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Review:

Over-the-air measurement for MIMO systems*

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Abstract: Over-the-air (OTA) testing is an industry standard practice for evaluating transceiver performance in wireless devices. For the fifth generation (5G) and beyond wireless systems with high integration, OTA testing is probably the only reliable method to accurately measure the transceiver performance, suitable for certification as well as for providing feedback for design verification and optimization. Further, multiple-input multiple-output (MIMO) technology is extensively applied for stable connection, high throughput rate, and low latency. In this paper, we provide an overview of the three main methods for evaluating the MIMO OTA performance, namely, the multiprobe anechoic chamber (MPAC) method, the reverberation chamber plus channel emulator (RC+CE) method, and the radiated two-stage (RTS) method, with the aim of providing a useful guideline for developing effective wireless performance testing in future 5G-and-beyond wireless systems.

Key words: Over-the-air (OTA) testing; Wireless performance testing; Fifth generation (5G) and beyond; Multiple-input multiple-output (MIMO); Multiprobe anechoic chamber (MPAC); Radiated two-stage (RTS); Reverberation chamber plus channel emulator (RC+CE)
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1 Introduction

To meet the unprecedented increase in the need for faster wireless devices with more stable performance in the upcoming fifth-generation (5G) and beyond wireless communication systems, various technologies have been studied and developed, such as multiple antenna systems, beamforming, and millimeter-wave applications (Alkhateeb et al., 2014; Qi et al., 2017). Multiple-input multiple-output (MIMO) antenna technology—a core technology for contemporary communication in Long-Term Evolution (LTE) and 5G terminals—allows for high speed, low latency, and high throughput (Sauter, 2013; Yadav and Dobre, 2018). MIMO technology and its evolutions are deemed a key component in future 5G-and-beyond wireless devices (Al-Mejibli and Al-Majeed, 2018), Internet of Things (IoT) devices, and devices used in connected vehicles, satellites, ship communication systems, and so on.

Before wireless MIMO devices can be placed on the market, their wireless performance should be tested and certified (CTIA, 2017; 3GPP, 2018a, 2018b, 2018c). MIMO over-the-air (OTA) testing becomes the only reliable method to accurately measure the wireless performance in 5G-and-beyond wireless devices in which antennas are tightly integrated with transceivers. Thus, MIMO OTA testing plays a major role in the research and development (R&D), certification, and mass product line stages for 5G-and-beyond wireless devices. It helps radio frequency (RF) and antenna engineers validate and optimize their

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designs in the R&D stage. In the certification stage, MIMO OTA testing serves as an industry standard. At the mass product line stage, it can be used to verify the RF consistency of wireless terminals to exclude inadequate products.

For IoT MIMO devices, such as smart, wearable health-care and smart home devices, the better designed the wireless systems with high transceiver performance and stability, the better the user experience and the easier the layout of the wireless network (Rumney et al., 2016; Jing et al., 2018; Shen et al., 2019b). For large-scale civilian MIMO equipment, such as intelligently connected vehicles, civil aviation aircrafts, and ships, the wireless MIMO performance is related to human safety. For military MIMO equipment, such as airborne radars, communication satellites, radar satellites, navigation satellites, military vehicles, and tanks, the wireless stability and transceiver performance are key factors for winning modern high-tech wars. Therefore, MIMO OTA testing, as a standard practice to evaluate wireless performance, needs to be accurate, objective, efficient, easy to conduct, affordable, and more importantly, reflects the performance in real-world applications under typical operations.

In MIMO OTA testing, the ultimate parameter is the measured throughput, which is based on the channel model defined by the Third-Generation Partnership Protocol (3GPP) and Cellular Telecommunications and Internet Association (CTIA). A channel model is a mathematical model that creates a repeatable measurement environment, which describes the multipath environment in a typical usage model of the device under test (DUT). Therefore, the channel model is the key to ensuring that the OTA testing can well reflect the DUT performance in its typical usage model and thus needs to be accurately implemented in OTA testing methods. Three MIMO OTA testing methods have been proposed herein and studied: the multiprobe anechoic chamber (MPAC) method, the radiated two-stage (RTS) method, and the reverberation chamber plus channel emulator (RC+CE) method (Chen et al., 2011; Valenzuela-Valdés et al., 2013; Chen, 2014). The MPAC method implements the channel model by distributing multiple antennas in the physical space in an anechoic chamber in a semiphysical, semimathematical fashion; the RC+CE method uses mechanical stirrers to emulate a statistically isotropic multipath environment; the RTS method implements the channel model entirely mathematically and delivers the desired signals directly to the receiver of the DUT (ports to ports) over the air. Among these MIMO testing methods, the MPAC and RTS methods (Yu et al., 2014; Shen et al., 2019a) have been accepted as the international standards for evaluating MIMO OTA performance by both the 3GPP and the CTIA.

The 5G MIMO technologies can be applied to various devices, from handheld IoT devices with small size to large-scale industrial and military equipment. In this paper, we introduce the basic principle of the channel model, provide an overview of MIMO OTA testing methods, and compare the MPAC and RTS methods in detail. The aim of this paper is to provide guidelines to help engineers select a proper and suitable method for MIMO measurements for their specific device.

2 Channel model for MIMO testing

The channel model (Cho et al., 2010; Li JZ et al., 2017) represents the total propagation environment from the transmitting side (the base station side) to the receiving side (the DUT side). As discussed earlier, it is crucial to create an accurate, stable, repeatable, and representative channel model in the testing chamber before performing MIMO OTA testing. Several standard channel models have been introduced to simulate the typical scenarios in MIMO devices. The basic parameters of the simulated channel models include the numbers of clusters and subpaths in each cluster, transmission delay, power distribution, angles of arrival (AoAs), angles of departure (AoDs), and Doppler effects.

