</td>
</tr>
<tr>
<td>4 sectors</td>
<td>[45,15, -15, -45]</td>
<td>4.7864 (178%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0855 (94%)</td>
</tr>
</tbody>
</table>

### 2.5 Large-scale active antenna array design and test

Performance gain of massive MIMO comes from spatial degree of freedom (DoF) with multiple antennas. As the foundation to support the benefits promised by theory, antenna array is essential to all aspects regarding performance, efficiency, and costs in real environments. Considering the limitations in practical implement, deployment and maintenance, traditional passive antenna array is not suitable for further extension of MIMO dimension. In such case, with the integration of RF and a part of baseband functionalities, AAS (active antenna array) serves as a better choice to realize massive MIMO. With the evolution of antenna array structure, the application of AAS will have great impacts on both physical layer and network architecture designs. For AAS-based schemes, antenna array related factors, such as architecture optimization, miniaturization, reliability assurance, calibration, transmission/reception (T/R) chain design, interface design, would be important in research and development of massive MIMO.

Some key issues involved in implement of large-scale active antenna are shown in Fig.52.

![Large-scale active antenna array](image)

**Figure 52: Key issues of large-scale antenna array design**

Based on the implementation scheme and structure of the front end, large-scale active antenna array can be divided into full-digital array and hybrid analog and digital array. With full-digital array, each element is adjustable at baseband.
Therefore, flexible user-specific and frequency-selective beamforming is achievable. An example of full-digital structure of array is shown in Fig.53.

As shown in Fig.54, a hybrid analog and digital array can be utilized to balance the overall performance and cost, power consumption and complexity.
2.6 massive MIMO and high-frequency transmission

As the frequency spectrum resources below 6GHz are more and more crowded, resource extension towards higher frequency band are drawing attentions of industrial community. However, disadvantages such as non-ideal propagation characteristics in high-frequency band would have negative impact on the coverage and signal quality. In such case, large beamforming gain inherent with massive MIMO is expected to be able to compensate the non-ideal factors mentioned above. With the increase of carrier frequency, the miniaturize of antenna array would facilitate the deployment of massive MIMO. Therefore, it’s anticipated that, massive MIMO and high-frequency transmission technologies will be integrated tightly to further increase the capacity and data rate in 5G system. Considering the cost, complexity and power consumption factors, especially for even wider bandwidth in high-frequency band, a better trade-off between performance and cost, complexity and power consumption is desired in implement of massive MIMO. Consequently, a hybrid analog and digital array structure is considered as a more suitable choice for higher-frequency bands.

2.7 Deployment of massive MIMO in future network

As different possibly revolutionary architectures, including C/U plane splitting, distributed frontend+cloud computing, hyper cell, NFV(network functionality virtualization), will be deployed in the 5G networks, massive MIMO schemes might face to denser, heterogenous and more complicated network scenarios. A tight integretion of physical layer and network archituctures should be taken into account to further explore the potential gain of massive MIMO.

As shown in Fig.55, two categories of deployment scenarios are considered to be the most possibly use cases of massive MIMO in the future: homogenous pico or macro coverage and the heterogenous coverage with overlaying ultra dense pico cells. Both centralized and distributed antenna systems can be used. With centralized antenna array, the system can offer higher gains in beamforming and multi-user multiplexing, and is more suitable for macro coverage. The latter is similar to joint processing of clusters of remote radio units. Therefore it’s applicable to denser and indoor deployments.

![Figure 55: deployment scenarios of massive MIMO](image)

Deployment of massive MIMO in small cell is a one of the promising scenarios for supporting higher throughput density. In order to guarantee network coverage in high-frequency band, we can consider the network structure based on cooperation of macro cell and small cells (also known as phantom cell), where

- Lower frequency band is used to insure the coverage of macro cell
Higher frequency band and large bandwidth is used in small cell to improve capacity. With higher band, a large number of antenna elements can be implemented in limited array size (i.e. 20cm × 20cm). Hybrid beamforming can be used to reduce cost.

With C/U splitting in Phantom Cell structure, requirements on both coverage and capacity can be satisfied.

Figure 56: Massive MIMO in small cell

3. Evaluation

3.1 System-level simulation

3.1.1 Centralized deployment scenarios

In Figure 57, system-level simulation results of massive MIMO systems with 128 and 256 antennas are shown for both TDD and FDD systems. As shown in the evaluation results, massive MIMO based on channel reciprocity in TDD provides significant gain over massive MIMO based on feedback in FDD. With 128 antennas, 49% and 104% gain is achieved in terms of SE of cell average and cell edge, respectively. The gain rises to 76% and 137% when 256 antennas are used. The more the antennas are equipped, the larger the gain is observed. The assumptions of parameters in the evaluation are listed in Table 12.

