Eliminating RSARP Reporting Errors in the RTS Method for MIMO OTA Test

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***Abstract*—A method for eliminating the received signal amplitude and relative phase (RSARP) reporting errors in the radiated two-stage (RTS) multiple-input multiple-output (MIMO) over the air (OTA) tests is proposed in this paper. The paper first introduced the concept of the RTS MIMO OTA test method, which is based on a first stage of multiple antennas pattern information measurement through RSARP reporting, followed by a second stage of throughput measurement using the signals generated by combining the measured antenna patterns with the selected spatial channel model. The RSARP reporting errors would be brought into the measured antenna patterns and then feed into the throughput test signals, which finally flow in the MIMO receivers and greatly affect the throughput test accuracy. The method proposed in this paper could solve this issue through eliminating the RSARP reporting errors and ensure the accuracy of the MIMO OTA performance test. Moreover, the method could simplify the RTS MIMO test procedure and reduce the measurement period.**

***Index Terms*—Multiple-input multiple-output (MIMO), radiated two stage (RTS), received signal amplitude and relative phase (RSARP) reporting errors.**

I. Introduction

WITH the exploding applications of multiple-input and multiple-output (MIMO) technologies, standardization of the MIMO over the air (OTA) measurements is critical to ensure system performance and compatibility with other systems and environments. Moreover, the MIMO OTA test is also important in the electromagnetic interference (EMI) analysis of MIMO systems, since the throughput result is an efficient metric for evaluating the receiver sensitivity degradation caused by the noise and interference generated by the wireless device's hardware circuit (especially the digital circuit and radio frequency circuit), which can couple to the antenna and then feed into the receiver.

The Cellular Telecommunication and Internet Association and the Third Generation Partnership Project (3GPP) have presented many MIMO OTA measurement white papers [1]–[2]. In these standards, one basic and efficient method for MIMO OTA test, radiated two-stage (RTS) method, was proposed which is based on a first stage of multiple antennas pattern information measurement through the received signal amplitude and relative phase (RSARP) reporting system, followed by a second stage of throughput measurement using the signals generated by combining the measured antenna patterns with the selected spatial channel model [3]–[7]. However, the RSARP reporting errors would be brought into the measured antenna patterns and then fed into the throughput test signals, which finally flow in the MIMO receivers and greatly affect the throughput measurement accuracy, as introduced below.

The first step of the RTS method is testing the multiple antenna patterns in an anechoic chamber. The measurement system should be able to perform full 3-D pattern measurements for both transmitting and receiving radiated performance on two orthogonal polarizations [3]. In order to measure the antenna patterns nonintrusively, the device under test (DUT) needs to support the RSARP reporting OTA [4]. However, a typical RSARP reporting system has an error of 2 dB for power evaluation and an error of 10° for phase evaluation, which are unknown and extremely hard to measure just in radiated test setups [8]–[10]. The errors would be actually brought into the measured antenna patterns of the MIMO DUT.

The second step in the RTS method is the throughput test. The measured antenna patterns and the selected channel models are incorporated in instruments for real-time emulation. Then, the output signals which include the information about transmitted signals, channel models, and DUT antenna patterns (within the RSARP reporting errors) should be sent into the MIMO receiver input ports, respectively, and separately in a radiated mode with an inverse matrix applied, as detailed in [3]. Therefore, the RSARP reporting errors could seriously affect the MIMO throughput test in the RTS.

In this paper, a method for eliminating the RSARP errors in the RTS MIMO test was proposed, which could significantly improve the MIMO OTA performance test accuracy. More importantly, based on the elimination method, the RTS test procedure can be significantly simplified, resulting in a great decrease in the test period. Therefore, the elimination method proposed in this paper not only improves the RTS MIMO OTA measurement accuracy, but also reduces the test period.

The mathematical derivation, the practical realization of the method, and the relative validations were presented in this paper as: the details of the proposed method are presented in Section II,

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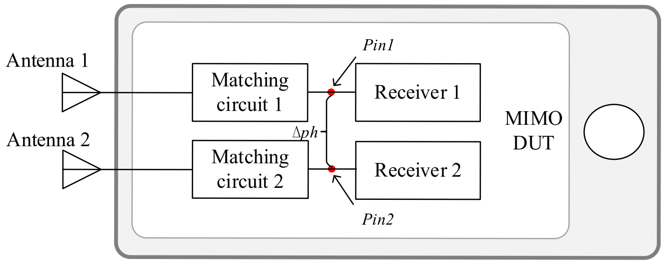

Fig. 1. Typical 2 × 2 MIMO system.