Fig. 1 presents an intuitive and clear description of the channel model, which represents an $M\times N$ MIMO system with M antennas in the base station and N antennas in the DUT. The properties of the subpaths include the antenna patterns of both the base station and the DUT, the signal delay, the Doppler effects produced by the objects with relative movement, the AoAs from the DUT, and the AoDs of the base station. The mathematical formula of the propagation environment in terms of the signals transmitted from the m^{th} transmitting port of the base station to the n^{th} receiving port of the DUT with L subpaths between the base station and the DUT can be expressed as follows (Shen et al., 2018, 2020):

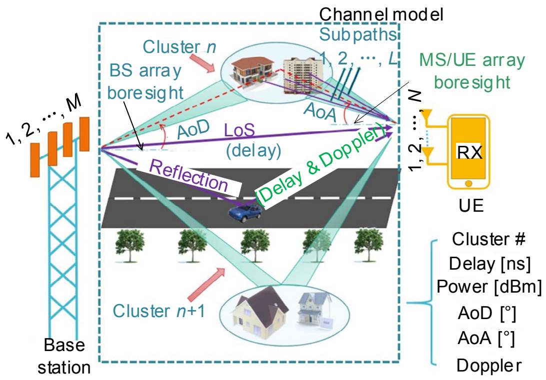

Fig. 1 Overview of MIMO channels

MIMO: multiple-input multiple-output; BS: base station; MS: mobile station; UE: user equipment; RX: receiver; AoD: angle of departure; AoA: angle of arrival; LoS: line of sight

$$h_{n,m}(t)=\sum_{l=1}^{L}\exp\left(\mathrm{j}2\pi\Phi_l t+\psi_l-\mathrm{j}2\pi f\tau_l\right)\cdot\begin{bmatrix}G^{\mathrm{V}}_{n,\mathrm{DUT}}(\alpha_{l,\mathrm{AoA}})\\ G^{\mathrm{H}}_{n,\mathrm{DUT}}(\alpha_{l,\mathrm{AoA}})\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}\chi_l^{\mathrm{V,V}} & \chi_l^{\mathrm{V,H}}\\ \chi_l^{\mathrm{H,V}} & \chi_l^{\mathrm{H,H}}\end{bmatrix}\begin{bmatrix}G^{\mathrm{V}}_{m,\mathrm{BS}}(\beta_{l,\mathrm{AoD}})\\ G^{\mathrm{H}}_{m,\mathrm{BS}}(\beta_{l,\mathrm{AoD}})\end{bmatrix},\tag{1}$$

where f is the frequency of interest, t is the time, and ψ_l, Φ_l, and τ_l are the prime phase, Doppler frequency component, and time delay of the l^{th} subpath respectively, $G^x_{n,\mathrm{DUT}}$ and $G^x_{m,\mathrm{BS}}$ represent the antenna gains of the n^{th} antenna at the DUT side and the m^{th} antenna at the base station side respectively, with the superscript x (x=V or H) representing the polarization of the antennas, $\alpha_{l,\mathrm{AoA}}$, $\beta_{l,\mathrm{AoD}}$, and $\chi_l^{x,y}$ are the AoA, AoD, and complex path loss from antenna polarization y to x (x, y=V or H) in the l^{th} subpath respectively. The total propagation environment can be described using $M\times N$ equations of Eq. (1); therefore, the total transmitting matrix from the base station with M antennas to the DUT with N antennas can be defined in a matrix form as follows:

$$\boldsymbol{H}(t)=\begin{bmatrix}h_{1,1}(t) & h_{1,2}(t) & \cdots & h_{1,M}(t)\\ h_{2,1}(t) & h_{2,2}(t) & \cdots & h_{2,M}(t)\\ \vdots & \vdots & & \vdots\\ h_{N,1}(t) & h_{N,2}(t) & \cdots & h_{N,M}(t)\end{bmatrix}.\tag{2}$$

$\boldsymbol{H}$ is the channel coefficient matrix in a MIMO channel model, and it represents the total propagation environment from the base station's antenna feeds to the receiver ports of the DUT. Hence, the signals received by the DUT can be expressed as follows:

$$\boldsymbol{y}(t)=\boldsymbol{H}(t)\boldsymbol{x}(t),\tag{3}$$

where the received signals $\boldsymbol{y}=[y_1, y_2, \ldots, y_N]^{\mathrm{T}}$ are functions of the transmitting signals $\boldsymbol{x}=[x_1, x_2, \ldots, x_M]^{\mathrm{T}}$. Before performing MIMO OTA testing, $\boldsymbol{H}$ has to be constructed or implemented in the chamber, and then the correct signals with the channel model included can be delivered to the DUT for MIMO OTA testing.

3 Overview of MIMO testing methods

The traditional method for MIMO testing uses cables to connect the instrument ports to the receiver ports of the DUT, and then the desired signals are delivered to the receiving ports to conduct the MIMO throughput measurement. In addition to the inconvenience of connecting the cables between the instrument and the receiving ports of the DUT, this manual operation could lead to mismatches and inconsistencies in the RF circuit connections. For the 5G-and-beyond wireless systems, especially millimeter-wave devices with integrated antennas, there may be limited or even no room for RF connectors, owing to the requirements of low cost and small size for wireless terminals. Then, OTA becomes the only possible solution for MIMO testing.