Figure 57: The performance of massive MIMO schemes in FDD and TDD
Table 12: Simulation assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>3D-Umi</td>
</tr>
<tr>
<td>BS antenna configurations</td>
<td>128, 256</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>20MHz (50RBs)</td>
</tr>
<tr>
<td>UE attachment</td>
<td>Based on RSRP from CRS port 0</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>2GHz</td>
</tr>
<tr>
<td>Number of UEs per cell</td>
<td>10</td>
</tr>
<tr>
<td>UE distribution</td>
<td>According to 3GPP TR36.873</td>
</tr>
<tr>
<td>UE speed</td>
<td>3kmph</td>
</tr>
<tr>
<td>UE antenna pattern</td>
<td>Isotropic, antenna gain pattern =1</td>
</tr>
<tr>
<td>Traffic model</td>
<td>Full-buffer</td>
</tr>
<tr>
<td>Scheduler</td>
<td>PF</td>
</tr>
<tr>
<td>Hybrid ARQ</td>
<td>Maximum 4 transmissions</td>
</tr>
<tr>
<td>Feedback</td>
<td>Channel reciprocity based feedback</td>
</tr>
<tr>
<td></td>
<td>CQI reporting triggered per 5ms</td>
</tr>
<tr>
<td></td>
<td>SRS delay is 5 ms</td>
</tr>
</tbody>
</table>

3.1.2 Dense deployed scenario

In order to demonstrate the feasibility of massive MIMO in dense small cell, we did the following system-level simulation.

- Simulation parameters

![Figure 58: dense deployed scenario](image-url)
### Table 13: simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius for small cell center dropping in a cluster</td>
<td>50 m</td>
</tr>
<tr>
<td>Radius for UE dropping in a cluster</td>
<td>70 m</td>
</tr>
<tr>
<td>Minimum distance (2D distance)</td>
<td></td>
</tr>
<tr>
<td>Small cell - small cell center: 20m</td>
<td></td>
</tr>
<tr>
<td>Small cell - UE: 5m</td>
<td></td>
</tr>
<tr>
<td>Macro – small cell cluster center: 105m</td>
<td></td>
</tr>
<tr>
<td>Macro – UE: 35m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro network layout</td>
<td>7 hexagonal cells, each with 3 sectors</td>
</tr>
<tr>
<td>Small cell layout</td>
<td>1 cluster per sector with [4, 8, 12] small cells per cluster. Small cell antenna panel is located at cell edge, with a distance to small cell center of 10m and boresight pointing to the cell center</td>
</tr>
<tr>
<td>UE dropping</td>
<td>All UEs are dropped within the small cell cluster. All outdoor UEs.</td>
</tr>
<tr>
<td>UE/BS antenna configuration</td>
<td>2D AAS (VxHxP)</td>
</tr>
<tr>
<td>BS antenna array structure</td>
<td>1x1x2, 2x2x2, 4x4x2, 8x8x2</td>
</tr>
<tr>
<td>UE antenna array structure</td>
<td>1x1x2</td>
</tr>
<tr>
<td>BS antenna pattern</td>
<td>3D pattern in TR36.871</td>
</tr>
<tr>
<td>BS height</td>
<td>25m (Macro), 10m (Small cell)</td>
</tr>
<tr>
<td>UE height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Traffic model</td>
<td>FTP Model 1</td>
</tr>
<tr>
<td>Packet size</td>
<td>0.5 Mbytes</td>
</tr>
<tr>
<td>Packet arriving rate</td>
<td>15 packet/s/cell</td>
</tr>
<tr>
<td>Channel model</td>
<td>3GPP 3D Umi</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.0 GHz (Macro), 3.5 GHz (Small cell)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10M</td>
</tr>
<tr>
<td>Tx power</td>
<td>46 dBm (Macro), 30 dBm (Small cell)</td>
</tr>
<tr>
<td>Cell selection</td>
<td>RSRP on small cell layer</td>
</tr>
<tr>
<td>DL scheduler</td>
<td>Subband PF</td>
</tr>
<tr>
<td>DL receiver</td>
<td>MMSE-IRC</td>
</tr>
<tr>
<td>DL HARQ</td>
<td>Ideal timing with max. 4 retransmissions</td>
</tr>
<tr>
<td>MIMO transmission</td>
<td>Dynamic SU/MU</td>
</tr>
<tr>
<td>MU-MIMO scheduler</td>
<td>ZF-BD, greedy</td>
</tr>
<tr>
<td>CSIT</td>
<td>Ideal CDL, realistic CQI</td>
</tr>
</tbody>
</table>
● Geometry in dense small cell

![Figure 59: Geometry in dense small cell](image)

For the high density small cell case, 2D AAS provides a much better coverage (in terms of wideband SINR) than that of omnidirectional antenna, while omnidirectional antenna introduces too much ICI in the dense small cell deployment.

