

Multi-Panel MIMO in 5G

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The authors give an overview of multi-panel MIMO systems, including downlink, uplink, and non-coherent transmissions, and discuss research challenges and future directions of multi-panel MIMO. They also propose new multi-panel codebook design and corresponding CSI feedback design for 5G systems as well as non-coherent MIMO transmission.

ABSTRACT

Massive MIMO is one of the key enabling technologies in 5G wireless communications. A large number of antenna elements bring extra degrees of freedom for increasing the throughput and considerable beamforming gains for improving the coverage. In practice, a large number of antenna elements can be assembled into multiple antenna panels for the purpose of cost reduction and power saving. Multi-panel MIMO is expected to become promising for millimeter-wave massive MIMO systems. This article gives an overview of multi-panel MIMO systems, including downlink, uplink, and non-coherent transmissions, and discuss research challenges and future directions of multi-panel MIMO. We also propose new multi-panel codebook design and corresponding CSI feedback design for 5G systems as well as non-coherent MIMO transmission.

INTRODUCTION

Massive multiple-input multiple-output (MIMO) [1–4] is one of the key enabling technologies for fifth generation (5G) communications, because it can provide more degrees of freedom than conventional MIMO. On the other hand, 5G is expected to provide more spectrum resources than LTE, especially in high-frequency bands above 6 GHz. In fact, significant beamforming gains brought by massive MIMO are vital to improve the coverage at very high-frequency bands [5]. In 5G, the base station is called gNB. To build a large-scale antenna array at gNB, integrated antenna in package/tile (AIP/AIT) technology is a potential solution for its easy implementation, low cost, and low complexity for the chip design, where antenna elements are usually configured in multiple panels [6]. In a multi-panel MIMO system, a gNB may be configured with more than one antenna panels, where multiple radio frequency integrated circuits (RFICs) are integrated in each antenna panel. Through the AIP technique, one RFIC can have multiple antenna elements (8, 16, etc.). However, there are few studies on the performance of MIMO transmission technique based on the multi-panel antenna structure.

In this article, we present an overview of multi-panel MIMO systems in 5G, including channel state information (CSI) feedback techniques, special reference signal (RS) design, user equipment (UE) beamforming and power control mechanisms, and so on. Considering that the legacy codebook and CSI feedback mechanism may cause beam distortion and beam gain

reduction for multi-panel MIMO transmission, we propose new multi-panel codebook design and corresponding CSI feedback design for 5G systems. Observing that the large-scale channel characteristics are usually different for various antenna panels (e.g., timing offset, frequency errors, average receiving power), we give an analysis of the impact of those factors on the system performance and propose non-coherent MIMO transmission. Further, new specific RS design and interference cancellation mechanisms are proposed accordingly. For the uplink, we propose transmission schemes and system design to support low-correlated multiple-antenna panels at the UE side. The UE may use one or multiple antenna panels for transmitting data streams according to its abilities. We analyze the application cases and propose transmission schemes, CSI acquisition, and a power control mechanism for uplink multi-panel MIMO.

This article is organized as follows. We first give an introduction of the application scenario and categories of multi-panel antenna array structure. Then we give analysis on the CSI feedback design for downlink coherent multipanel MIMO transmission. We also analyze the performance degradation caused by timing/frequency errors for coherent MIMO transmission and then propose related design for noncoherent multi-panel MIMO transmission. Finally, we present the application cases and transmission schemes for uplink multi-panel MIMO in future 5G communication systems. Some research challenges and issues are also discussed.

MULTI-PANEL ANTENNA ARRAY

A multi-panel antenna array provides a flexible way to dynamically configure or dismantle the panels according to practical applications. Figure 1 shows typical scenarios for multi-panel-based wireless transmission in 5G. The panels could be hung on the walls inside a room, outside a building, or on the top of a house and streetlamps. The distributed antenna panels could be used jointly for downlink transmission to the users, or used at the transmitter in the wireless backhaul. The benefits of multi-panel MIMO include less hardware cost and less power consumption. This is because more antenna elements integrated in a single panel will result in higher complexity of routing of circuit components and antenna elements. Moreover, the cooling requirement of the circuits is also higher. In addition, separating antenna panels at a proper distance may result in high multiplexing gain with the reduction of correlations between antennas.

