Radiated Two-stage Method for LTE MIMO User Equipment Performance Evaluation

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Abstract**—Two stage method for long-term-evolution (LTE) multiple-input-multiple-output (MIMO) wireless user equipment (UE) performance evaluation is one of the methods proposed for standard organizations. The conducted two stage method has been challenged for its lack of support for "over-the-air"（OTA） and inclusion of UE's self-interference in the throughput test. In order to solve the problems, a radiated two-stage (RTS) test method for LTE MIMO UE test is presented. By applying an invert calibration matrix to the input signal of the throughput test, the proposed method performs over-the-air second-stage test, which eliminates the problems of connecting an RF cable directly to the UE receiver. The RTS OTA MIMO test method can be executed in a standard single-input-single-output anechoic chamber, reduces overall system cost, and offers high reliability and repeatability. Meanwhile, the measurement provides extensive sub-component level performance information and makes it an ideal solution for both R&D and certification test.**

Index Terms**—Wireless, MIMO, OTA, radiated two stage (RTS) method.**

[1] Introduction

THE Cellular Telecommunication and Internet Association (CTIA) [1], the Third Generation Partnership Project (3GPP) [2], and the European Cooperation in Science and Technology (COST) [3] have been promoting the standardization of multiple-input-multiple-output (MIMO) over-the-air (OTA) test for many years, for the purpose of developing accurate, realistic, and cost-effective OTA test standards for universal mobile telecommunication system (UMTS) and long term evolution (LTE) system. Many different MIMO test methods have been proposed, which have significant difference in their propagation channel characteristics, size, and cost. These methods fall into several categories: the multi-probe method, the reverberation chamber method and the two-stage method [4]-[6] etc. The multi-probe method uses hardware enabled environment to simulate mathematical multipath environment. It is straightforward, simple in concept but suffers the highest cost and needs extensive system calibration effort. The reverberation chamber method is cost-effective, but it can only emulate limited channel characteristics and has no control over spatial aspects. The two-stage method is able to closely model the real 3D multipath channel and measure not only MIMO throughput but also active antenna pattern and antenna correlation which are essential for UE terminal research and development (R&D). The two-stage method, which only requires standard SISO chamber, provides highly correlated result with multi probe method, while provides more flexibility, and significantly reduces system and maintenance complexity and cost. I Initially, the two stage method demands cable connection to the UE's receiver thus cannot evaluate the UE's self-interference. It also causes additional uncertainty because of imperfect mode conversion and inconsistent connection between coaxial cable and onboard connector (and its connected transmission line).

In this paper, a radiated two-stage (RTS) method is introduced. This new method measures complex antenna pattern in the first stage and then measures throughput through over-the-air radiated means in the second stage. This important improvement in the RTS method not only has all the advantages of the standard two stage method, but also solves the problems associated with the RF cable connection.

[2] Original Two-stage Method for MIMO Test

The traditional two-stage method first measures the MIMO terminal antenna patterns and then incorporates the measured antenna patterns information with selected MIMO OTA propagation channel models for real-time emulation. The input signals into the MIMO receivers, which are determined by transmitting signals, radio propagation channel models and UE antenna patterns, are emulated by base station emulator plus channel emulator and then fed into the MIMO receivers via RF cables conductively. The second stage of the traditional two-stage test method uses cable connection to the device under test (DUT), it does not require the use of an anechoic chamber for conducting throughput test [4],[7].

Stage 1: Test multiple antennas system in a traditional anechoic chamber. The measurement system should be able to perform full 3-D pattern measurements for both transmitting (Tx) and receiving (Rx) radiated performance and to measure two orthogonal polarizations (typically linear theta (θ) and phi (ϕ) polarizations) as shown in Fig. 1. In order to measure the antenna pattern non-intrusively, the DUT needs to support amplitude and relative phase measurements of the antennas. Test system set up for the first stage is shown in Fig. 1.

Stage 2: Combine the antenna patterns measured in stage 1 into MIMO channel model, emulate the MIMO channel model with the measured antenna patterns incorporated in the

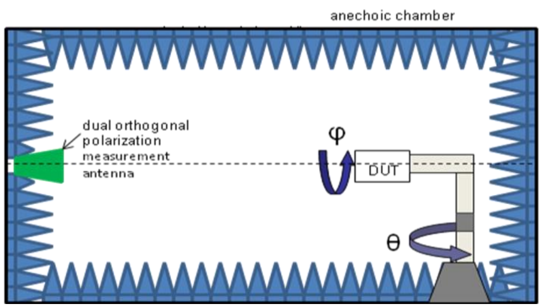

Fig. 1. The anechoic chamber and coordinate system used in the measurements

commercial channel emulator and perform the OTA throughput test using the conducted approach [8]. Both ray-based channel models and correlation-based channel models can be applied [9]. The measurement procedure diagram of the traditional two-stage MIMO OTA method is illustrated in Fig. 2.

