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Standardization and Challenges

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Over-the-Air Performance Testing of 5G New Radio User Equipment: Standardization and Challenges

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***Abstract*—Third Generation Partnership Project (3GPP) is accelerating 5G new radio (NR) global standards that aim at a significant enhancement of the wireless system performance for higher date rate, better energy efficiency, and higher reliability than the current 4G cellular systems. The operators, manufacturers and test equipment vendors have worked together to develop the standardized over-the-air (OTA) test methodologies for the overall performance evaluation of 5G NR devices. 3GPP is taking the lead in standardizing the OTA testing of 5G NR under the fading channel conditions. In 3GPP specifications, test methods have been studied to verify the multiple-input multiple-output (MIMO) performance of 5G NR user equipments (UEs) in an OTA mode. This article follows the 3GPP standardization work and discusses the MIMO OTA test methodologies for 5G NR UEs working at the frequency range 1 (FR1) and FR2, with a focus on its new challenges and solutions compared to 4G MIMO OTA testing methods. Then, the OTA throughput testing results of real 5G NR UEs are demonstrated under the standard channel models. Finally, the challenges and limitations of standard 5G MIMO OTA test solutions are also highlighted.**

***Index Terms*—5G NR, 3GPP standardization, MIMO OTA testing, MPAC, RTS.**

I. Introduction

OVER-the-air (OTA) radiated testing is performed without radio frequency (RF) cable connection to the device under test (DUT), i.e. without obligation to break or modify the DUT. OTA testing of wireless device performance was initially standardized by Cellular Telecommunications and Internet Association (CTIA) and Third Generation Partnership Project (3GPP) for the single antenna systems in 3G mobile radio, i.e. single-input single-output (SISO) OTA [1]. Figures of merit (FoMs) such as total radiated power (TRP) and total isotropic sensitivity (TIS) are selected to characterize the transmit and receive capability, respectively. However, the SISO OTA testing FoMs are deemed not sufficient to characterize the performance of 4G Long Term Evolution (LTE) devices, due to the introduction of multiple-input multiple-output (MIMO) technology. The performance enhancements introduced by the multi-antenna techniques, e.g. spatial multiplexing and transmit diversity, are heavily reliant on the propagation channels, not merely on the antenna design.

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The performance testing under realistic deployment scenarios is essential to the research and development of MIMO radios. A field trial is an intuitive way to evaluate how the MIMO DUT performs under the realistic conditions. However, the test results of field trials are uncontrollable and unrepeatable. The virtual drive testing (VDT), which aims to mimic the field trials in laboratory conditions with the help of testing instruments, is an alternative to the field trials. The VDT in cable conducted setup has been widely adopted in the industry since the testing can be done in a controllable, repeatable, and reproducible manner. Conventionally, in the cable conducted setup for the MIMO performance testing, RF coaxial cables are employed as the communication interface between the DUT antenna ports and the testing instrument ports. However, the conductive testing becomes impractical without accessible antenna ports for an integrated design. Besides, antenna effects such as self-interference are not considered. Due to these reasons, there is a need for the MIMO OTA radiated performance testing for 4G MIMO DUTs, though the conductive testing is still widely used. The OTA testing for 4G MIMO capable terminals have been developed and researched for many years, where several OTA methods were proposed [2], [3], e.g. the reverberation chamber (RC), the radiated two-stage (RTS), and the multiprobe anechoic chamber (MPAC) methods.

As mobile technology evolves toward 5G new radio (NR) systems [4], [5], the new enabling technologies, e.g. 3D beamforming, high-order MIMO, mmWave frequency bands, large system bandwidth, integrated antenna and transceiver design, etc., make the OTA testing of 5G NR essential for the performance evaluation [6]. The standardization work toward the OTA testing of 5G terminals is underway in 3GPP. In this article, we discuss the 5G MIMO OTA performance testing status in the 3GPP standardization. The test methodologies of 5G MIMO OTA are revisited and their differences from 4G MIMO OTA are discussed. Furthermore, the throughput measurement results of real 5G NR under standard channel models in OTA test setups are demonstrated. Finally, we highlight the challenges of two standard 5G MIMO OTA test solutions, and conclude the article.

II. Standardization

3GPP TR 38.827 specification studies the performance metrics, measurement methodologies, channel models and validation procedures for the MIMO performance evaluation of 5G NR user equipments (UEs) [7]. Two frequency ranges are defined for the study, namely the frequency range 1 (FR1, sub-7 GHz) covering 410 MHz to 7.125 GHz and the frequency range 2 (FR2, mmWave) covering 24.25 to 52.6 GHz. The MPAC solution has been selected as the reference testing method for 5G FR1 terminals, while the RTS method can be utilized as well after the harmonization of test results with the MPAC method. For 5G FR2 terminals, only 3D MPAC solution has been selected. In this section, the test methodologies are detailed according to [7] for both frequency ranges under the standard channel models.