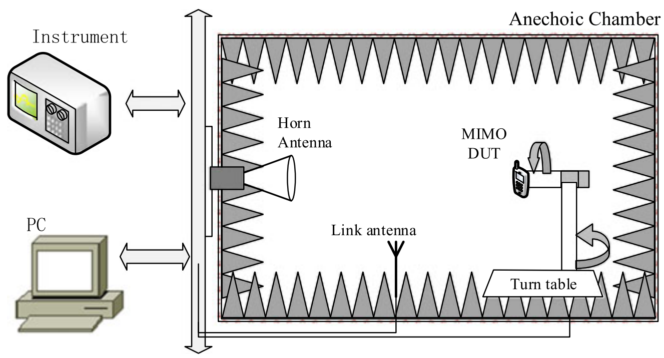

Fig. 2. RTS MIMO OTA test system.

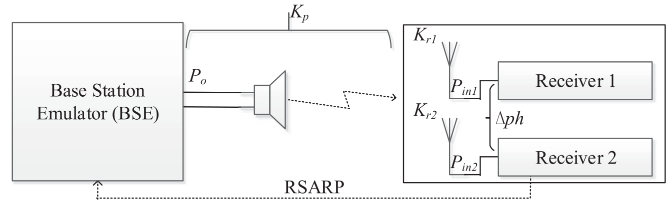

Fig. 3. Simplified block diagram from Fig. 2.

started with the derivation of the theoretical foundation; validations are discussed in Section III, followed by conclusions in Section IV.

II. Theoretical Foundation

The theoretical foundation of this elimination method is presented in this section, which can be divided into four parts: the RSARP reporting errors description, the current realization of the RTS method, the calculations combining the antenna patterns and the channel models, and the elimination method in the RTS MIMO test.

A. RSARP Reporting Errors Description

As discussed earlier, in the RTS, the MIMO DUT complex antenna patterns are obtained through the RSARP reporting, which includes the power levels at all receiver input ports and the relative phase offsets of received signals between any two receivers. For more clear description, a typical 2 × 2 MIMO DUT can be illustrated in Fig. 1, where P_{inx} is the power level at the *x*th receiver and Δph is the relative phase offset between the two receivers.

The RTS MIMO test system can be illustrated in Fig. 2, where a horn antenna is used for the 3-D antenna patterns test in both polarizations. The simplified block diagram can be shown in Fig. 3, where P_o is the base station emulator (BSE) output power; K_p is the total path loss including the range path loss due to the range length, the gain of the measurement antenna, and any loss terms associated with the cables, connections, amplifiers, etc.; K_{rx} is the gain of the *x*th DUT antenna; P_{inx} is the real power level at the *x*th receiver input port; and Δph is the real relative phase offset between the two receivers.

From Fig. 3, it is easy to have the antenna gains and relative phase as (in format of dB in this part)

$$\begin{aligned} K_{r1} &= P_{\text{in}1} - P_o - K_p \\ K_{r2} &= P_{\text{in}2} - P_o - K_p \\ &\Delta ph. \end{aligned} \tag{1}$$

The unknown parameters $P_{\text{in}1}$, $P_{\text{in}2}$, and Δph can be achieved through RSARP readings with the reporting errors existed as

$$\begin{aligned} P_{in1} &= P_{RS1} + \Delta\text{RS}_1 \\ P_{in2} &= P_{RS2} + \Delta\text{RS}_2 \\ \Delta ph &= \Delta ph_{RS} + \Delta\text{RP} \end{aligned} \tag{2}$$

where P_{RSx} is the power reporting value at the *x*th receiver input port evaluated by RSARP, ΔRS_x is the corresponding power reporting error, Δph_{RS} is the relative phase reporting of the two receivers, and ΔRP is the corresponding phase reporting error.

From (1) and (2), the gains and phase can be rewritten as

$$\begin{aligned} K_{r1} &= P_{RS1} - P_o - K_p + \Delta\text{RS}_1 \\ K_{r2} &= P_{RS2} - P_o - K_p + \Delta\text{RS}_2 \\ \Delta ph &= \Delta ph_{RS} + \Delta\text{RP}. \end{aligned} \tag{3}$$

Therefore, at this step, the MIMO DUT antenna patterns are obtained with RSARP reporting errors existed. It is noted that the errors are unknown and extremely difficult to calculate just through radiated tests.

B. Current Realization of the RTS Method

The elimination method proposed in this paper should be inset into the RTS test procedure properly. Moreover, the method can help to simplify the RTS test procedure which could greatly reduce the RTS test period. Therefore, it is required to introduce the RTS test procedure.