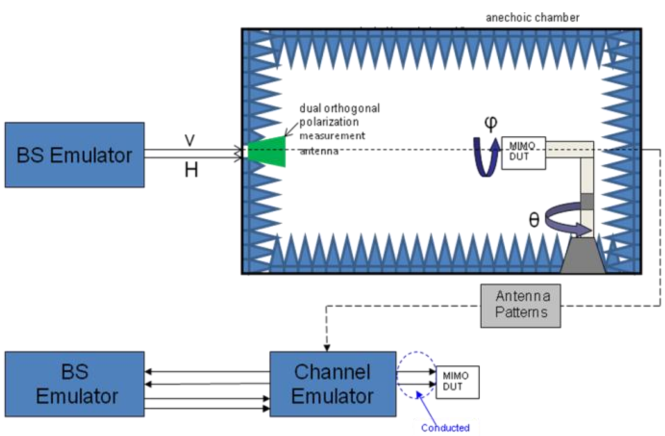

Fig. 2. Traditional two-stage method

The signals that are fed into MIMO receivers S_1 and S_2 contain information about the channel model and antenna gain. They simulate the power that the UE receivers receive in the real environment with phase information between the two antennas at each angle as shown in Fig. 3.

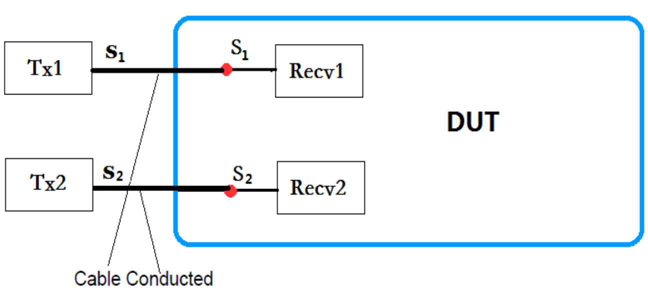

Fig. 3. Conductive throughput test in the second stage of the traditional method.

[3] RADIATED TWO-STAGE METHOD FOR MIMO OTA

The second stage of traditional two-stage method is to measure throughput through a conducted approach. Besides the inconvenience of connecting cables to the DUT, the major problem of the traditional two-stage method lies in the fact that the conductive measurement cannot substitute for the radiated test completely. In the normal working mode, the noise and interference generated by the UE can be coupled to the UE antennas and then fed into the MIMO receivers, which would potentially affect the MIMO performance significantly. As illustrated in Fig. 4, in the second stage of the two-stage

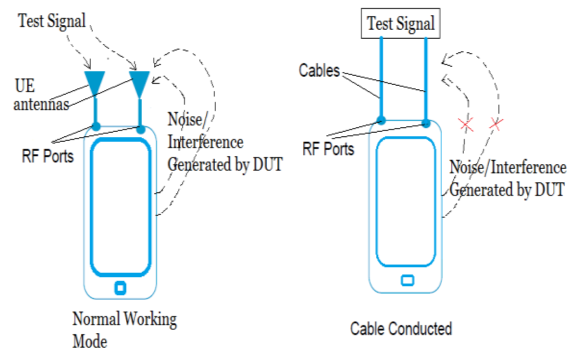

Fig. 4. Self-interference and noise coupled to the UE antennas

method, the UE antennas are bypassed in the conductive test. Thus the coupling caused by the noise/interference generated by the DUT to the MIMO receivers via the UE antennas is largely ignored. That noise/interference can be as large as a few dB, in radio development stage an more than 10 dB of interference is commonly seen. But if the radio has no sensitivity degradation, the conducted measurement will have the same measurement results from the noise/interference point of view. Another problem in the conducted throughput test is that it does not include the signal correlation introduced by the MIMO receiving antenna pair. These factors could affect the MIMO performance test significantly. Thus the test results of the traditional two stage method do not reflect the influence of the signal correlation, self-generated noise and interference. In addition, the conducted test can also introduce inconsistence due to impedance mismatch.

We propose an RTS method in which the stimulus signal is fed to the DUT over-the-air inside an anechoic chamber. In the proposed system, the number of reference antennas is equal to (or larger than) the number of MIMO receiving antennas. We take 2×2 MIMO as an example to illustrate the proposed idea.