A. *Standard Channel Model*

The standard channel models defined in 3GPP are the stationary channel models, which means that the cluster-level parameters of channel are not time-variant, e.g. average power, angle, delay, etc. However, the channel is still time-variant due to the small-scale fading. In the 3GPP standardization, the following channel models are required to be measured for the NR MIMO OTA testing: FR1 Urban Micro (UMi) clustered delay line (CDL)-A with 23 clusters, FR1 Urban Macro (UMa) CDL-C with 24 clusters, FR2 Indoor (InO) CDL-A with 23 clusters, and FR2 UMi CDL-C with 24 clusters. Note that the spatial profiles of the NR channel models are directive, due to the different power levels among clusters and the narrow angular spread of clusters. To explain the directivity of the NR channels, the reference power angular spectra (PAS) of the four channel models are shown in Fig. 1, which shows how the channel clusters weighted by power are allocated in the space for the impinging paths to the UE. Furthermore, the spatial profiles of the channel seen by the UE will become more directive with the base station beamforming implemented (i.e. base stations form beams towards the dominant clusters) in the FR2. Therefore, only few dominant clusters will be observed by the UE in FR2.

In the current standardizations of MIMO OTA testing, only the downlink fading channel is emulated for both 4G and 5G UE testing. Note that a separate communication antenna is generally used for the uplink connection with the base station (BS) emulator or communication tester, i.e. the uplink channel is modeled as a free space line-of-sight channel without the fading. This might be due to the concerns of cost and complicity. Moreover, the current commercial BS emulator is not able to receive the fading signals. For this reason, real BSs are needed in the testing if both downlink and uplink fading channels are realized in the test system.

B. *MPAC*

The MPAC method is evolved from a conventional anechoic chamber based SISO OTA testing system in two ways. On the one hand, multiple probes are used for both measurements. All probes are sequentially activated for the SISO OTA testing, while activated simultaneously in the MPAC setup for emulating the spatial channels. On the other hand, the MPAC method directly measures the end-to-end throughput, while the SISO TIS test records the minimum power level with a certain throughput or bit error rate (BER). Both measurements evaluate the DUT as a whole, including its baseband, RF, and antenna capability.

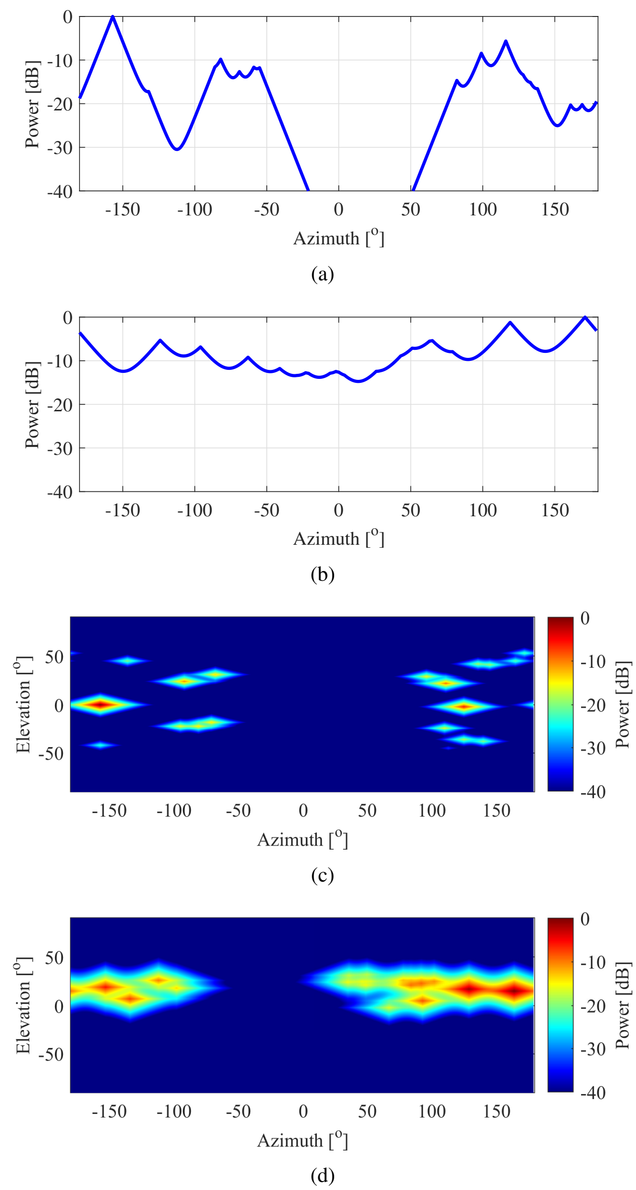


Fig. 1. Reference PAS of four standard NR channel models. (a) FR1 UMi CDL-A; (b) FR1 UMa CDL-C; (c) FR2 InO CDL-A; (d) FR2 UMi CDL-C. Note that the two FR1 channel models are 2D without elevation modelling for the impinging paths, i.e. all clusters have the arrival elevation of 0° with the elevation spread of 0°.