Generally, antenna elements with the same polarization in one panel are equally spaced in the vertical or horizontal direction when they are placed onto different panels. For massive MIMO with multiple antenna panels, the following two potential antenna structures are considered, as shown in Fig. 2:

- Uniform panel array (UPA): The antenna elements of the same polarization are uniformly distributed across the whole panel array such that the spacing between two adjacent antenna elements from different antenna panels is the same as the spacing between two antenna elements in the same antenna panel.
- Non-uniform panel array (NUPA): The antenna elements of the same polarization are non-uniformly distributed in terms of multiple panels such that the spacing between two adjacent antennas from different panels is larger than the spacing between antennas in the same panel.

DOWNLINK MULTI-PANEL MIMO

For downlink transmission with multiple antenna panels, the accuracy of CSI acquisition is critical for the system performance. To characterize the channel directional information, the codebook and related feedback mechanism are usually designed for CSI acquisition, especially for frequency-division duplex (FDD) systems [7]. For users in the cell edge of time-division duplex (TDD) MIMO, reciprocal channel estimation based on uplink reference signal is also inaccurate, and codebook-based CSI feedback can help improve the performance.

Codebook design for massive MIMO in 5G should be flexible for different antenna array structures and applicable to various number of antennas. For UPA, the codebook is designed similarly to the one used for full-dimension MIMO (FD-MIMO) in LTE/LTE-A [8]. While a single discrete Fourier transform (DFT) vector can only characterize one spatial channel path, an advanced codebook taking the combination of two or more DFT vectors as the precoder can capture the characteristics of multipath channels better [9, 10].

For NUPA, the antenna elements in the horizontal/vertical direction cannot be viewed as a uniform array. Thus, array response vector is not in DFT form, and additional phase difference exists between the panels. In other words, the DFT vector cannot capture the actual channel response, but can cause beam distortion and beam gain reduction. Moreover, panels at one Tx/Rx point (TRP) are not easily calibrated in implementation, where a fixed or random phase may exist among different panels. A good codebook design should use phase/amplitude factors among panels to combine the beamforming vectors of the panels to match the array response.

MULTI-PANEL CODEBOOK DESIGN

In multi-panel MIMO codebook design, we propose to use 2D-DFT vectors as the per-panel beamforming vectors representing the spatial propagation properties for each panel. Further, an inter-panel co-phasing factor is added across the DFT-based codeword to reduce performance loss. Taking the two-panel case as an example, we

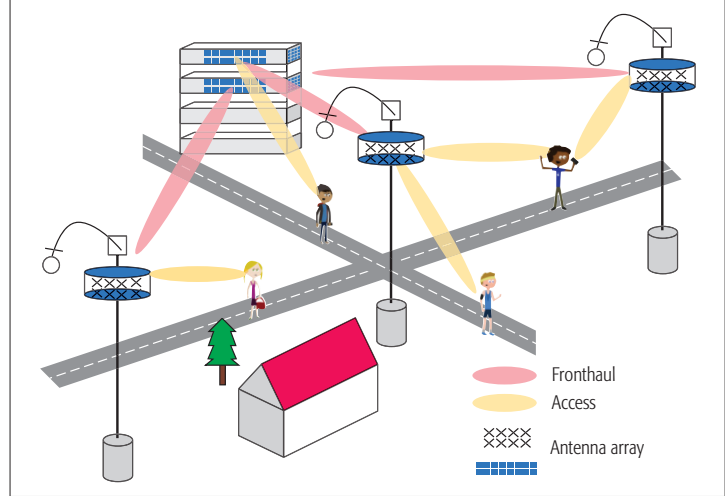


Figure 1. Multi-panel MIMO transmission in 5G

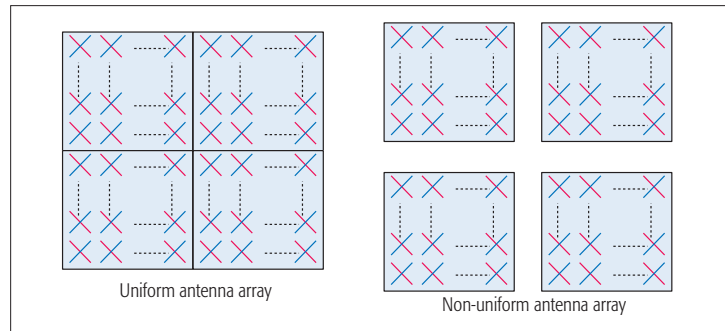


Figure 2. UPA vs. NUPA

design the multi-panel codebook $\mathbf{W}$ with the following format for dual polarized antenna arrays.