In addition, for MIMO measurement using cables, the potential problem of sensitivity degradation due to device self-interference is not properly considered. As shown on the left panel of Fig. 2, in real applications, the noise radiating from the DUT hardware (mainly from the digital circuits and the switching power converters) could be coupled to the antennas, increasing the noise level and decreasing the signal-to-noise ratio of the receivers, especially with poor electromagnetic compatibility (EMC) designs. When the antenna ports are connected with cables, self-interference is not included in the testing, resulting in large uncertainty in the measurement results compared with the real application scenario. Therefore, OTA is more accurate in reflecting the real-world RF performance of the DUT. The sensitivity degradation effect may be more significant in the MIMO testing of 5G-and-beyond wireless devices due to the higher complexity of the system, possibility of more sources of noise, higher density, and tighter integration with antennas.

Therefore, MIMO OTA testing has become standard practice. The principles of the three proposed MIMO OTA methods are introduced in the following.

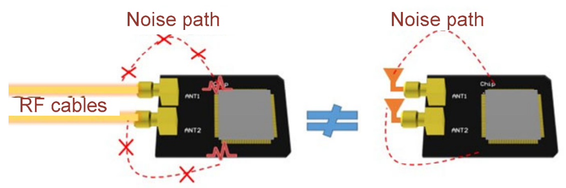

Fig. 2 Noise interference in connection and OTA modes
OTA: over-the-air; RF: radio frequency

3.1 RC+CE method for MIMO testing

The RC+CE testing method involves a metallic cavity that emulates an isotropic multipath environment, which represents a reference propagation environment for MIMO OTA measurement. As shown in Fig. 3, the RC+CE method includes fixed wall-mounted antennas, mechanical metallic stirrers, and a turntable to hold the DUT. In addition, the chamber may include one or more cavities coupled through waveguides or slotted plates. For MIMO OTA measurement, instead of creating line-of-sight signals, the RC+CE method can use mechanical stirrers to emulate statistically isotropic channel models based on the reflections in the chamber, which could be useful for evaluating MIMO OTA performance.

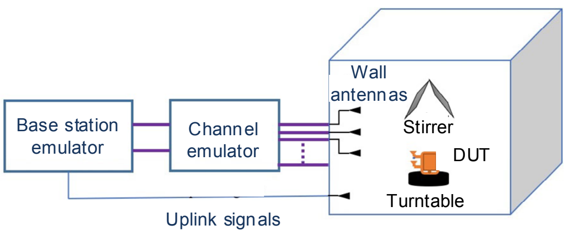

Fig. 3 Schematic of the reverberation chamber plus channel emulator (RC+CE) method
DUT: device under test

However, the details of the RC+CE method are not discussed in this paper for two reasons. First, some standard mathematical channel models, such as the spatial channel models and the spatial channel model extension, are not available and thus are not realized in the RC+CE method. In addition, the RC+CE method is not found in 3GPP and CTIA standards, and thus it is not a standard methodology for MIMO OTA testing yet (3GPP, 2017; CATR, 2017).

3.2 MPAC method for MIMO testing

The MPAC method has already been recognized by the CTIA and 3GPP as a standard MIMO OTA testing method for throughput measurement to evaluate the receiver performance of a DUT (Xiao and Foegelle, 2016; Fan et al., 2017; Hekkala et al., 2017).

As shown in Fig. 4, to produce the two-dimensional (2D) channel model, the DUT is placed on a turntable at the center of the chamber, and at least eight probe antennas with dual polarizations form a ring surrounding the DUT. The ring is covered by absorbers to decrease reflections during the MIMO testing. The transmitting signals x_1, x_2, …, x_M from the base station emulator are delivered to the DUT through the channel emulator and the propagation environment between the output ports of the channel emulator and the input receiving ports of the DUT. In other words, the desired propagation environment is implemented in a semiphysical and semimathematical fashion in the MPAC method. For the mathematical part, the antenna patterns of the DUT are measured and imported into the channel emulator, to calculate the desired transmitting signals according to the parameters of the channel model, such as time delay and the Doppler effect. For the physical part, the AoA and AoD are realized by synthesis of the multiple signal clusters transmitted from the multiple probe antennas.

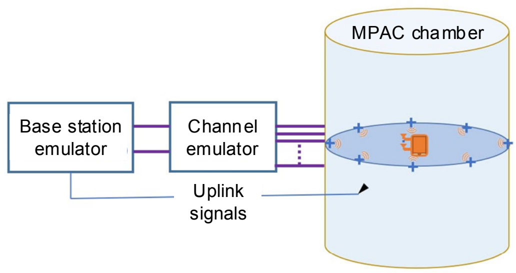

Fig. 4 Schematic of the multiprobe anechoic chamber (MPAC) method

To perform MIMO throughput measurement using the MPAC method, the amplitude and phase of the propagation environment from each channel emulator port to the DUT must first be calibrated, and then the desired signals are calculated and delivered to the receiver of the DUT. During MIMO throughput measurement, the DUT should be rotated to different angles on the turntable to measure the MIMO performance in different angles.

MPAC is an intuitive testing method that creates a standard channel model defined by the 3GPP in a semiphysical and semimathematical realization. The MPAC method has been widely used in LTE MIMO measurement for MIMO devices in 2D environments. With the growing need for more comprehensive and accurate performance evaluations, the three-dimensional (3D) MIMO OTA testing is needed. It is difficult to upgrade a preexisting MPAC chamber for the 3D MIMO test. Building a new MPAC chamber for the 3D MIMO test is also challenging because the realization of the channel models in 3D would require more antennas at different elevation planes, resulting in additional measurement time, smaller quiet zone, and more complicated calibration steps. As specified by the 3GPP, the MIMO measurement uncertainty for the MPAC method is ±2.65 dB; however, it has been reported to reach 7.3 dB (Huawei, 2017) in some MPAC tests. The large uncertainty is probably related to the issues in the calibration. In addition, the size of a standard MPAC chamber for 4G MIMO measurement usually exceeds 7.2 m. With the higher requirements of 5G-and-beyond wireless systems, the MPAC method for MIMO testing should be further improved to meet the future requirements of MIMO OTA measurement.