The RTS method is developed from the conducted two-stage (CTS) method, which is based on a same first stage of antenna pattern test with RTS and followed by a second stage of conducted throughput test. As shown in Fig. 4, the throughput test signals (recorded as T_1, T_2), which include the information about transmitted signals, channel models, and DUT antenna patterns, are emulated by the BSE plus channel emulator and then fed into the MIMO receivers via RF cables conductively and without interference between each other, respectively [3].

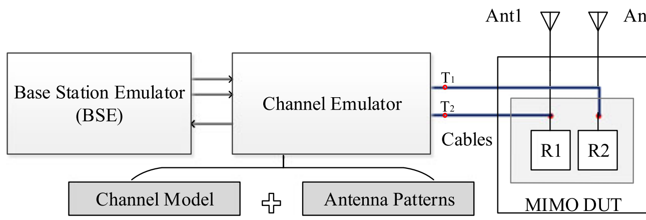

Fig. 4. Simplified diagram for the CTS method.

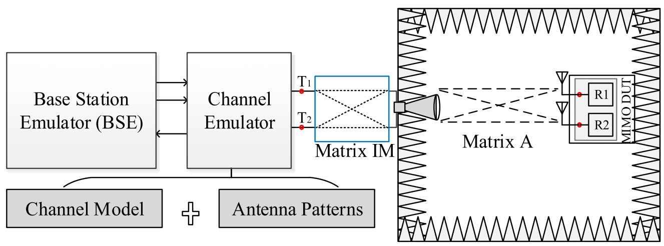

Fig. 5. Simplified diagram for the RTS method.

By contrast, the throughput test signals should be transfused into the receivers in a radiated mode in the RTS method. With the DUT located in the anechoic chamber, the signal coupling scenario with transmit antennas' feeding points and received input ports can be expressed as a 2×2 matrix (recorded as the calibration matrix A in the rest of the paper), as shown in Fig. 5, where a special 2×2 matrix (recorded as IM) is applied to ensure that the throughput test signals (recorded as T_1, T_2) are transfused into the DUT receivers, respectively, and without crosstalk. The relationship between T_1, T_2, and the received signals at DUT receivers R_1, R_2 can be expressed as (in format of real in the rest of this paper)

$$A \times \mathrm{IM} \times \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \end{bmatrix}. \tag{4}$$

Measure the calibration matrix A and calculate the matrix IM to get the equation as

$$A \times \mathrm{IM} = I \tag{5}$$

where I is the 2×2 identity matrix.

Then, we can have that

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \end{bmatrix}. \tag{6}$$

Formula (6) indicates that the throughput test signals are transfused into the DUT receivers without cross-talking, in a radiated mode. That is also the realization of the RTS method.

An important step in the RTS is to measure the calibration matrix A. As stated in [3], the calibration matrix is a function of gains of the chamber antennas, gains of the DUT antennas, free-space path loss, and phase offsets caused by the antennas and the free-space. Generally, the accurate calibration matrix is measured though a conducted way, as shown in Fig. 6, where four steps are conducted.

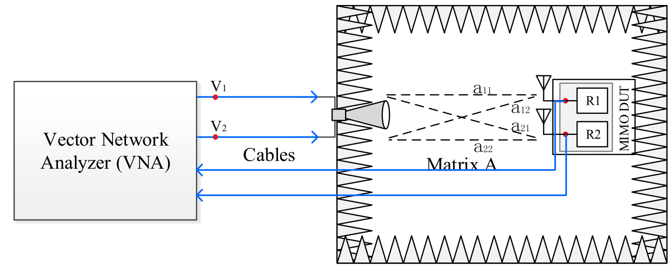

Fig. 6. Conducted method for the calibration matrix measurement.

1) Keep the DUT located in a fixed orientation relative to the chamber antennas during the calibration matrix test.
2) Connect a vector network analyzer (VNA) output ports to the chamber antennas' feeding points and the DUT received input ports, as shown in Fig. 6.
3) Measure the *S*-parameters and the phase offsets and calculate the calibration matrix A.
4) Calculate the matrix IM (the inverse matrix of A).

This conducted solution is straightforward for calculating the calibration matrix. However, it is an intrusive measurement, which is cumbersome and time consuming in the RTS MIMO OTA test, since different instruments are used during a whole test procedure (that means we need to switch the instruments manually).

In this paper, with the elimination method applied into the RTS test process, a more efficient method for calculating the matrix A was presented, as below.

C. Calculations of the Antenna Patterns and the Selected Channel Model

There are several recognized channel models defined in 3GPP standards, such as Urban Micro (UMi), Urban Macro (UMa), and other ray-based channel models [4], [7]. In order to guarantee the universality of the following derivations, a typical 3-D channel model defined in [7] is introduced in this paper for calculating the combination of the antenna patterns and the channel model.