With a careful system calibration, accurate complex antenna pattern information can be obtained in the first stage of traditional two-stage MIMO OTA. Hence our proposed radiated two-stage method for MIMO OTA follows the similar procedure for the first stage antenna pattern measurement.

After the first stage, , the obtained antenna patterns need to be combined into MIMO channel model to emulate the channel characteristics for performing throughput test. There are several MIMO channel models for throughput evaluation in 3GPP including urban micro (UMi) and urban macro (UMa) model; Applying antenna pattern to ray-based channel is used in this paper to illustrate the combining process.

Ray-based channel model is a geometry-based stochastic model. It does not explicitly specify the locations of the scatters, but provides the directions of the rays on stochastic base to simulate the channel characteristics. Geometry-based modeling shows explicitly the contribution of antennas and propagation parameters.

For a standard U number of transmitter and S number of receiver MIMO system, the time variant impulse response channel matrix is given by

$$H(t;\tau) = \sum_{n=1}^{N} H_n(t;\tau) \tag{1}$$

Where t is time, τ is delay and N is number of paths. The channel model is composed of factors of the transmitter (Tx) antenna array pattern F_{tx} and receiver (Rx) antenna array pattern F_{rx}, and the dual-polarized propagation channel response matrix hn for cluster n.

$$H_n(t;\tau) = \iint F_{rx}(\varphi) h_n(t;\tau,\phi,\varphi) F_{tx}^{T}(\phi) d\phi d\varphi \tag{2}$$

The channel from Tx antenna element s to Rx element u for cluster n is expressed as

$$H_{n,s,u} = \sum_{m=1}^{M} \begin{bmatrix} F_{rx,u,V}(\varphi_{n,m}) \\ F_{rx,u,H}(\varphi_{n.m}) \end{bmatrix}^{T} \begin{bmatrix} \alpha_{n,m,VV} & \alpha_{n,m,VH} \\ \alpha_{n,m,\mathrm{HV}} & \alpha_{n,m,\mathrm{HH}} \end{bmatrix} \begin{bmatrix} F_{tx,s,V}(\phi_{n,m}) \\ F_{tx,s,\mathrm{H}}(\phi_{n,m}) \end{bmatrix} \times \exp(j2\pi\lambda_0^{-1}(\bar{\varphi}_{n,m} \cdot \bar{r}_{rx,u})) \exp(j2\pi\lambda_0^{-1}(\bar{\phi}_{n,m} \cdot \bar{r}_{tx,s})) \exp(j2\pi v_{n,m}\,\mathrm{t}\,\delta(\tau-\tau_{n,m}) \tag{3}$$

Where $F_{rx,u,V}$ and $F_{rx,u,H}$ are the antenna element u radiation pattern for vertical and horizontal polarizations. $F_{tx,s,V}$ and $F_{tx,s,\mathrm{H}}$ are the antenna element s radiation pattern for vertical and horizontal polarizations respectively. $\alpha_{n,m,VV}$, $\alpha_{n,m,\mathrm{HV}}$, $\alpha_{n,m,VH}$, $\alpha_{n,m,\mathrm{HH}}$ are the complex propagation losses of vertical-to-vertical, vertical-to-horizontal, horizontal-to-vertical and horizontal-to-horizontal polarizations of ray n,m respectively. λ_0 is the wave length of the carrier frequency. $\phi_{n,m}$ is the angle of departure unit vector and $\varphi_{n,m}$ is the angle of arrival unit vector. $\bar{r}_{tx,s}$ and $\bar{r}_{rx,u}$ are the local vectors of element s and u respectively and $v_{n,m}$ is the Doppler frequency component of ray n,m. For dynamic radio channel all the small-scale parameters are function of time. This generic channel model is applicable for all scenarios including indoor, urban and rural areas.

With the channel model and applicable Tx power the signal S_1 and S_2 can be generated.

In order to perform over-the-air throughput test, an important issue is how to achieve the specified S_1 and S_2 for relevant MIMO receivers over the air. In an anechoic chamber, the signal coupling scenario with transmit antennas and receiving antennas is shown in Fig. 5, where,

(1) $G(tx\_ant_{11})$ is the directional gain of the transmit antenna 1 at the direction of the UE antenna 1; $G(rx\_ant_{11})$ is the directional gain of the UE antenna 1 at the direction of the transmit antenna 1; P_{11} is the path loss from the transmit antenna 1 to the UE antenna 1;

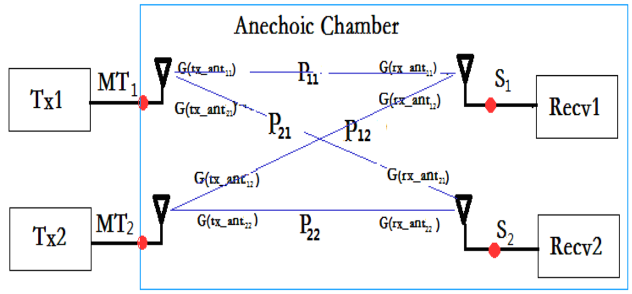

Fig. 5. Concept of feeding the stimulus signals over the air inside an anechoic chamber.