3.3 RTS method for MIMO testing

The RTS method allows for a direct connection from a transmitting port to a receiving port over the air. Thus, it mimics the real application. The self-interference at the antennas of the DUT is included in the test, eliminating the measurement uncertainty. The implementation of the propagation environment in the RTS method is purely mathematical. Theoretically, any arbitrary MIMO configuration can be implemented, without the need for additional probe antennas and complicated calibration. The potential measurement uncertainties related to the reflections and the imperfect calibrations are thus eliminated. Thus, the RTS method is expected to play a major role in the MIMO OTA measurement for evaluation of 5G-and-beyond wireless systems.

The RTS method can be described in two main stages. However, dividing the measurement into two stages is unnecessary in practice because the same setup can be used for each stage:

Stage 1: Test the patterns of the receiving antenna of the DUT in a conventional anechoic chamber. During the first stage, the phase differences among the multiple transmitting signals corresponding to each receiving antenna of the DUT are tested and recorded for stage 2. In addition, the DUT needs to report the measured received signal strength indication (RSSI) to the base station emulator for obtaining a propagation matrix $\boldsymbol{H}'$ using the rotation vector method.

Stage 2: Calculate the inverse matrix of the propagation matrix and apply it to the instrument. Then, combine the antenna patterns and the channel models in the channel emulator to calculate the desired output signals that are fed into the transmitting antennas. Subsequently, perform the MIMO OTA throughput test and evaluate the results.

To deliver the signals calculated in stage 2 to the receiver of the DUT over the air, the channel coefficient matrix $\boldsymbol{H}$ must be calibrated, because multiple virtual paths exist from the transmitting ports of the instrument to the receiving ports of the DUT. In MIMO OTA testing, P antennas can be assumed to be present at both the transmitter and the receiver sides. Then, we have

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_P \end{bmatrix} = \boldsymbol{H}' \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_P \end{bmatrix}, \tag{4}$$

where $\boldsymbol{x}=[x_1, x_2, \ldots, x_P]^{\mathrm{T}}$ represents the desired transmitted signals calculated in the channel emulator, which combines the channel models and the antenna gain patterns, $\boldsymbol{y}=[y_1, y_2, \ldots, y_P]^{\mathrm{T}}$ is the received signal vector at the receiving ports, which is not the same as $\boldsymbol{x}$ due to multiple virtual paths among the transmitting and receiving antennas, and $\boldsymbol{H}'$ is the real-space propagation matrix from the transmitting antennas to the receiving ones. To remove the effects of $\boldsymbol{H}'$ and make the received signals the same as those desired at the transmitting ports, the inverse matrix of $\boldsymbol{H}'$, defined as $\boldsymbol{M}$, needs to be determined and applied before the desired signals are delivered to the transmitting antennas. The received signals are related to the transmitted signals as follows:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_P \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,P} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,P} \\ \vdots & \vdots & & \vdots \\ h_{P,1} & h_{P,2} & \cdots & h_{P,P} \end{bmatrix} \cdot \begin{bmatrix} m_{1,1} & m_{1,2} & \cdots & m_{1,P} \\ m_{2,1} & m_{2,2} & \cdots & m_{2,P} \\ \vdots & \vdots & & \vdots \\ m_{P,1} & m_{P,2} & \cdots & m_{P,P} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_P \end{bmatrix}. \tag{5}$$

To make $\boldsymbol{y}$ the same as $\boldsymbol{x}$, the following relationship is necessary:

$$\begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,P} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,P} \\ \vdots & \vdots & & \vdots \\ h_{P,1} & h_{P,2} & \cdots & h_{P,P} \end{bmatrix} \begin{bmatrix} m_{1,1} & m_{1,2} & \cdots & m_{1,P} \\ m_{2,1} & m_{2,2} & \cdots & m_{2,P} \\ \vdots & \vdots & & \vdots \\ m_{P,1} & m_{P,2} & \cdots & m_{P,P} \end{bmatrix} = \boldsymbol{I}. \tag{6}$$

After the position of the DUT is selected, the inverse matrix $\boldsymbol{M}$ can be calculated and applied to the MIMO OTA testing hardware with an amplitude-and-phase adjuster, and the MIMO throughput can then be measured using the desired signals to evaluate the receiver performance of the DUT in a conventional single-input single-output (SISO) chamber.

4 Outlook of MIMO OTA measurements in 5G-and-beyond wireless systems

With the continuous evolution of wireless technologies, there are two emerging trends in 5G-and-beyond wireless systems that could affect how MIMO OTA can be tested in a standard laboratory setting. First, more antennas are being used, and the 4×4, arbitrary $M\times N$, and massive MIMO (Ali et al., 2017; Gao et al., 2019) configurations with large M and N numbers are currently under study for future systems. Second, wireless terminals are becoming more versatile. In addition to small devices such as cell phones, large-scale equipment, such as connected vehicles, satellites, and ships, are becoming wireless terminals. These new trends present new challenges in MIMO OTA testing.

4.1 MIMO measurement in large-scale equipment

Large-scale DUT can create some unique challenges in MIMO OTA testing. Let us take a vehicle as an example in the discussion in this subsection. When using the RC+CE method, the vehicle is placed in a reverberation chamber that does not have absorbers. Due to the large size of the vehicle, multiple reflections occur between the vehicle and the chamber walls. Thus, it is unrealistic to create a correct channel model because of the high-level reflection. In this regard, the RC+CE method is not suitable for large-scale DUT in the current form.