$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_1^1 \mathbf{W}_2^1 \\ \mathbf{W}_1^2 \mathbf{W}_2^2 \phi_1 \end{bmatrix} \quad (1)$$

where $\mathbf{W}_1^1$ and $\mathbf{W}_2^1$ consist of DFT vectors reflecting the long-term channel characteristics of antenna panel 1 and panel 2, respectively. $\mathbf{W}_1^2$ and $\mathbf{W}_2^2$ consist of phase factors reflecting the short-term and frequency-selective channel elements of panel 1 and panel 2, respectively. The precoding vectors for both panels are restricted to be the same in order to reduce the feedback overhead. ϕ_1 is the inter-panel co-phasing factor, which is designed for feedback in a wideband manner or subband manner according to the use cases.

In Fig. 3, we give some evaluation results of multi-panel codebook performance. In the simulation, we consider a 2×2 panel array, and a dual polarized antenna structure is used. The number of antenna ports on each panel is 4, which is virtualized from 8×8 antenna elements. The spacing between the antenna elements inside the panel is 0.5λ . The spacing between the panels in the horizontal and vertical dimension are 8λ and 4λ , respectively. The carrier frequency is 30 GHz and system bandwidth is 10 MHz. We use 4 bits for phase compensation in the codebook in the vertical and horizontal dimensions with 2

The RS transmitted from geographically separated panels may experience different Doppler shift and Doppler spread, because UE may move in a different direction relative to the panels. If the UE assumes the panels have the same Doppler shift and Doppler spread, the frequency offset estimation would be inaccurate, which incurs performance degradation.

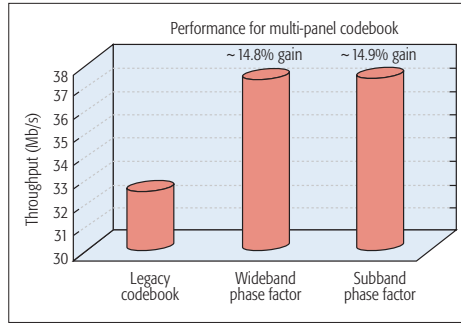


Figure 3. Performance comparison of multi-panel codebook.

bits per dimension. In Fig. 3, we see that about 15 percent performance gain is achieved compared to the legacy codebook if wideband phase factor or subband phase factor is added. The reason wideband and subband phase factors have similar performance is that the panel calibration error is not considered.

LOW-COMPLEXITY CODEBOOK DESIGN

To utilize the multi-panel codebook proposed in the previous section, channel state information reference signal (CSI-RS) is needed for each panel. Further, as the number of antenna ports increases with the number of panels, the computation complexity, such as codeword selection in the codebook and signal-to-interference-plus-noise ratio (SINR) estimation under the selected codeword, at the UE side also increases. In practice, the same CSI-RS antenna ports of each panel could be used for channel estimation in order to reduce the RS overhead. Thus, we propose a low-complexity algorithm codebook design next. First, we rewrite Eq. 1 as follows,

$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_1^1 \mathbf{W}_2^1 & 0 \\ 0 & \mathbf{W}_1^2 \mathbf{W}_2^2 \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{I} \phi_1 \end{bmatrix} \quad (2)$$

To reduce the overhead of the codebook, we separate the design of single-panel codebook (codeword $\mathbf{W}_1^1 \mathbf{W}_2^1$ or $\mathbf{W}_1^2 \mathbf{W}_2^2$ [11]) and inter-panel codebook (containing ϕ_1) and give the following algorithm for design of $\mathbf{W}$:

- In the first step, RS corresponding to the antenna ports on one of the panels is used to determine the best codeword in the per-panel codebook.
- Then another RS consisting of beamformed CSI-RS antenna ports from a different antenna panel is used for the estimation of inter-panel phase factor ϕ_1 and codeword selection in the inter-panel codebook.
- Finally, channel quality information (CQI) could be calculated and reported based on the beamformed CSI-RS ports.