(2) $G(tx\_ant_{21})$ is the directional gain of the transmit antenna 1 at the direction of the UE antenna 2; $G(rx\_ant_{21})$ is the directional gain of the UE antenna 2 at the direction of the transmit antenna 1; P_{21} is the path loss from the transmit antenna 1 to the UE antenna 2;

(3) $G(tx\_ant_{12})$ is the directional gain of the transmit antenna 2 at the direction of the UE antenna 1; $G(rx\_ant_{12})$ is the directional gain of the UE antenna 1 at the direction of the transmit antenna 2; P_{12} is the path loss from the transmit antenna 2 to the UE antenna 1;

(4) $G(tx\_ant_{22})$ is the directional gain of the transmit antenna 2 at the direction of the UE antenna 2; $G(rx\_ant_{22})$ is the directional gain of the UE antenna 2 at the direction of the transmit antenna 2; P_{22} is the path loss from the transmit antenna 2 to the UE antenna 2.

In the throughput test in the proposed RTS method, instead of using RF cables to deliver the stimulus signals S_1 and S_2 to the MIMO receivers directly, we use two transmit antennas to deliver the signals MT_1 and MT_2 over the air to the MIMO UE antennas respectively, in a way that the signals fed into the MIMO receivers equal the signals S_1 and S_2, as shown in Fig. 5. In Fig. 5, the DUT is located in an anechoic chamber with a fixed orientation relative to the reference antennas. MT_1 and MT_2 are fed into the transmit antennas in order to get S_1 and S_2 at the input ports of Receiver 1 and Receiver 2, respectively.

[4] Then, S_1 and S_2 are related to MT_1 and MT_2 as

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} MT_1 \\ MT_2 \end{bmatrix},$$

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{4}$$

where the physical meaning of matrix A is shown in Fig. 6 , and,

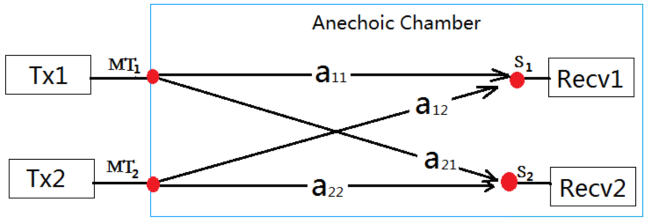

Fig. 6. The ccalibration mmatrix inside the anechoic chamber

a_{11} is the complex path loss from the output port of the transmit antenna 1 to the input port of the UE antenna 1;

a_{12} is the complex path loss from the output port of the transmit antenna 2 to the input port of the UE antenna 1;

a_{21} is the complex path loss from the output port of the transmit antenna 1 to the input port of the UE antenna 2 (i.e., the input port of the receiver 2);

a_{22} is the complex path loss from the output port of the transmit antenna 2 to the input port of the UE antenna 2 (i.e., the input port of the receiver 2). The complex path loss values can be obtained from the antenna gains and the path loss values as:

$$
\begin{aligned}
a_{11} &= G(tx\_ant_{11}) + P_{11} + G(rx\_ant_{11}) \\
a_{21} &= G(tx\_ant_{21}) + P_{21} + G(rx\_ant_{21}) \\
a_{12} &= G(tx\_ant_{12}) + P_{12} + G(rx\_ant_{12}) \\
a_{22} &= G(tx\_ant_{22}) + P_{22} + G(rx\_ant_{22})
\end{aligned}
\tag{5}
$$

With the known patterns of the reference antennas and the measured patterns of the UE antennas from the first stage, the matrix A can be determined if the orientation of the UE is fixed relative to the reference antennas. The Matrix A in Fig. 6 seems to be the MIMO channel matrix but it is actually the channel matrix between the reference antennas and the UE antennas inside an anechoic chamber. We name the matrix A as the Calibration Matrix in the rest of this paper for convenience.

The calibrations matrix is a function of the directive gains of the reference antennas, the directive gains of the UE antennas and the free-space path loss values between the reference antennas and the UE antennas. It is always possible that the UE can be rotated to a fixed orientation such that the matrix A is non-singular. Then, the required signals to the reference antennas can be determined as

$$
\begin{bmatrix} MT_1 \\ MT_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \tag{6}
$$

In summary, the proposed radiated two-stage method is described as following:

Stage 1: Measure the DUT complex antenna patterns in the same way through azimuth and elevation as the traditional two-stage method.