1) FR1: For FR1 MIMO OTA testing, a MPAC setup consists of a BS emulator, a digital channel emulator (CE), power amplifiers, an anechoic chamber and 16 uniformly spaced dual polarized probes arranged around the DUT in a horizontal plane, as illustrated in Fig. 2(a). The DUT is in the centre of the anechoic chamber, in a geometrical volume called a test zone. The transmit (Tx) signals generated from the BS emulator are fed to the CE input ports. The CE performs a convolution of the channel model impulse responses and the Tx signals, which constructs the multipath environment including path delays, Doppler spread and fast fading. Besides, the channel polarization and spatial characteristics are mapped into the CE and then allocated by the physical probes installed in the chamber. The resulting field distribution in the test

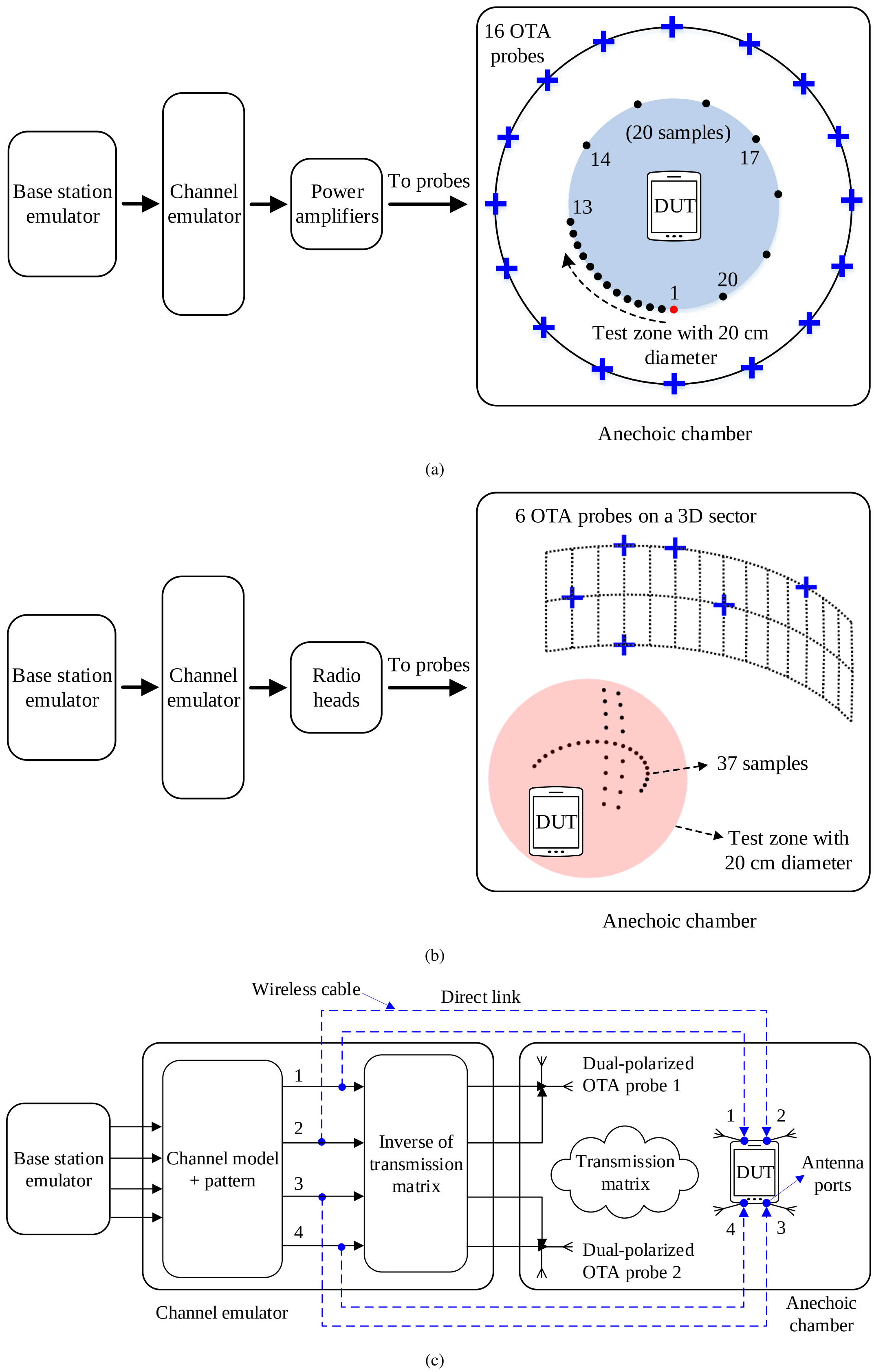


Fig. 2. Principle diagram of 5G UE MIMO OTA test system. (a) MPAC for FR1 where each probe is connected to an output port of the CE, through a power amplifier. The power amplifiers might be required between the CE outputs and the probes to compensate for the path loss between the probes and the DUT; (b) 3D MPAC for FR2 where the radio heads combine the functions of frequency conversion and power amplification. The addition of radio heads allows the CE that originally only supports FR1 testing to be used in FR2; (c) RTS for FR1 (the second stage is shown). Note that the test zone size is exaggerated for illustration purpose in Fig. 2(a) and Fig. 2(b). The actual sizes are shown in Table I.

zone is then integrated by the DUT antennas and processed by the receivers just as it would do so in any real multipath environment.