● Packet throughput in dense small cell

![Figure 60: Packet throughput in dense small cell](image)

Generally speaking, w/o inter-cell interference coordination, the packet throughput decreases with the increasing small cell density, but this performance degradation is minor for a larger antenna array.

● Area throughput
The area throughput with a smaller antenna array begins to become saturated or decrease with the increasing small cell density, while for a larger antenna array an almost linear increase can still be observed for area throughput. Massive MIMO itself can mitigate ICI to some extent, therefore, a much denser small cell deployment becomes feasible.

### 3.2 Prototype design

#### 3.2.1 Prototype from ZTE

![Figure 62-a Outlook](image)

![Figure 62-b Architecture](image)

Figure 62: 3D/ Massive MIMO base station of ZTE

In November of 2014, the world’s first TD-LTE 3D/ Massive MIMO base station was Preliminary commercially tested by ZTE and CMCC. The measurement was launched and organized by the Research Institute of China Mobile, and characters of the base station is 64 ports, 128 antenna elements and integrated between base band and RF, which the Figure 62 shows outlook and architecture of ZTE’s 3D/ Massive MIMO, and relating index of the base station can be found from Table 14.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>2.6GHz (2555-2655Hz)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20MHz</td>
</tr>
<tr>
<td>Tx Power</td>
<td>40W/Carrier</td>
</tr>
<tr>
<td>Weight</td>
<td>40Kg</td>
</tr>
<tr>
<td>Dimension</td>
<td>900mm×500mm×12mm</td>
</tr>
</tbody>
</table>

Table 14: Parameter list about ZTE’s 3D/ Massive MIMO base station
The measurement focused on coverage ability of 3D/ Massive MIMO base station to a skyscraper. In existing network, current 8-antennas base station, small of vertical cover angle and fixed beam direction angle, have a weak coverage ability and strongly interference in high-rise, meanwhile SINR and throughput the receiver is low, which results a terrible user experience and a huge challenge to an operator. However, because of 3D-beamforming, the measurement shows that 3D/ Massive MIMO fully cover a 35th floor of the building, which can be found by Figure 60. Furthermore, its throughput is considerably higher than a 8-antennas base station; in 35th floor, comparing a 8-antennas base station, there is a 3.36 time throughput gain to 3D/ Massive MIMO base station. Therefore, the measurement prove that 3D/ Massive MIMO, as a advanced wireless technology, can fully solve coverage problem of high-rise, which only one 3D/ Massive MIMO base station will completely replace current multi-base station.

In January 2015, a multi-user and multi-stream measurement of 3D/ Massive MIMO in the outfield was successfully finished by ZTE. The test shown that transmitted data of multi-user or multi-stream almost dose not interfere with other on the same time-frequency resource, which the spatial-diversity gain can be observed in outdoor and indoor environment. Therefore, the measurement proved that 3D/ Massive MIMO could effectively work and have been close to commercial.

3.2.2 Prototype from Datang

The 5G prototype from Datang is shown in Figure 64, where a full-digital active array with 128 antennas and 128 T/R channels is used for centralized deployment. The system operates at 3.5GHz carrier frequency and 40MHz bandwidth. Multiple features, such as C/U splitting, HetNet as well as distributed antenna systems, can be supported by this prototype.
3.2.3 Prototype System of China Mobile—Invisible Base Station

The concept of invisible base station was first presented by China Mobile Research Institute (CMRI) in 2012, as the novel base station used in 5G. The most important feature of invisible base station is the RF antenna array constituted by separate active antenna modules with two antennas in each module. The invisible base station can support centralized MIMO and distributed MIMO. By the flexible configuration of antenna array’s scale and shape, it can be in harmony with the surrounding environment and achieve the goal of invisibility.

The invisible base station is mainly constituted by two parts: BBU and RF active antenna module.

1) **BBU**

In order to support the transmission and processing ability of Massive MIMO System (128\*256\*512), the exchange architecture is based on the standard design architecture ATCA (Advanced Telecom Computing Architecture) and integrates with exchange processing board, high-performance core processing board and large capacity interface board. The exchange processing board mainly focuses on the scheduling and interactive processing of data; The large capacity interface board is used on the connectivity with RRU interface and the data processing of CPRI, SERDES. The high-performance core processing board is the main calculating unit of BBU and is responsible for the digital signal processing in the uplink and downlink transmission.