When using the MPAC method to evaluate the MIMO OTA performance of the vehicle, several issues need to be considered. First, since the propagation environment in the MPAC method is implemented in a semiphysical and semimathematical way, the quiet zone of the chamber is limited by the number of probe antennas used in the chamber. The more the probe antennas placed in the chamber, the smaller the quiet zone. This greatly limits the size of the DUT since the channel models are not correct outside the quiet zone. To address this issue, the MPAC chamber needs to be sufficiently large. Second, due to the mechanical limitations of the turntable and the vehicle, it is mechanically challenging to turn a large vehicle sideway in the standard MPAC test, which generally achieves the 3D measurement by multiple 2D tests. Third, the receiving antennas often are located off the center of rotation in the chamber. This antenna offset can introduce large errors in the measurement results. Innovations and improvements in the MPAC method are required to address the challenges of MIMO OTA testing for large-scale DUTs.

Since the RTS method is realized in a purely mathematical way, the quiet zone issue is not as serious as in the MPAC method. As shown in Fig. 5, the RTS method for vehicle MIMO OTA measurement is even applied in a small chamber with nonconventional chamber design and enhanced absorbers. The antenna patterns are measured in the radiating near-field region in the chamber and then transformed into the far-field patterns using the near-field to far-field transformation. Next, the transmitting matrix between probes 1 and 2 and two receiving antennas 1 and 2 is obtained for the MIMO throughput measurement. During the entire testing process, the vehicle is needed only to turn in a 2D plane or is fixed in the chamber without rotation depending on the deployment of the scanning probe antennas, as the scan can be completed by the probe arms. In this manner, the antenna-offset issue in MIMO throughput testing is also resolved. At this stage, the RTS method appears to be more flexible and may be a more suitable method for MIMO OTA testing for large-scale DUTs with the creative chamber design. The challenge in the RTS method is always related to the implementation of the mathematical formulation, especially related to achieving a reliable inverse matrix $\boldsymbol{M}$.

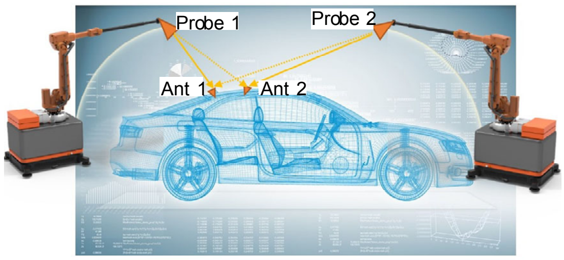

Fig. 5 RTS method for vehicle MIMO OTA measurement
RTS: radiated two-stage; OTA: over-the-air; MIMO: multiple-input multiple-output

4.2 MIMO methods in $M\times N$ measurement

Both the MPAC and RTS methods are widely applied currently for evaluating 4G LTE MIMO performances, while the RC+CE method is not an international standard yet due to the issues involving the handling of certain channel models. When more antennas are used in MIMO devices, the realization of channel models is increasingly more complex, which presents further challenges in channel model implementation in the RC+CE method.

Based on previous reports and publications, the MPAC method has been successfully applied in the testing of the 2×2 MIMO configuration in 2D environments (CTIA, 2017). For arbitrary $M\times N$ MIMO measurement with M, N>2, more probe antennas are required in the chamber due to the semiphysical and semimathematical implementation of the MPAC method, resulting in higher cost, smaller quiet zone, and more complex calibration steps. Without further innovations or improvements, this issue remains the bottleneck for the intuitive MPAC method in more complicated applications.

The RTS method has already been successfully applied to MIMO OTA testing for the 2×2 (Li J et al., 2021) and 4×4 MIMO configurations. Moving toward arbitrary $M\times N$ and massive MIMO, there is no theoretical roadblock because the channel models are implemented purely mathematically in the RTS method. The potential advantages of the method in this regard include the following:

1. The RTS method is based on mathematical realization, so it is flexible and easily improvable to handle 3D $M\times N$ and massive MIMO measurements.

2. Except for the path loss in the chamber, there are no complex calibration steps. With enhanced absorbers, the quiet zone of the chamber is not an issue and the chamber size can be smaller.

3. The RTS method can work in an existing chamber with multiple antennas, without the need for building a new special chamber for $M\times N$ and massive MIMO measurements.

As mentioned earlier, the main challenge in the RTS method is related to achieving a reliable inverse matrix $\boldsymbol{M}$ in method implementation. With more antennas, the rank of the matrix increases accordingly. An automatic algorithm needs to be developed to smartly tune and choose the measurement locations and angles to obtain the optimal inverse matrix.

5 RTS MIMO testing details

As an example, the OTA testing for a 2×2 MIMO configuration using the RTS method is described in detail in this section.

The antenna patterns of the DUT are measured in the first stage and imported into the channel emulator to calculate the desired transmitted signals. In the ideal case shown in Fig. 6a, the transmitted signals are directly delivered to the receiver of the DUT to conduct the MIMO measurement. Notice that the transmitted signals have already included the effects of the transmitting antennas, the free-space path loss, and the receiving antennas. This is ideal if it can be realized.