The key idea of the MPAC solution is to accurately emulate the target radio channel condition within the test zone around DUT so that DUT cannot distinguish the target from the emulated spatial channels [8]. Therefore, the channel model validation is required to ensure that the channel models are correctly emulated in the test zone. Two of the key questions addressed by 3GPP standards are how many probe antennas (and respective channel emulator resource) are required and how large test zone can be supported for the MPAC setup. The required number of probe antennas determines how well the channel spatial characteristics are reproduced within the test zone (i.e. test zone performance). A large test zone typically necessitates more probe antennas.

To evaluate the test zone performance with the given number of probe antennas, the deviation between the target and the emulated spatial correlation is investigated for FR1 in the standardization. The spatial correlation is defined as the correlation between the fading signals received at the specified spatial samples and the reference spatial sample. The spatial samples for the spatial correlation validation measurements are on the circumference of the test zone with a diameter of 20 cm. Depending on the test frequency, the number of spatial samples varies according to Table 7.4.1.3-1 of [7]. For all frequency bands, the sample spacing is not larger than half wavelength to meet the Nyquist sampling criteria, i.e. to avoid the spatial aliasing problem.

For each test frequency, the spatial samples are set in a non-uniform manner, e.g. 20 non-uniform spatial samples at 2.45 GHz, as marked in Fig. 2(a). The red circle is the reference sample (the first one) and the numbering continues in the clock-wise order. The correlation values are calculated with respect to the reference sample. Such non-uniform sampling is used to obtain spatial samples that yield reasonable measurement times and at the same time adequately capture the main lobe of the correlation curve. The non-uniform sampling is used for all standard channel models. Taking the standard FR1 UMa CDL-C channel model as an example, Fig. 3(a) shows the target and the emulated spatial correlation within the test zone of 20 cm diameter at 2.45 GHz. Excellent agreement can be observed between the emulated and target curves, with an error less than 0.2. Note that the maximum acceptable limit for the difference between the target and the emulated spatial correlation is for further study in the standardization.

2) FR2: As discussed in [9], it would require massive OTA probes and associated CE resources for the MPAC setup with a uniform probe configuration (e.g. as done in NR FR1 and LTE) to generate a test zone large enough for FR2 mmWave antenna systems, which would lead to cost-prohibitive designs. Fig. 2(b) illustrates a simple 3D sectored MPAC setup for FR2 MIMO OTA testing, which consists of a BS emulator, a CE, radio heads, an anechoic chamber, and 6 dual-polarized probes placed on a 3D sector with minimum radius of 0.75 m from the centre of the test zone with 20 cm diameter. The six probe positions are specified in Table 6.2.3-1 of [7]. The six-probe configuration is the same for each channel model and has been