Stage 2: Calculate the calibration matrix A and generate MT_1 and MT_2 based on formula (3). Keep the DUT being fixed in the anechoic chamber (both location and orientation relative to the transmit antennas), feed MT_1 and MT_2 into the transmit antennas to perform the MIMO throughput test.

In the 2×2 MIMO throughput test configuration discussed earlier, the horizontal and vertical polarizations of one reference antenna could be used as the two reference antennas mentioned above.

By delivering the stimulus signals over the air rather than through RF cables, the DUT antennas remain connected and the MIMO throughput is measured in a nonintrusive way so that the effect of desensitization and self-interference can be evaluated. Since the cable connection to the DUT is eliminated in stage 2, the DUT stays in the anechoic chamber untouched during the entire test. Thus, the radiated two stage method process can be fully automated, test process can go through the two stages continually and smoothly without interruption and operator intervention.. The overall set up of the RTS method is shown in Fig. 7.

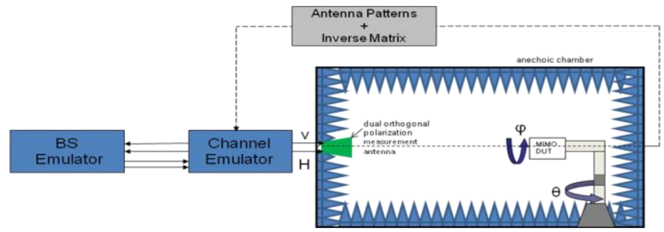

Fig. 7. Proposed radiated two-stage method.

[5] MEASUREMENT RESULTS

To verify the radiated two stage method, an HTC device has been tested connecting to three different CTIA MIMO reference antennas, good, normal and bad [10] in GTS lab. The results in Fig. 8 first show high correlation between radiated and cable-conducted results. The cable-conducted result is measured with the standard antenna patterns incorporated and serves as reference result

Meanwhile, the test results are highly comparable to other

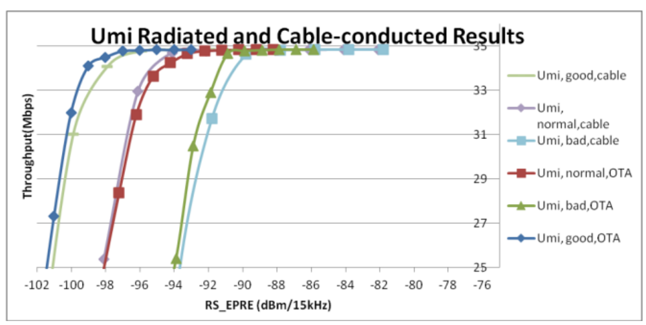

Fig. 8. Radiated and cable-conducted result comparison in UMi Model

radiated two stage method test results and results from multi-probe methods [11].

	Good (dBm)	Nominal(dBm)	Bad(dBm)
GTS	-101.5	-98.2	-94.2
Agilent	-103.6	-99.4	-94.7
Intel	-100.5	-99	-94.2

SATIMO	-102.8	-100	-94.2
Spread +/-	+/- 1.55	+/- 0.9	+/- 0.25

Table 1. Summary of UMi results at 70% throughput

	Good(dBm)	Nominal(dBm)	Bad(dBm)
GTS	-96.6	-95.8	-92
Agilent	-97.9	-97.6	-89.2
Intel	-98	-96.8	-91.5
SATIMO	-98	-94.7	-89.3
Spread +/-	+/- 0.7	+/- 1.45	+/- 1.4

Table 2. Summary of UMa results at 70% throughput

[6] SUMMARY

An innovative RTS method is proposed in this paper for LTE MIMO performance test. The proposed method maintains all the advantages of the traditional two-stage method and avoids its main shortcomings. It is also a continuous test procedure for MIMO OTA test without interruption for cable connection. The The RTS method offers highly correlated results as multi-probe while is much more cost effective. It reuses the standard SISO anechoic chamber Meanwhile, the channel number for the channel emulator is required only to match the number of device receiver inputs regardless of the complexity of the chosen channel model. The channel models are highly accurate due to being implemented electronically and are also fully flexible to suit any desired operating conditions such as indoor-outdoor, high or low Doppler spread, high or low delay spread, beam width, in 2D or full 3D etc. The RTS method measures both the UE antenna patterns and the MIMO throughput performance non-intrusively, which makes it an ideal solution for various applications from early-stage R&D to compliance test.

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