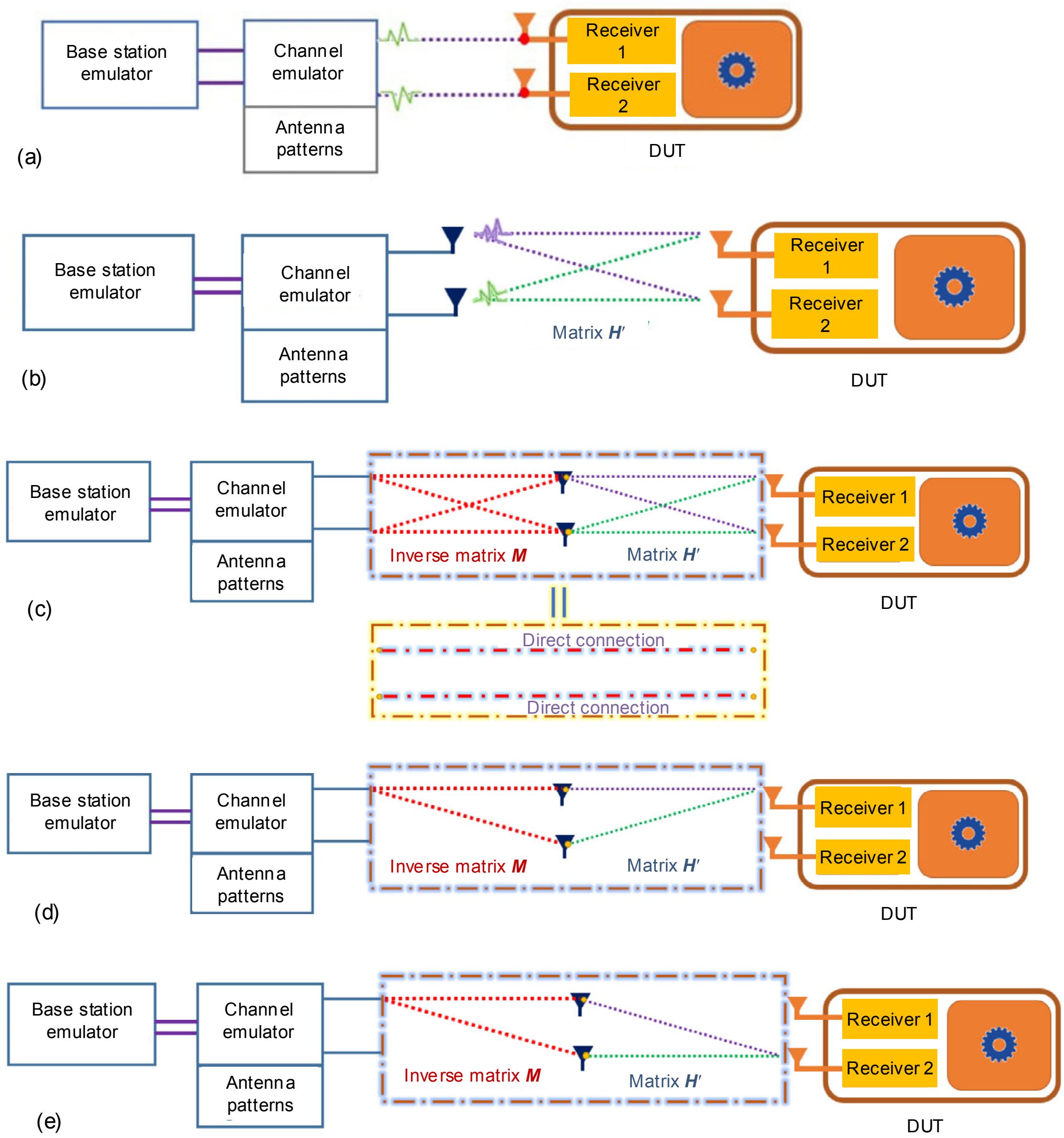

Fig. 6 Detailed steps of the RTS method: (a) the ideal case for RTS MIMO measurement; (b) the real case for RTS MIMO measurement; (d) inverse matrix *M* applied; (d) two signal paths from the transmitting signal T_1 to receiver 1; (e) two signal paths from the transmitting signal T_1 to receiver 2

RTS: radiated two-stage; MIMO: multiple-input multiple-output; DUT: device under test

However, as shown in Fig. 6b, the realistic scenario is not the same as the ideal case. In the real case, the signal radiating from one transmitting antenna can be received by both receiving antennas. As a result, the received signals are not the same as the transmitted signals. As described in Section 3, there is a propagation matrix $\boldsymbol{H}'$ between the transmitting ports and the receiving ports. In other words, the received signals are not the desired signals for testing.

To deal with this issue, it is difficult for us to focus only on how to eliminate the cross signals after the transmitting antennas. However, if we can find the inverse matrix $\boldsymbol{M}$ before the transmitting antennas of the propagation matrix $\boldsymbol{H}'$ and implement $\boldsymbol{M}$ in the instruments, we would cancel the effects of $\boldsymbol{H}'$ mathematically and equivalently realize the direct connection scenario shown in the ideal case. As shown in Fig. 6c, after $\boldsymbol{M}$ is applied, the desired transmitted signals are delivered into the receiver without distortions.

Figs. 6c–6e illustrate the steps used to determine $\boldsymbol{M}$. It can be seen that there are two ways ($L_1=m_{11}h_{11}$ and $L_2=m_{21}h_{12}$) through which signal T_1 can be transmitted to receiver 1, and two other paths ($L_3=m_{11}h_{21}$ and $L_4=m_{21}h_{22}$) from transmitted signal T_1 to receiver 2. To remove the total path from T_1 to receiver 2, the amplitude and phase of m_{11} and m_{21} can be adjusted to satisfy the following requirements:

1. L_3 and L_4 have the same amplitude and opposite phases (phase difference equals π) on receiver 2.

2. L_1 and L_2 are superimposed on receiver 1, resulting in the signal of receiver 1 equal to the transmitted signal L_1.

The two other signal paths from the transmitted signal T_2 to receivers 1 and 2 can go through the same process to find the amplitude and phase of m_{12} and m_{22}. After the values of inverse matrix $\boldsymbol{M}$ are calculated and its effects are included into the settings of the channel emulator, the desired signals can be delivered to the receiver of the DUT over the air.