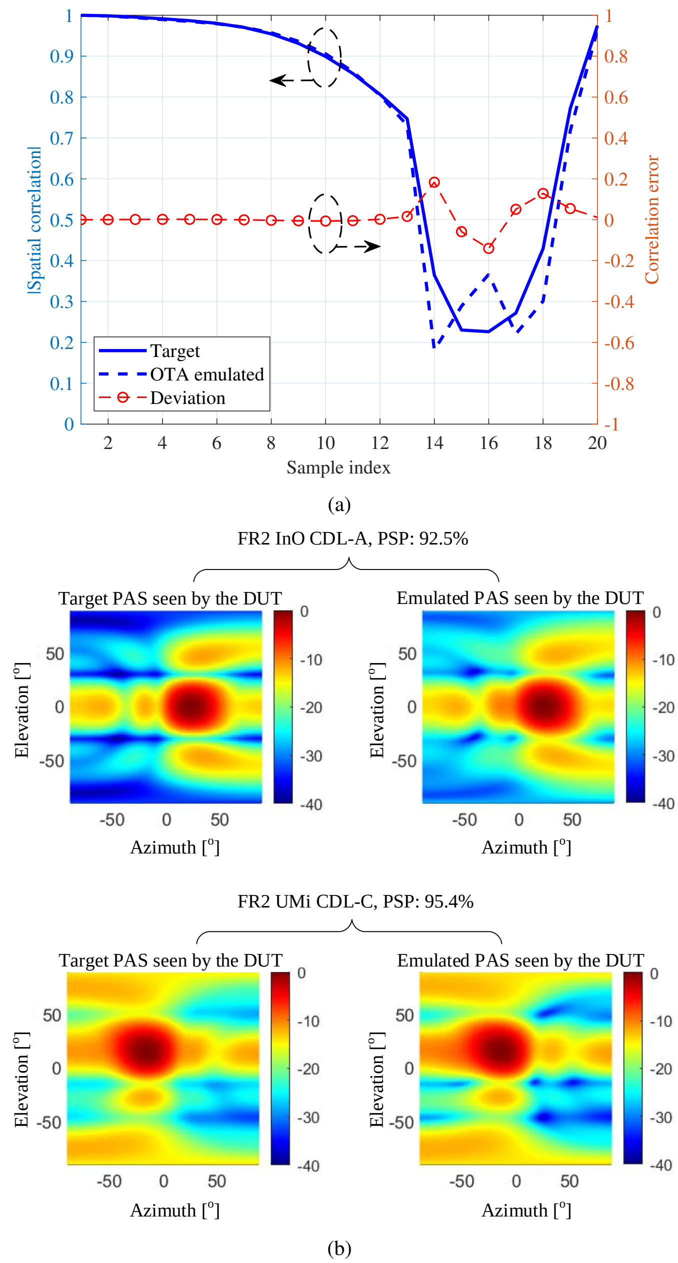


Fig. 3. Test zone performance in simulations. (a) target and emulated spatial correlations sampled within the test zone at 2.45 GHz for FR1 UMa CDL-C channel model; (b) target and emulated PAS seen by 4×4 DUT within the test zone at 28 GHz for FR2 InO CDL-A and FR2 UMi CDL-C models.

optimized only to support both FR2 InO CDL-A and FR2 UMi CDL-C channel models.

One of the enablers for 3D MPAC FR2 testing is the beamforming operation in the mmWave BS side, which filters out effectively weak multipath clusters of the channel model. After the spatial filtering by the BS, the spatial channel profiles at the UE side are greatly simplified, e.g. with only one or two dominant clusters present. In this case, a few probes are sufficient for an accurate emulation of specified spatial channels, since the probes can be arranged to only cover the dominant multipath directions. Due to the channel sparsity and directivity, the PAS characteristics of spatial channels are more

TABLE I
COMPARISON OF 4G AND 5G MPAC OTA

MPAC	4G	5G FR1	5G FR2
Frequency range	Sub-6 GHz (e.g. 2.35 GHz)	0.41 $\sim$ 7.125 GHz (e.g. 2.45 GHz)	24.25 $\sim$ 52.6 GHz (e.g. 28 GHz)
Probe configuration	8 dual-polarized probes, uniformly spaced on a 2D ring with radius of 2 m	16 dual-polarized probes, uniformly spaced on a 2D ring with minimum range length of 1.2 m, as shown in Fig. 2(a)	6 dual-polarized probes, non-uniformly placed on a 3D sector with minimum range length of 0.75 m, as shown in Fig. 2(b)
Channel model	3GPP TR 37.977 SCME UMi, UMa	3GPP TR 38.827 UMi CDL-A, UMa CLD-C	3GPP TR 38.827 InO CDL-A, UMi CDL-C
Emulation metric	Spatial correlation	Spatial correlation	PSP (the similarity between the emulated PAS and the target PAS seen by the DUT, with 100% for full similarity and 0% for full dissimilarity)
Test zone size	0.85 λ (e.g. 10 cm at 2.35 GHz)	20 cm (1.6 λ at 2.45 GHz)	20 cm (18.7 λ at 28 GHz)
Test zone samples	11 uniform linear positions with sampling interval of 0.1 λ [2]	Non-uniform sampling on the circumference of the test zone, e.g. 20 samples at 2.45 GHz, as shown in Fig. 2(a)	Uniform sampling on 1 horizontal ($\pm 90^\circ$) and 2 vertical ($\pm 30^\circ$) semi-circles, e.g. 37 samples at 28 GHz, as shown in Fig. 2(b)

relevant for the beam-steerable DUTs in FR2 since it indicates directly where the signal originates while the spatial correction in this case is always high due to the narrow angular spread. Therefore, a metric of PAS similarity percentage (PSP) defined in Table I is adopted replacing the spatial correlation error to validate how well the target channel model is emulated in the test zone.

According to the standard PSP validation procedure in [7], the frequency responses are recorded at all spatial sampling points within the test zone by a measurement array with a 3D semi-circle and sectored array configuration illustrated in Fig. 2(b), e.g. 37 elements at 28 GHz with half-wavelength spacing. As explained in Section II-B1, all spatial information can be captured as long as the sampling spacing is below half wavelength. Then the emulated PAS by the MPAC OTA setup is estimated for the measurement array configuration by applying the multiple signal classification (MUSIC) estimate algorithm. Next, a 4×4 beam-steerable phased array (mimicking a realistic DUT) with the conventional Bartlett beamforming is adopted to estimate the emulated PAS seen by the DUT. Finally, the similarity between the reference PAS and the emulated PAS seen by the DUT is calculated. Fig. 3(b) shows the PSP simulation results at 28 GHz under two standard FR2 channel models. PSPs of 92.5% and 95.4% are observed for FR2 InO CDL-A and UMi CDL-C models, respectively. The emulated PAS seen by the DUT agrees well with the target PAS seen by the DUT. In this case, the DUT within the test zone would not distinguish the emulated and the target testing conditions seen by the DUT in FR2.

3) Comparison with 4G MPAC: Although the 5G MPAC setup can be seen as a direct extension from the 4G MPAC setup, the differences between them are highlighted in Table I. The spatial correlation metric is adopted due to the importance of MIMO correlation in multi-antenna performance (i.e. spatial multiplexing and diversity) for 4G and 5G FR1 [10], while PSP is selected for 5G FR2 due to the importance of beamforming for mmWave systems. Due to the support of larger test zone size in wavelength for 5G FR1, more OTA probes are required for 5G OTA comapred to LTE. Although the physical size of test zone is the same for both FR1 and FR2, FR2 supports the DUT with much larger electrical size due to small wavelength at mmWave bands. The test zone sampling with linear and circular configuration can distinguish azimuth range of 180° and 360° respectively for 2D channel models. However, such sampling configurations are not sufficient for 3D channel models validation. In FR2 3D MPAC setups, the 3D virtual arrays in 3 semi-circles are employed as a trade-off between measurement time and accuracy, which can be easily implemented with a 3D turntable in an automated manner.