The high-performance core processing board integrates with four high-performance FPGA chips of Xilinx V7 series. The FPGA has abundant hardware resources and can finish complex base-band signal processing such as MU-MIMO, matrix decomposition and channel estimation. For example, the calculation of inversion and SVD decomposition in matrix decomposition involves lots of complex calculation such as multiplication, division and extraction of square root, which may increase in the form of index with the antenna number; The large-scale FFT and IFFT real-time processing requires 128 IFFT/FFT processors’ working at the same time. For these demand, each FPGA of V7 series can provide millions of logical gates and thousands of DSP. On this condition, the core processing board with four such FPGA chips can provide the whole base-band processing ability for the massive MIMO system with the antennas from 128 to 512. Besides, there are also 96 pairs of GTX and LVDS for the connectivity between FPGA and ATCA back board or some other uses.
The design principle of SmarTile is miniaturization, low cost and low power consumption. It is mainly constituted by RRU and antennas. The architecture of the digital part of SmarTile is ARM+FPGA and mainly used for the digital up/down frequency conversion, CPRI and local management. The RF part of SmarTile is constituted by low-cost terminal RFIC with 2 channels, power amplifier and LNA which can minimize the volume and power consumption of the product without any performance loss.

By integrating antennas with RRU and the low profile PCB antenna design scheme, SmarTile can get high gain and miniaturization. In the practical application, different SmarTiles can be configured flexibly to constitute the antenna arrays with different scales and shapes.

So far the joint test of the system has been finished and the system can work with terminals. The verification of beam forming technology was firstly finished in the OTA darkroom. Besides, as the lead for new technology exploring in 5G,
some deep research have been implemented on the algorithm of irregular antenna arrays. The massive MIMO system, as the earliest flexible and invisible system, has been exhibited in many famous exhibitions such as Barcelona Exhibition.

### 3.2.4 Prototype from Huawei

As early as the end of 2014, Huawei, with NTT-DoCoMo, has begun demonstration and measurement of massive MIMO technologies. The massive MIMO system Huawei demonstrated is equipped with 64 RF chains, 64 antenna elements, and bandwidth up to 100MHz, which are all supported by high-processing-capability CRAN architecture. The planar array is shown in Fig.68 (left).

To practically demonstrate massive MIMO performance, Huawei’s demonstration site is located in complex filed environment, which is encompassed with buildings, as shown in Fig. 68 (right). It is the first-ever industrial field test, which 24 spatial streams are achieved with MU-MIMO multiplexing, as shown in Fig. 69.

![Fig. 68 Huawei massive MIMO 3D map](image)

![Fig.69 Huawei massive MIMO field test – single UE and UE distribution](image)

In October, 2015, Huawei’s field test is deployed in Chendu, China. The test shows significant performance improvement of massive MIMO. With 100MHz bandwidth, the average single cell downlink throughput reached 1.34Gb/s(167.5MB/s), and peak throughput 3.6Gb/s(400MB/s).
4. Candidates for standardization

For 5G standardization, three kinds of transmission schemes should be supported, i.e., separate horizontal and vertical beamforming, wideband high-order MU-MIMO transmission, and hybrid beamforming. To support the aforementioned transmission schemes, some specification impact shall be considered, including (but not limited to)

- Frame structure and/or numerology revision to support more flexible beamforming schemes
- Reference signal enhancement, including SRS, DMRS, CSI-RS, and BRS, etc.
- Feedback enhancement, including beam index, and beamformed CQI/CSI, etc.

5. Summary

The evolution of physical layer technologies are still of great important for future mobile communication systems to further improve the spectral efficiency, power efficiency and system capacity. With the introduction of massive MIMO theory and the development of AAS technology, spatial domain resources can be more efficiently utilized with further extension of MIMO dimension.

Research and initial evaluation results have shown the potential of massive MIMO in improving spectral efficiency. Meanwhile, initial version of massive MIMO scheme in 3GPP, i.e., full dimension MIMO (FD-MIMO), is being standardized in Rel-13. Both vendors and operators are showing their growing interests in evolution of MIMO technology in future networks.

The technical background of massive MIMO is summarized in this report. Some key issues, including channel measurement and modeling, transmission and reception algorithms, reference signal designs, CSI acquisition schemes, large-scale active antenna array designs, massive MIMO in high-frequency band and deployment of massive MIMO in heterogenous and denser networks, are discussed. Initial evaluation results and prototype design are also presented.
References


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