Theoretically, based on the 3-D channel model, for a $U \times S$ MIMO system, the relationship between the transmitted signals and the received signals can be expressed as

$$y\ (t) = \ H\,(t)\,x\,(t) + n\,(t) \tag{7}$$

where $x(t)$, $y(t)$, and $n(t)$ denote transmitted vector, received vector, and noise vector, respectively. $H(t)$ is a complex channel coefficient matrix. The (u, s) component $(u = 1, 2, \ldots, U; s = 1, 2, \ldots S)$ of $H(t)$, denoted as $h_{u,s}(t)$, can be written as formula (8), where P_{us} is the power transferred through the subchannel $T_{X\,s} - R_{X\,u}$; $g_{l,k}$ and $\Phi_{l,k}^{(x,y)}$ are the gain and phase shift between V (H) component of the transmit antenna and V (H) component of the receive antenna, respectively, caused by the interaction of the local scatterers TS_k and RS_l; D_{sk} is the distance from the scatterer TS_k to the *s*th transmit antenna $T_{X\,s}$; D_{lu} is the distance from the scatterer RS_l to the *u*th receive antenna $R_{X\,u}$; D_{kl} is the distance from the scatterer TS_k to the scatterer RS_l; $F_s^{T_X\,(v)}(\Omega_k^{T_X})$ is the complex field pattern of the *s*th transmit antenna $T_{X\,s}$ for V polarization; $F_s^{T_X\,(h)}(\Omega_k^{T_X})$ is the complex field pattern of the *s*th transmit antenna $T_{X\,s}$ for H polarization; $F_u^{R_X\,(v)}(\Omega_l^{R_X})$ is the complex field pattern of the *u*th receive antenna $R_{X\,u}$ for V polarization; $F_u^{R_X\,(h)}(\Omega_l^{R_X})$ is the real complex field pattern of the *u*th receive antenna $R_{X\,u}$ for H polarization; $k_{l,k}^v$ and $k_{l,k}^h$ are the inverse XPD for VV/HV and HH/VH transmission, respectively; $\chi_{l,k}$ is the inverse of the copolar ratio; k_0 is the wavenumber, $k_0 = \frac{2\pi}{\lambda}$, where λ is the wavelength; and $\boldsymbol{k}_1$ denotes the wave vector pointing in the propagation direction from the scatterer RS_l [7].

However, in the RTS method, the antenna patterns are achieved through RSARP with reporting errors existing. For the *u*th receiver, the relationship between the RSARP reporting and the real antenna patterns can be expressed as, eqs. (8) and (10) shown at the bottom of this page

$$\begin{bmatrix} F_u^{R_X\,(v)}\left(\Omega_l^{R_X}\right) \times E_u e^{\,j\psi_u} \\ F_u^{R_X\,(h)}\left(\Omega_l^{R_X}\right) \times E_u e^{\,j\psi_u} \end{bmatrix} = \begin{bmatrix} R|F_u^{R_X\,(v)}\left(\Omega_l^{R_X}\right) \\ R|F_u^{R_X\,(h)}\left(\Omega_l^{R_X}\right) \end{bmatrix} \quad (9)$$

where $R|F_u^{R_X\,(x)}(\Omega_l^{R_X})$ is the complex field pattern reporting value in the polarization x for the *u*th receiver; E_u is the corresponding amplitude reporting error; and ψ_u is the corresponding relative phase reporting error (especially, $\psi_i = 0$ when the *i*th received signal's real phase offset was used as reference).

The combination of the measured antenna patterns (with RSARP errors) and the 3-D channel model can be expressed as (10), where $R|h_{u,s}(t)$ is the (u, s) component of the special channel coefficient matrix $R|H(t)$, which is calculated by combining the measured antenna patterns and the channel model.

From (8), (9), and (10), the relationship between the accurate channel coefficient matrix component $h_{u,s}(t)$ and the RSARP errors-based channel coefficient matrix component $R|h_{u,s}(t)$ can be expressed as

$$R|h_{u,s}\ (t) = h_{u,s}\ (t) \times E_u e^{\,j\psi_u}. \quad (11)$$

Therefore, taking 2 × 2 MIMO systems, for example, the relationship between $\mathrm{R}|H(t)$ and $H(t)$ is

$$\begin{aligned} \mathrm{R}|H\,(t) &= \begin{bmatrix} R|h_{1,1}\,(t) & R|h_{1,2}\,(t) \\ R|h_{2,1}\,(t) & R|h_{2,2}\,(t) \end{bmatrix} \\ &= \begin{bmatrix} h_{1,1}\,(t)\,E_1 e^{\,j\psi_1} & h_{1,2}\,(t)\,E_1 e^{\,j\psi_1} \\ h_{2,1}\,(t)\,E_2 e^{\,j\psi_2} & h_{2,2}\,(t)\,E_2 e^{\,j\psi_2} \end{bmatrix} \\ &= \begin{bmatrix} E_1 e^{\,j\psi_1} & 0 \\ 0 & E_2 e^{\,j\psi_2} \end{bmatrix} \times \begin{bmatrix} h_{1,1}\,(t) & h_{1,2}\,(t) \\ h_{2,1}\,(t) & h_{2,2}\,(t) \end{bmatrix} \\ &= \begin{bmatrix} E_1 e^{\,j\psi_1} & 0 \\ 0 & E_2 e^{\,j\psi_2} \end{bmatrix} \times H\,(t). \end{aligned} \quad (12)$$