C. RTS

1) Principle: An example of the RTS system layout for 4×4 NR FR1 MIMO OTA testing is illustrated Fig. 2(c), which is different from 4G RTS OTA testing where 2×2 MIMO is applied. The DUT is placed in the center of the anechoic chamber with two dual-polarized probe antennas (i.e. 4 antenna ports) surrounded for the downlink connection. The number of OTA probe antenna ports should be no smaller than the DUT antenna ports in theory. Specifically, the RTS method divides the MIMO OTA test procedure into two stages. The first stage is to acquire the DUT's antenna pattern in a non-intrusive manner using the DUT antenna test function (ATF) [11]. In the second stage of RTS, a "wireless cable" connection is established between the CE output ports and the DUT target receivers prior to the throughput test where a downlink signal is guided to the DUT receivers through the radiated "wireless cable" connection [12].

The quality of the wireless cable connection is measured by the isolation level, i.e. the power ratio between the desired link and the un-desired crosstalk link. In practice, the isolation level between the DUT receiver branches can be measured by establishing one link and measuring the differences between the reference signal received power (RSRP) values reported for the target receiver and other undesired receivers in the DUT [13]. The minimum isolation level sufficient for the second stage throughput testing is for further study in 3GPP standardization.

2) Comparison with FR1 MPAC: Both the MPAC and the RTS methods are capable of emulating any arbitrary channel models in principle. However, the RTS method needs specific DUT function support (e.g. ATF and DUT beam-lock mode), while no restriction on the DUT is assumed for the MPAC method. In the MPAC method, the same testing environments can be reused for different DUTs under the same target channel model, while the wireless cable connections of the RTS method need to be rebuilt when the DUT condition is changed. The number and position of OTA probes need to match the spatial channel models for the MPAC method, while the RTS method links the probe configuration to the number of DUT antenna ports and the transmission matrix.

III. Throughput Testing Results

This section shows the typical throughput measurement results using the MPAC test methodology for both FR1 and FR2. The objective is to measure the downlink data rate of commercial 5G NR UEs under realistic deployment scenarios (i.e. specified fading channel conditions and 5G radio communication tester mimicking 5G BS) in a controllable and repeatable manner.

A. Measurement Setup

Following 3GPP standardization of 5G MPAC OTA testing detailed in Section II, the practical MPAC measurement chambers are shown in Fig. 4 for both frequency ranges. The non-standalone (NSA) mode is deployed due to the lack of an end-to-end standalone 5G network in the measurement. Band N41 (2.5 GHz) for 5G NR and Band 3 (1.8 GHz) for LTE were adopted in FR1, while Band N258 (26 GHz) for 5G NR and Band 3 for LTE in FR2. The bandwidth for NR and LTE was 100 MHz and 20 MHz, respectively. In FR1, UMa CDL-C channel model with the UE velocity of 3 km/h was implemented in the test zone. In FR2, InO CDL-A with 3 km/h UE velocity and UMi CDL-C with 12 km/h UE velocity were implemented in the test zone.

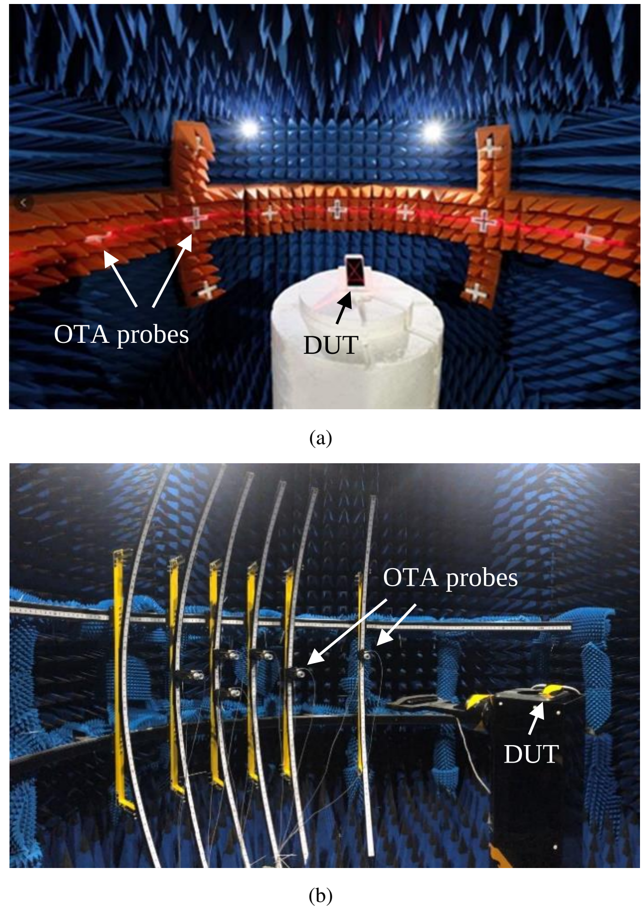


Fig. 4. Measurement photo of practical MPAC setup. (a) FR1 chamber; (b) FR2 chamber. Note that the total number of DUT orientations to be measured for FR1 and FR2 is 12 and 36, respectively.