In addition, a non-constant multi-panel codebook could also be considered in the future for refinement of CSI acquisition. For example, the large-scale channel fading of different panels observed at the UE are different, especially for largely spaced panels. Moreover, the virtualization for the antenna elements in different panels may be different. When a single antenna port in one

panel is connected to more antenna elements compared to another panel, the average gain observed by the UE will also be larger. As a consequence, eigen-vectors of the channel matrix will be ill conditioned. In this case, adding amplitude factors among panels into the multi-panel codebook could characterize the eigen-vector better.

NON-COHERENT MULTI-PANEL MIMO

For UPA or NUPA with ideal synchronization or small phase drift, coherent transmission can be conducted to achieve spatial multiplexing/diversity gain. However, the performance of coherent transmission may be degraded in practice for several reasons. For example, different reflection and refraction propagation paths cause different average channel delay and different average channel gain for a given direction of arrival and departure. If antenna ports from different panels experience different large-scale fadings, thereby causing eigen-vectors of the channel matrix ill conditioned and resulting in the inaccurate CSI for coherent MIMO transmission. Moreover, time-varying amplitude or phase calibration error among the panels occurs in practice, especially when the antenna panels have independent clocks and the working temperature is not stable. In addition, the frequency offset for different panels observed at the receiver may be different when there is a time-varying relative phase between different antenna panels. In the following, we first analyze the impact of frequency offset error and improper timing offset on performance of multi-panel MIMO. Then we propose some solutions to address the design challenges for multi-panel MIMO transmission.

FREQUENCY OFFSET ANALYSIS

The RS transmitted from geographically separated panels may experience different Doppler shift and Doppler spread, because user equipment (UE) may move in a different direction relative to the panels. If the UE assumes the panels have the same Doppler shift and Doppler spread, the frequency offset estimation would be inaccurate, which incurs performance degradation. The relative frequency offset between panels can be from 0 to 300 Hz, based on the following factors:

- Doppler shift: For a UE moving with the speed of 30 km/h at the carrier of 2 GHz, the maximum difference between the experienced Doppler shift is 111 Hz.
- Frequency error: In 2G/3G/LTE, the tolerable accuracy error of the oscillator is ± 0.05 ppm at its maximum for the wide area TRPs according to TS 36.104 [12]. Accordingly, the maximal frequency error between two non-calibrated panels with independent oscillators at the carrier frequency of 2 GHz is about 200 Hz.

Thus, the total amount of relative frequency offset is around 300 Hz. From Fig. 4, it can be observed that as the frequency carrier becomes higher, the frequency offset problem would be more critical.

TIMING OFFSET ANALYSIS

The same timing offset assumption for different panels may impact the accuracy of channel estimation. With a timing offset, a random lin-

ear phase factor will be added into the channel coefficient on adjacent subcarriers, which is hard to estimate accurately. The inter-symbol interference (ISI) caused by the timing offset impacts the channel estimation accuracy seriously in both CSI measurement and data demodulation, thereby degrading the MIMO performance significantly. The simulation results shown in Fig. 5 illustrate the impact of timing offset on the throughput performance, where the positive timing offset represents the signal from one TRP to UE is later than the reference timing, while negative timing offset represents the signal arriving at UE in advance. It shows that the performance loss due to timing offset is not negligible, especially in the case of negative timing offset. For positive timing offset, when the aggregated signals are received with the timing difference shorter than the CP length, less ISI is incurred. For the negative timing offset, since the incurred ISI cannot be addressed by removing the CP, the performance loss is severely caused.

NON-COHERENT MULTI-PANEL MIMO

Based on the above analysis, it can be known that for non-calibrated and geographically separated panels, coherent MIMO transmission may cause obvious performance degradation due to frequency offset and timing offset. To deal with these problems, non-coherent MIMO transmission with multi-panels is one solution. In our proposed non-coherent multi-panel transmission, data streams are divided into several groups according to the number of panels, and the data streams in different groups are transmitted using the antenna array in different panels, so the timing offset and frequency errors can be estimated for each panel independently. In the following, we discuss several techniques corresponding to non-coherent multi-panel transmission, especially with regard to the interference cancellation and RS design.

Receiver capability of interference suppression is critical for the performance of non-coherent MIMO transmission. For coherent MIMO transmission, a traditional linear receiver like MRC/minimum mean square error (MMSE) can be used to achieve acceptable performance, while for non-coherent MIMO transmission, an advanced receiver is required. Some examples are given in the following.

If data streams come from different directions (especially in the case of widely spaced panels) and arrive at UE in different angles, a simple linear receiver like MMSE may be sufficient. However, the performance gain depends on the remaining interference after the space domain interference rejection operation by MMSE processing.