To find out $\boldsymbol{M}$ for MIMO OTA measurement, a prerequisite for the DUT is its ability to report the RSSI of each receiver back to the base station. By adjusting the amplitude and phase for each antenna link path, $\boldsymbol{H}'$ and $\boldsymbol{M}$ can be determined. During the search process, the first requirement cannot be completely satisfied in practical MIMO OTA measurement due to the limited accuracy of the amplitude and phase regulator; therefore, the cross path (from transmitting port 1 to receiving port 2, and from transmitting port 2 to receiving port 1) cannot be completely removed. Thus, the relationship between $\boldsymbol{M}$ and $\boldsymbol{H}'$ in the 2×2 MIMO testing can be rewritten as follows:

$$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} S_1 & C_1 \\ C_2 & S_2 \end{bmatrix}, \tag{7}$$

where, in the ideal case, $S_1=S_2=1$ and $C_1=C_2=0$, whereas, in reality, the C_1 and C_2 terms are nonzero. To quantify the amplitude of the cross-path signals, the isolation is introduced as follows:

$$\mathrm{ISO}_1 = |S_1 / C_1|, \tag{8}$$

$$\mathrm{ISO}_2 = |S_2 / C_2|, \tag{9}$$

$$\mathrm{ISO}_\mathrm{t} = \min(\mathrm{ISO}_1, \mathrm{ISO}_2), \tag{10}$$

where ISO_t is a significant parameter of inverse matrix $\boldsymbol{M}$ which is related to the position and orientation of the DUT, and the selected transmitting antennas in the anechoic chamber. ISO_t can affect the throughput test in the second stage of the RTS method, and it must reach a certain large value to ensure that the effects of the cross path on the MIMO throughput results are negligible. To maintain a low uncertainty and high repeatability in the MIMO OTA testing, an isolation value of at least 18 dB is required before performing the MIMO OTA evaluation.

6 Measurement setup and results

This section describes the measurement setup and steps for the MIMO OTA measurement using the RTS method and thereafter compares the results of the MPAC method and the RTS method.

6.1 Measurement setup

The RTS method is divided into the following steps (in concept only, while in practice, the entire testing is conducted automatically without any intervention from the operator) during the measurement in the anechoic chamber:

1. Measure the receiving antenna patterns of the DUT.

2. Select the proper positions of the DUT and the transmitting antennas in the anechoic chamber to maintain a high isolation defined in Eq. (10).

3. Obtain the propagation matrix $\boldsymbol{H}'$ and calculate inverse matrix $\boldsymbol{M}$.

4. Import the antenna patterns into the channel emulator, and execute the MIMO throughput test with the inverse matrix applied.

As shown in Figs. 7a and 7b, in the first stage, the DUT is placed on the turntable for antenna pattern measurement. During the measurement in the second stage, the position of the DUT should be fixed after the inverse matrix is obtained. Any changes to the position would result in uncertainties in MIMO throughput measurement. In addition, a low-power amplifier may be used to ensure stable communication between the DUT and the instrument.