It is assumed that S_1, S_2 are the transmitted signals; T_1, T_2 are the throughput test signals; and R_1, R_2 are the received signals. Then, T_1, T_2 are associated with S_1, S_2 as

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \mathrm{R}|H\,(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \quad (13)$$

From (12) and (13), it is easy to get

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} E_1 e^{\,j\psi_1} & 0 \\ 0 & E_2 e^{\,j\psi_2} \end{bmatrix} \times H\,(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \quad (14)$$

Combining (4), (5), and (6), in the RTS test procedure, the throughput test signals in (14) can be rewritten as

$$\begin{aligned} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} &= \begin{bmatrix} E_1 e^{\,j\psi_1} & 0 \\ 0 & E_2 e^{\,j\psi_2} \end{bmatrix} \times H\,(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \\ &= \begin{bmatrix} E_1 e^{\,j\psi_1} & 0 \\ 0 & E_2 e^{\,j\psi_2} \end{bmatrix} \times H\,(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \end{aligned} \quad (15)$$

As discussed earlier, in the RTS test, the calibration matrix is measured in a conducted mode, and the inverse matrix is calculated to ensure (4), (5), and (6). So from (4), (5), (6), and

$$\begin{aligned} h_{u,s}\,(t) = {} & \sqrt{P_{us}} \lim_{K,L\to\infty} \frac{1}{\sqrt{KL}} \sum_{k=1}^{K} \sum_{l=1}^{L} g_{l,k} exp\left(-jk_0\left(D_{sk}+D_{kl}+D_{lu}\right)\right) \exp\left(-j\boldsymbol{k}_1\boldsymbol{v}t\right) \times \begin{bmatrix} F_s^{T_X\,(v)}\left(\Omega_k^{T_X}\right) \\ F_s^{T_X\,(h)}\left(\Omega_k^{T_X}\right) \end{bmatrix}^T \\ & \times \begin{bmatrix} \exp\left(j\Phi_{l,k}^{(v,v)}\right) & \sqrt{k_{l,k}^h}\sqrt{\chi_{l,k}} exp\left(j\Phi_{l,k}^{(v,h)}\right) \\ \sqrt{k_{l,k}^v} exp\left(j\Phi_{l,k}^{(h,v)}\right) & \sqrt{\chi_{l,k}} exp\left(j\Phi_{l,k}^{(h,h)}\right) \end{bmatrix} \times \begin{bmatrix} F_u^{R_X\,(v)}\left(\Omega_l^{R_X}\right) \\ F_u^{R_X\,(h)}\left(\Omega_l^{R_X}\right) \end{bmatrix} \end{aligned} \quad (8)$$

$$\begin{aligned} R|h_{u,s}\,(t) = {} & \sqrt{P_{us}} \lim_{K,L\to\infty} \frac{1}{\sqrt{KL}} \sum_{k=1}^{K} \sum_{l=1}^{L} g_{l,k} exp\left(-jk_0\left(D_{sk}+D_{kl}+D_{lu}\right)\right) exp\left(-j\boldsymbol{k}_1\boldsymbol{v}t\right) \times \begin{bmatrix} F_s^{T_X\,(v)}\left(\Omega_k^{T_X}\right) \\ F_s^{T_X\,(h)}\left(\Omega_k^{T_X}\right) \end{bmatrix}^T \\ & \times \begin{bmatrix} exp\left(j\Phi_{l,k}^{(v,v)}\right) & \sqrt{k_{l,k}^h}\sqrt{\chi_{l,k}} exp\left(j\Phi_{l,k}^{(v,h)}\right) \\ \sqrt{k_{l,k}^v} exp\left(j\Phi_{l,k}^{(h,v)}\right) & \sqrt{\chi_{l,k}} exp\left(j\Phi_{l,k}^{(h,h)}\right) \end{bmatrix} \times \begin{bmatrix} R|F_u^{R_X\,(v)}\left(\Omega_l^{R_X}\right) \\ R|F_u^{R_X\,(h)}\left(\Omega_l^{R_X}\right) \end{bmatrix} \end{aligned} \quad (10)$$