If different streams arrive at the UE from the same or adjacent directions (e.g., different antenna panels located in a centralized manner), inter-stream interference is unavoidable and is the dominant factor to degrade the demodulation performance. In this case, a nonlinear receiver may be needed. When the received signal power difference among the streams is larger than 3 dB, the codeword-level successive interference cancellation (SIC) receiver can work very well. However, when the received signal power is almost the same for different data streams, the performance of SIC will deteriorate. A parallel interference cancellation (PIC) receiver is a good choice for this scenario.

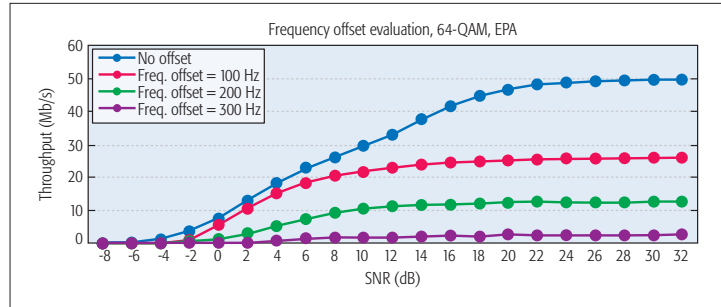


Figure 4. Frequency offset evaluation.

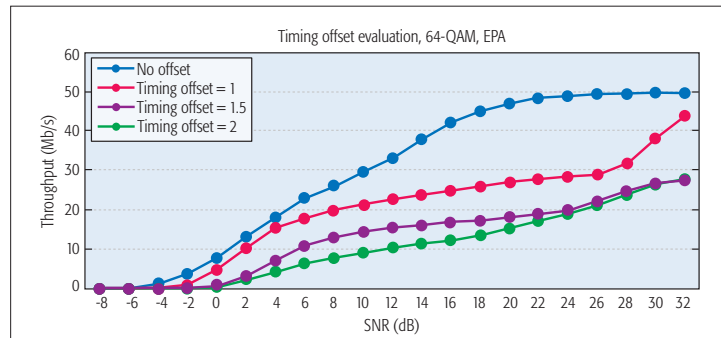


Figure 5. Timing offset evaluation.

In 5G, the enhanced demodulation reference signal (DMRS) and newly introduced tracking reference signal (TRS) are proposed to estimate the timing offset and frequency errors [13]. To guarantee that the timing offset and frequency error of the antenna panels can be estimated independently, the DMRS and TRS should be grouped, and the grouping results are indicated to UE. The UE distinguishes the time-frequency resource of RS allocated for different data streams. In this way, timing offset and frequency errors can be independently estimated for different MIMO layers in non-coherent MIMO transmission to improve the performance. Moreover, the timing offset and frequency errors could be used together with a SIC receiver to improve the performance.

UPLINK MULTI-PANEL MIMO

As the antenna size can be significantly reduced in the high-frequency domain, it is possible to integrate multiple antennas within a chip and support multiple antenna panels with low correlation at the UE side. The antenna panels could be placed along the top and bottom edges of a mobile phone, where the distance between antenna panels is designed to achieve low correlation. In the following, we discuss some design aspects for the uplink multi-panel transmission.

BEAM MANAGEMENT

Multi-panel antennas provide possibility and flexibility for UE to form both transmitter beamforming and receiver beamforming. Since the antenna panels can be largely spaced, UE can form multiple receiving and transmitting beamforming simultaneously, which brings several benefits as follows. For instance, UE could form multiple beams pointing in different directions simultaneously. If one of the

In 5G, new tracking RS needs to be designed for more accurate estimation of timing error and frequency offset at the UE side.

Traditionally, the RS has sufficient density in the time domain for timing error estimation and for frequency offset estimation in the frequency domain. The trade-off between the estimation accuracy and the RS overhead should be taken into account.

beams encounters blockage, UE can still receive beams from other beams. In this case, different beams of the UE need to access different panels, and the corresponding beam refinement procedure can be carried out. One well paired beam can bear some useful information and help the beam access and refinement procedure of other beams.

TRANSMISSION SCHEMES AND CSI ACQUISITION

There are several typical cases for uplink multi-panel MIMO transmission.