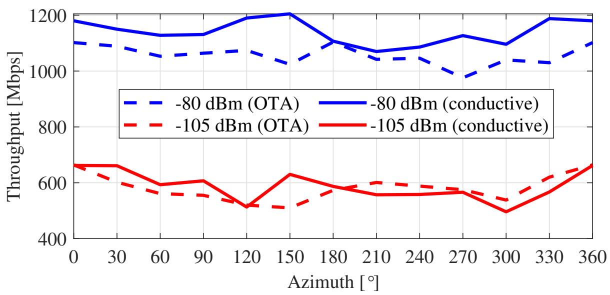
B. Measurement Procedure

The throughput performance can be affected by RSRP [14] or signal-to-interference ratio (SIR) [2]. Note that the SIR control is alternatively included for LTE MIMO OTA testing, depending on the test cases according to [2]. However, only RSRP control is included for NR MIMO OTA testing [7]. The throughput performance characterized as a function of RSRP is investigated in the following measurement procedure:

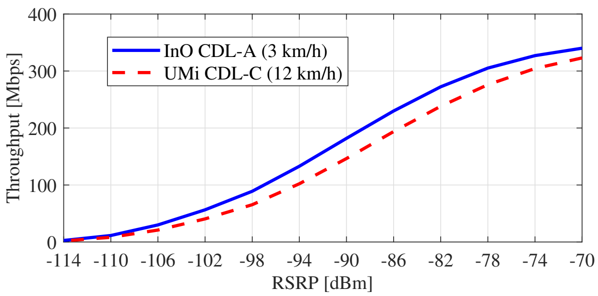
1) According to the link budget, the link attenuation is adjusted by attenuators (at the CE output ports) to achieve an initial RSRP level of the DUT.
2) In FR1 testing, the DUT is oriented toward azimuth 0° as the initial position, while the "Test Point 1" is specified as in Table 6.2.3.2-1 of [7] for FR2 testing.
3) To investigate the RSRP effects, the link attenuation is increased by adjustable attenuators with a fixed step until the DUT disconnected from the link. The average throughput of DUT within a period of time is counted for each attenuation status where the current RSRP is determined by adding the current attenuation to the initial RSRP in Step 1).
4) DUT is rotated to other 11 positions with a uniform step of 30° in FR1 testing, while other 35 positions are set as in Table 6.2.3.2-1 of [7] with the help of 3D turntable for FR2 testing. For each DUT position, Step 3) is repeated.
5) According to [7], the final throughput test result under the current channel environment is obtained by simply averaging the throughput measured over 12 and 36 DUT positions in Step 4) for FR1 and FR2 testing, respectively.

C. Measurement Results

1) FR1: Fig. 5(a) depicts the downlink throughput testing results varied with 12 DUT positions for FR1. The throughput results under RSRP values of -80 dBm and -105 dBm are about 1.1 Gbps (close to the downlink peak throughput in NR) and 600 Mbps, respectively. One evident explanation is that the high-order modulation and coding scheme (MCS) can be utilized for the high link power, which can increase the data rate. Throughput conductive testing results are also included



(a)



(b)

Fig. 5. Downlink throughput testing results. (a) FR1 OTA and conductive throughput results varied with 12 DUT positions for two RSRP values under FR1 UMa CDL-C channel model; (b) FR2 throughput averaged over 36 DUT positions as a function of RSRP under two FR2 channel models.

in Fig. 5(a), since the conductive testing is also available for FR1. The throughput difference between the conductive and the OTA testing methods is within 10%, which is a reasonable and promising accuracy in practice In addition, it has been observed in the measurement campaigns (not shown in the figure) that for certain types of UEs, the downlink performance shows a remarkable decrease with the increase of Doppler, which highlights the importance of performance testing under realistic channel conditions.

2) FR2: The testing results of FR2 downlink throughput averaged over 36 DUT positions are shown in Fig. 5(b) as a function of RSRP with an initial RSRP of -70 dBm. For the strong RSRP, i.e., -70 dBm, the throughput results under the InO CDL-A and UMi CDL-C channel models are about 340 Mbps and 323 Mbps respectively, which accounts for about 60% of the peak throughput. However, the throughput at the RSRP of -114 dBm drops to zero where the UE is close to be disconnected. The throughput under the InO CDL-A channel model is slightly better than that under the UMi CDL-C channel model. The drop trend of throughput can be found with the decrease of RSRP, since the RSRP decrease reduces the transmission quality of the channel.

IV. Challenges

This section discusses some of the potential challenges and limitations of two standard 5G MIMO OTA test solutions.