(15), we can have

$$\begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} & 0 \\ 0 & E_2 e^{j\psi_2} \end{bmatrix} \times H(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} & 0 \\ 0 & E_2 e^{j\psi_2} \end{bmatrix} \times H(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \quad (16)$$

The signals at DUT receivers are strictly expressed in (16) in the RTS method. It is obvious that the received signals include the RSARP reporting errors which are unknown and not expected. Experiments show that both the power reporting error and the phase reporting error have quite large influences on the throughput test [11]. More importantly, for the devices which have different power reporting errors at different receivers, the accuracy of the RTS MIMO test results would get worse and harder to analyze.

D. Elimination Method in the RTS

Formula (16) illustrates the calculation from the transmitted signals to the received signals in the RTS method. It is assumed that a_{xy} is the (x, y) component of the calibration matrix A. Thus, (16) further becomes

$$\begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \times \mathrm{IM} \times \begin{bmatrix} E_1 e^{j\psi_1} & 0 \\ 0 & E_2 e^{j\psi_2} \end{bmatrix} \times H(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \quad (17)$$

Mark A^R as

$$\mathrm{A}^R = \begin{bmatrix} E_1 e^{j\psi_1} & 0 \\ 0 & E_2 e^{j\psi_2} \end{bmatrix} \times \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} a_{11} & E_1 e^{j\psi_1} a_{12} \\ E_2 e^{j\psi_2} a_{21} & E_2 e^{j\psi_2} a_{22} \end{bmatrix}. \quad (18)$$

Formulas (17) and (18) are the primary mathematical foundation of the elimination method proposed in this paper. The corresponding deviations are described as below.

It is showed that once the matrix A^R is measured accurately, we can just calculate the matrix IM through PC to ensure

$$A^R \times \mathrm{IM} = \mathrm{I} \quad (19)$$

where I is the identity matrix. Then, we can eliminate the RSARP reporting errors as below.

Substitute (18) into (19), we have

$$\begin{bmatrix} E_1 e^{j\psi_1} & 0 \\ 0 & E_2 e^{j\psi_2} \end{bmatrix} \times \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \times \mathrm{IM} = \mathrm{I}. \quad (20)$$

Formula (20) further becomes

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \times \mathrm{IM} \times \begin{bmatrix} E_1 e^{j\psi_1} & 0 \\ 0 & E_2 e^{j\psi_2} \end{bmatrix} = \mathrm{I}. \quad (21)$$

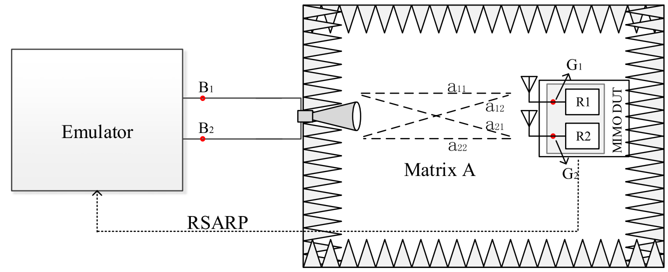

Fig. 7. Innovative calibration matrix measurement method in the RTS.

From (17) and (21), we can have

$$\begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = H(t) \times \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \quad (22)$$

Equations (17), (19), (21), and (22) indicate that once the matrix A^R is measured accurately, the received signals at MIMO DUT receiver input ports would not include the RSARP reporting errors, which is also the theoretical foundation of the elimination method proposed in this paper.

The approach to measure the matrix A^R can be shown in Fig. 7, where B_1, B_2 are the instrument output signals, and G_1, G_2 are the signals at DUT receivers' input ports. The relationship between B_1, B_2 and G_1, G_2 can be expressed as

$$\begin{bmatrix} G_1 \\ G_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \times \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}. \quad (23)$$

The matrix A^R measurement can be divided into the following three steps.

Step 1: Adjust output signals as

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \quad (24)$$

From (23) and (24), the accurate signals at receivers (recorded as G_1^{v}, G_2^{v} at this step) are

$$\begin{bmatrix} G_1^{\mathrm{v}} \\ G_2^{\mathrm{v}} \end{bmatrix} = \begin{bmatrix} a_{11} \\ a_{21} \end{bmatrix}. \quad (25)$$

Get the signals at receivers through RSARP and record the reporting as $G_1^{RS(v)}$, $G_2^{RS(v)}$. As discussed earlier, for the uth receiver; E_u is the corresponding amplitude reporting error; ψ_u is the corresponding phase reporting error. Therefore, $G_1^{RS(v)}$, $G_2^{RS(v)}$ are associated with G_1^{v}, G_2^{v} as

$$\begin{bmatrix} G_1^{RS(v)} \\ G_2^{RS(v)} \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} G_1^{\mathrm{v}} \\ E_2 e^{j\psi_2} G_2^{\mathrm{v}} \end{bmatrix}. \quad (26)$$