UEs with low capability may only use one of the equipped antenna panels for transmitting data. In this case, UE performs panel selection before data transmission. For example, UE could transmit RS from different antenna panels alternately. Then the gNB selects the panel with the strongest receiving power and informs the UE the index of the selected panel and the corresponding CSI for uplink data transmission.

For a UE with high capability, multiple antenna panels can jointly transmit data streams to the coordinated TRPs. In this case, if the multiple panels are steered toward the same orientation, coherent MIMO transmission is preferred to improve the beamforming gain in the cases of both diversity and multiplexing. The uplink codebook design with inter-panel co-phasing across panels combining the precoders of different panels can be used for gNB indicating CSI to the UE.

More advanced UEs equipped with multiple antenna panels could form transmit beams toward different orientations. Apart from joint precoding among all antenna panels, the UEs can use different panels to transmit data streams to different gNBs. Thus, independent link adaption can be used, and each gNB can indicate CSI to the UE.

To facilitate these application cases, UE needs to report supported panel information (e.g., the maximum number of panels, the index of antenna elements in each panel, the capability of simultaneous data transmission to different gNBs) to assist the decision making of the gNB.

TIMING AND POWER CONTROL

For advanced UE capable of using different panels to transmit data streams to different gNBs, the panels may have different time clocks and require different receiver timing. Even if the gNBs are ideally synchronized and have the same receiver timing, the path loss from different gNBs to the UE may be different, which still results in different receiver timing. If the UE uses a common uplink timing adjustment for the data stream transmission of different panels, the performance loss will be expected. Specifically, gNB could indicate the UE with multiple uplink timing adjustment, each corresponding to one of the panels. Besides, if the UE needs to transmit beams to different gNBs, the beams naturally would have different power requirements since the path loss is different. In other words, the power allocation of each panel should adapt to the corresponding gNB and the total power of the UE.

RESEARCH CHALLENGES FOR MULTI-PANEL MIMO

Capacity Analysis: So far the throughput of both coherent and non-coherent multi-panel MIMO is unknown. Further, capacity of coherent

and non-coherent multi-panel MIMO also needs to be studied by taking various practical factors into account, including the number of antenna elements, panel spacing, calibration errors among panels and power consumption, and so on. Capacity analysis will help us get a better understanding on whether to use coherent multi-panel MIMO to acquire beamforming and multiplexing gain or to use non-coherent multi-panel MIMO where timing/frequency timing offset is easier to handle.

High Resolution CSI: The multi-panel codebook designed in 5G belongs to a low overhead CSI mechanism, such as for low-capability UEs. To facilitate a high-resolution multi-panel codebook, non-constant modulus codebook design should be considered. Since the panels may not be calibrated or separated with large spacing, a delicate design of a high-resolution codebook may be essential for multi-panel MIMO.

Advanced Receiver: The advanced receiver design with low cost and low complexity is highly desired for non-coherent multi-panel MIMO transmission in 5G. Correspondingly, a new interference measurement mechanism should be studied, which could be used for scheduling and modulation and coding scheme (MCS) selection at the base station.

Efficient RS Design: In 5G, a new tracking RS needs to be designed for more accurate estimation of timing error and frequency offset at UE side. Traditionally, the RS has sufficient density in the time domain for timing error estimation and for frequency offset estimation in the frequency domain, respectively. The trade-off between the estimation accuracy and the RS overhead should be taken into account.

Uplink Transmission: For a UE equipped with multiple antenna panels, various uplink precoding schemes are needed for different application cases, such as closed loop precoding, semi-open loop precoding, or diversity schemes. Moreover, power saving techniques and transmission schemes need to be studied on the premise of reaping the beamforming or multiplexing gain of multi-panel MIMO.

CONCLUSION

Multi-panel MIMO, as one of the practical applications of massive MIMO, assembles a large number of antenna elements into multiple antenna panels. In this article, we give an overview of multi-panel MIMO-based 5G mobile communication systems, including antenna structures, application cases, and the specific design of multi-panel MIMO, and discuss the research challenges and future research directions. We demonstrate that multipanel MIMO can also be used for uplink transmission at the UE side, which could be used to either improve the downlink performance or increase the coverage in the uplink. We discuss the design issues in multi-panel MIMO, including a high-resolution CSI mechanism, tracking RS design, advanced receivers, UE beamforming, and so on. We envision multi-panel MIMO unlocking an unprecedented capacity breakthrough in 5G communications.

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