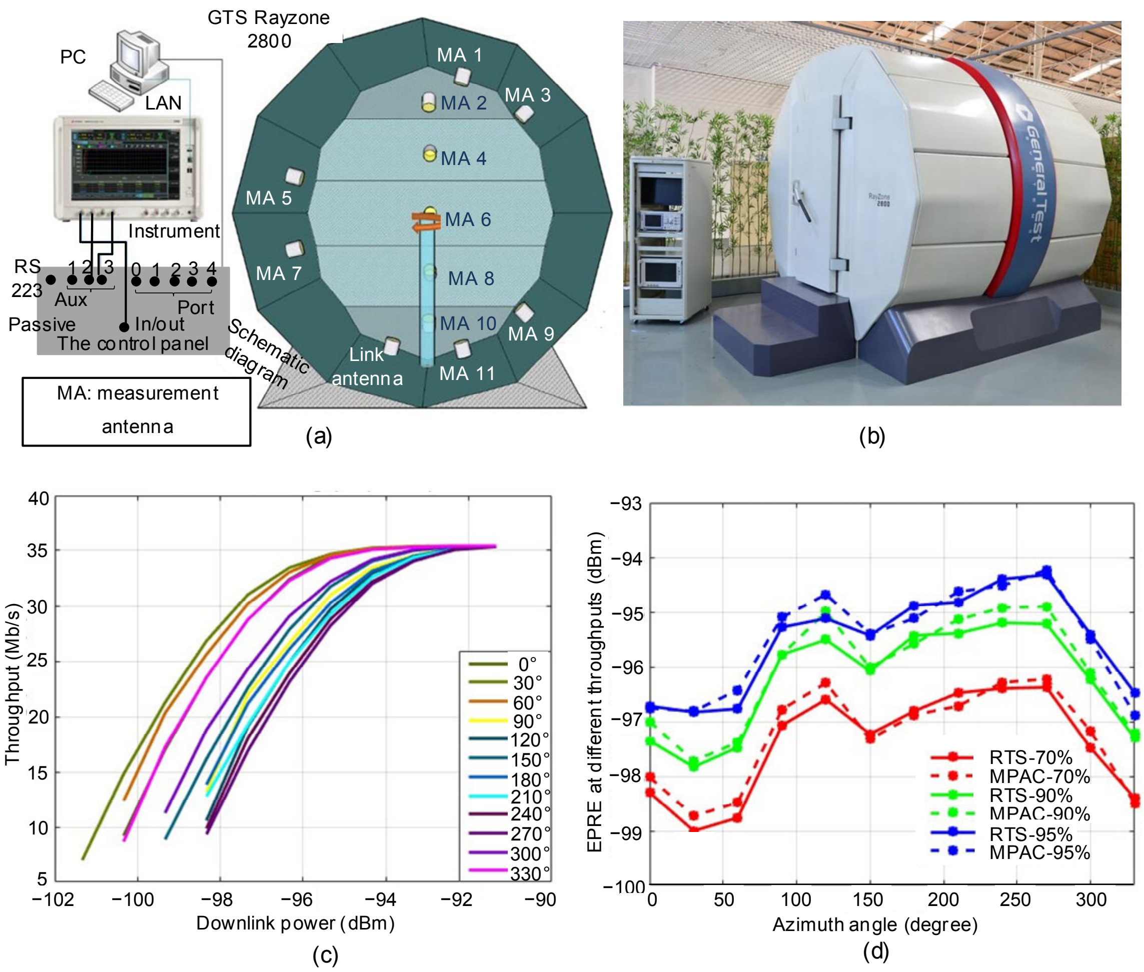

Fig. 7 Test setup and results: (a) schematic view of the MIMO test setup; (b) front view of the test setup; (c) RTS MIMO OTA throughput measurement (band 3); (d) comparison of RTS and MPAC methods on LTE MIMO
References to color refer to the online version of this figure. MIMO: multiple-input multiple-output; RTS: radiated two-stage; OTA: over-the-air; MPAC: multiprobe anechoic chamber; LTE: Long-Term Evolution; EPRE: energy per resource element

In this study, the MIMO OTA testing is performed using a Rayzone 2800 RTS anechoic chamber. During MIMO measurement, two transmitting ports are connected with cables from the instrument as downlink test signals, and an additional communication antenna is connected to the instrument for communication between the instrument and the DUT as the uplink signals. The instrument used is a UXM wireless test set E7515A, along with a highly integrated signaling tester with a base station, channel emulator, and the hardware for regulating the inverse matrix function.

6.2 Measurement results

The 2D LTE MIMO testing results in band 3 using the RTS method are shown in Fig. 7c. The 12 lines in the figure describe the relationship between the downlink power level and the MIMO throughput in different angles. When the downlink power level increases, the signal-to-noise ratio is improved, resulting in higher MIMO throughput. During the throughput measurement in the second stage, the DUT is fixed on the turntable, and the MIMO results for different angles are obtained by rotating the antenna pattern in the UXM and combining the channel models to create the needed rotation.

As the standard methods for MIMO measurement in 3GPP and CTIA, the RTS and MPAC methods are compared here for the same DUT. In Fig. 7d, the downlink power levels are shown using the RTS and MPAC methods when the DUT reaches 70%, 90%, and 95% of its maximum MIMO throughput.

The results for different angles show the same tendencies, and the maximum difference between the RTS and MPAC methods is no more than 0.5 dB, which might be introduced by uncertainties of test instrument, the reflection in the chamber, or the temperature. Although there are differences between the RTS and MPAC methods, their purpose is the same: to achieve the specified channel models for MIMO throughput measurement to evaluate the receiver performance of a DUT. The results are in good agreement and strongly suggest that both methods provide correct results. In addition, the comparison of the RTS and MPAC methods is shown in Table 1 for researchers to select the proper method based on their own requirement and budget. Furthermore, a comparison with related works is shown in Table 2.

7 Conclusions

With the rapid development of 5G-and-beyond wireless systems, MIMO OTA testing plays a major role in the wireless performance evaluation for wireless devices.

This paper provides an intuitive and clear description of channel models. In addition, the evolution of MIMO measurement has been introduced from the conducted chipset MIMO measurement to MIMO OTA measurement and its related methods (MPAC method, RC+CE method, and RTS method) for the first time. This effort will make engineers more aware of the fundamentals of and developments in various MIMO measurement methods. It can help application engineers select the right method for the MIMO test. It can also help test development scientists and engineers research test solutions for future automobile, space, and maritime MIMO applications.

The MPAC and RTS methods are both standard MIMO OTA testing methods accepted by 3GPP and CTIA, and they are compared side by side in this paper. Moreover, an outlook of the MIMO OTA testing for two emerging applications has been presented, which provides guidelines for engineers to choose a suitable testing method according to their specific needs, requirements, and limitations. Directions for improvements and further development of the testing methods are discussed as well. In a standard 2×2 2D MIMO testing, both the MPAC and RTS methods are demonstrated to be effective.

Contributors

Yihong QI and Jun LI conducted the research. Jun LI processed the data and drafted the manuscript. Yihong QI and Jun FAN revised and finalized the paper. All authors participated in the technical discussions.

Compliance with ethics guidelines

Jun LI, Yihong QI, and Jun FAN declare that they have no conflict of interest.

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Table 1 Comparison of RTS and MPAC methods

Method	Time (2D)	RSSI from DUT	Price	3D test	Large DUT test
RTS	<50 min	Needed	Low	Convenient	Appropriate
MPAC	<30 min	Not needed	High	Inconvenient, high cost	Inappropriate

RTS: radiated two-stage; MPAC: multiprobe anechoic chamber; RSSI: received signal strength indication; DUT: device under test

Table 2 Comparison with related works

Item	This paper	Yu et al., 2014	Shen et al., 2019b	Shen et al., 2020
Basic RTS theory	√	√	√	√
RTS in near-field test	×	×	√	×
RTS for front-end test in a small chamber	×	×	×	√
Detailed description and comparison for RTS, MPAC, and RC+CE methods	√	×	×	×
Discussion for 5G-and-beyond systems	√	×	×	×

RTS: radiated two-stage; MPAC: multiprobe anechoic chamber; RC+CE: reverberation chamber plus channel emulator

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