From (25) and (26), we can have

$$\begin{bmatrix} G_1^{RS(v)} \\ G_2^{RS(v)} \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} a_{11} \\ E_2 e^{j\psi_2} a_{21} \end{bmatrix}. \quad (27)$$

Step 2: Adjust output signals as

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{28}$$

From (23) and (28), the absolute signals at receivers (recorded as G_1^{h}, G_2^{h} at this step) are

$$\begin{bmatrix} G_1^{\mathrm{h}} \\ G_2^{\mathrm{h}} \end{bmatrix} = \begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix}. \tag{29}$$

Get the signals at receivers through RSARP and record the reporting as $G_1^{RS(h)}$, $G_2^{RS(h)}$, which are associated with G_1^{h}, G_2^{h} as

$$\begin{bmatrix} G_1^{RS(h)} \\ G_2^{RS(h)} \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} G_1^{\mathrm{h}} \\ E_2 e^{j\psi_2} G_2^{\mathrm{h}} \end{bmatrix}. \tag{30}$$

From (29) and (30), we can have that

$$\begin{bmatrix} G_1^{RS(h)} \\ G_2^{RS(h)} \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} a_{12} \\ E_2 e^{j\psi_2} a_{22} \end{bmatrix}. \tag{31}$$

Step 3: Combining (18), (27), and (31), the matrix A^R is obtained as

$$\begin{bmatrix} G_1^{RS(v)} & G_1^{RS(h)} \\ G_2^{RS(v)} & G_2^{RS(h)} \end{bmatrix} = \begin{bmatrix} E_1 e^{j\psi_1} a_{11} & E_1 e^{j\psi_1} a_{12} \\ E_2 e^{j\psi_2} a_{21} & E_2 e^{j\psi_2} a_{22} \end{bmatrix} = \mathrm{A}^R. \tag{32}$$

In summary, the matrix A^R is measured just through several RSARP reporting readings. Then, the inverse matrix of A^R can be achieved just through the calculations in the PC.

More importantly, the measurements of A^R can be conducted just in an anechoic chamber in a radiated mode, without any hardware changes in the whole RTS test procedure. Therefore, the method can significantly simplify the RTS test procedure, resulting in a great reduction on the test period and complexity.

As stated before, generally, the calibration matrix A was measured in the conducted mode with a VNA, which is cumbersome and time consuming. Moreover, the RSARP reporting errors are brought in the RTS MIMO OTA test. By using the elimination method proposed in the paper, the two mentioned issues are both solved completely. Therefore, it is of great value to the RTS MIMO OTA test.

III. Validations of the Proposed Method

This section presents lots of experiments for validation. With and without the elimination method applied, the RTS MIMO OTA test results can significantly reflect the influence on the final throughput test caused by the RSARP errors.

Specifically, the validation work can be divided into the following four parts:

Part 1: The RSARP reporting errors were measured. First, measure the calibration matrix A, in a conducted approach, as shown in Fig. 6. Then, measure the matrix A^R, in a radiated approach, as shown in Fig. 7. Finally, the RSARP reporting errors can be calculated through (18).

TABLE I
Different Validation Configurations

Experiments	Antenna patterns configuration	Calibration matrix solution	Elimination method using
1	With RSARP errors	Conducted mode	No
2	Without RSARP errors	Conducted mode	No
3	With RSARP errors	Radiated mode	Yes

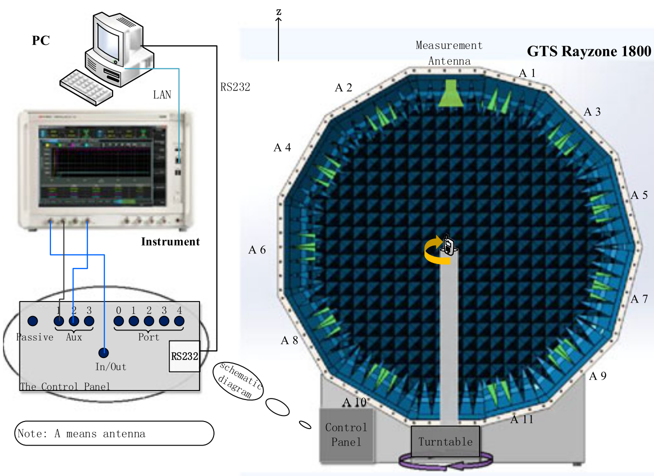

Fig. 8. Test set-up for the RTS MIMO OTA test.