A. MPAC

1) Dynamic and Multi-User Channel Emulation: The beamforming and beam management techniques are the key for the high data throughput and stable link connectivity in FR2. However, the current FR2 test cases are based on the stationary channel environment since a dynamic channel might be too difficult to be emulated with the current FR2 probe configurations. Besides, a test with the dynamic channel emulation brings in several new questions, e.g. how repeatable the test should be under different random seeds, test equipments and chambers? In the current stationary channel emulation, an average throughput is the focus of interest. However, the average throughput FoM might be unsuitable for the dynamic case where the final FoM is still yet to be determined, e.g. the time-variant throughput or the cumulative distribution function of throughput, etc. Furthermore, in dynamic scenarios, multiple users inside the test zone might experience different channel conditions at the same time. It is an open question how to evaluate multi-user performance under the dynamic channel conditions.

2) FR2 Test Zone Validation: The test zone size in wavelength is much larger for FR2 MPAC setups. Moreover, 3D virtual measurement arrays are required to support the validation of 3D spatial channels. As a result, significantly more spatial locations are required to sample the test zone for FR2, which leads to long measurement time. Another challenge is the violation of far field assumption due to large test zone size and compact MPAC setup (due to cost consideration). Therefore, the channel validation method suitable for near-field setups is required.

3) Applicability for Large DUTs: In 3GPP standardization, the MPAC method for both FR1 and FR2 is initially defined for NR UE test. However, for the DUTs with large physical size, e.g. automotive systems and massive MIMO base stations, the current MPAC setup (including the uniform MPAC configuration in FR1 and the simplified MPAC configuration in FR2) still cannot meet all testing requirements due to cost considerations. The large test zone size would necessitate a massive number of OTA antennas and associated CE resources. Therefore, the main challenge is to reduce the test system complexity yet still ensuring realistic fading channels for the performance testing. In this context, the BS performance testing could be another future direction, which is not currently much standardized due to the lack of traditionally strict requirements and exact specifications (e.g. models, scenarios, test facilities, etc.).

B. RTS

1) Adaptive DUT: The RTS method is only applicable to the devices which do not change their antenna patterns or configurations in response to the radio environment and the devices that support for the ATF. One challenge of the RTS method is how to acquire the transmission matrix if the DUT antenna pattern is adaptive. To solve this issue, the new test interface might be defined to configure the DUT working under different fixed pattern modes (i.e. beam-lock mode). The test process might be upgraded to measure multiple antenna patterns in the first stage and load the corresponding antenna patterns in the second stage, according to the emulated channel model.

2) Test Complexity for High-Order MIMO DUT: In the RTS method, at least one probe is required, in principle, for each DUT antenna port connected to an independent receiver. For the high-order MIMO DUT, more probe antennas and associated CE resource are needed. For future 5G NR, digital beamforming structure, where each antenna is associated with an individual RF chain is required, which consequently would necessitate more probe antennas. Besides, as the MIMO order gets large, the condition of the transfer matrix will deteriorate and it becomes more difficult to achieve the wireless cable connection with good quality. New solutions are required to ensure good wireless cable quality for the high-order MIMO DUTs.

3) Application for Automotive Systems: The wireless cable method has found large success for the performance testing of MIMO capable mobile terminals. In principle, it works well for large-size DUTs like automotives with a few receiver antennas, unlike the MPAC solution which would necessitate a significant number of probe antennas. However, in the first stage of RTS, the antenna pattern measurement for the automotive systems requires very large measurement facilities. Though recently reported in a few works for the automotive testing [15], it is still in its infancy for the automotive antenna system testing.

4) Harmonization Measurement with MPAC: To accomplish the harmonization with the MPAC method, the test results reported from the RTS method are required to be the same as the MPAC method with a deviation within the system measurement uncertainty for the same test case (e.g. the same setting in the base station emulator, the same emulated channel model, and the same DUT, etc.). For NR FR1, the progress on the RTS method in the standardization has been slow and so far, no measurement results have been reported, to the best knowledge of the authors. Therefore, there is a strong need for the harmonization measurement with the MPAC method for NR FR1 in the future work.

V. Conclusion

This article discusses 5G MIMO OTA test methodologies in 3GPP standardization with a focus on new test requirements compared with 4G MIMO OTA test methodologies. The test methodologies born of 4G MIMO OTA, e.g. MPAC and RTS, are extended to support larger DUT electrical size, high-order MIMO, and beamforming for 5G MIMO OTA. In 5G MIMO OTA, only MPAC solution is considered as the reference test method for both FR1 and FR2. In FR1, the RTS method can be used as well if the consistent results with the reference MPAC solution can be achieved. Throughput measurements of commercial 5G NR UEs under realistic deployment scenarios were performed in two standard 5G MPAC OTA testing chambers for FR1 and FR2, respectively. The throughput testing results show that the FR1 downlink rate (e.g. 1.1 Gbps) can be achieved in good signaling conditions, as expected. Finally, the two standard 5G MIMO OTA test solutions might still be challenging in some aspects and necessitate further investigation in the future, e.g. FR2 dynamic OTA testing, BS testing, RTS harmonization measurement, etc.

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