Part 2: Carry out the RTS MIMO tests by using the DUT complex antenna patterns obtained through RSARP. Especially, in this part, the elimination method is not applied and the calibration matrix A is measured in a conducted mode as shown in Fig. 6.

Part 3: While the RSARP reporting errors were measured in part 1 and the DUT complex antenna patterns were obtained through RSARP, the absolute DUT antenna patterns can be calculated. Then, in this part, the RTS tests are carried out with the accurate antenna patterns, without using the proposed elimination method (the calibration matrix A is measured in a conducted mode).

Part 4: Carry out the RTS tests by using the DUT complex antenna patterns obtained through RSARP. Especially, in this part, the elimination method is applied and the new calibration matrix A^R is measured in a radiated mode as in Fig. 7 and stated before.

In summary, three kinds of throughput test configurations are required to conduct in this section. The corresponding settings are shown in Table I.

A. Test Set-up

The test set-up for the RTS MIMO OTA test is illustrated in Fig. 8, including a control PC, test instruments (a BSE, a channel emulator, and a VNA), and an anechoic chamber.

The Spatial Channel Model Extension (SCME) UMi and SCME UMa (defined in the 3GPP standard [4]) were carried out for experiments. It is noted both of them are 2-D channel

TABLE II
MEASUREMENT PARAMETERS

Parameters	Value
Instruments	PC, Vector network analyzer, Keysight UXM
Anechoic chamber	Rayzone 1800 from GTS
Downlink frequency	2132.5 MHz
Protocol	FDD
DUT	Samsung Tab 2
Channel model	SCME UMa and SCME UMi
Orientation	Portrait [8]

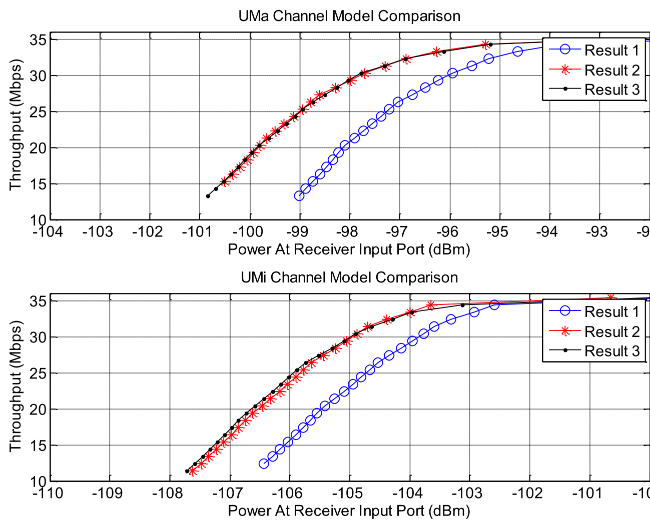

Fig. 9. Throughput test results.

models (since no 3-D channel model is specified in the white papers). The portrait orientation of the DUT was selected [12].

The measurement parameters are shown in Table II.

B. Results

Experiments shows that using this DUT, the RSARP reporting system has an error of +1.6 dB for the power evaluation at the first receiver; an error of +1.4 dB for the power evaluation at the second receiver and an error of −7.5° for the relative phase offset evaluation between the two receivers.

The throughput measurement results under the three test configurations discussed before are shown in Fig. 9, where the relationships between the power at receiver input port and the throughput are described. From the results, several conclusions can be achieved as described below.

Conclusion 1: Compared to the results 1 and 2, for the selected DUT, the RSARP reporting errors have an influence of about 1.6 dB on the final throughput tests under the UMa channel model, and an influence of about 1.2 dB on the final throughput tests under the UMi channel model.

Conclusion 2: An extremely different (<0.15 dB) is existed between the results provided by experiments 2 and 3. It is obvious that the proposed method could significantly eliminate the RSARP reporting errors in the RTS MIMO OTA tests.

Moreover, by using the proposed eliminating method, during the whole RTS MIMO OTA tests, it is not required to change the hardware, which results in a great convenience to operate and a large decrease in test period.

In summary, the proposed method in this paper could not only ensure the RTS MIMO OTA test accuracy, but also simplify the test procedure.

IV. CONCLUSION

This paper proposed an innovative method for eliminating the RSARP errors and ensuring the throughput test accuracy in the RTS MIMO OTA test. The strict mathematical derivation and the corresponding validations were detailed. Experiments show that the proposed method could significantly eliminate the reporting errors and greatly improve the RTS MIMO test accuracy. Moreover, based on the elimination method, the RTS test procedure can be significantly simplified. No more conductive tests are required during the entire test, which greatly decreases the RTS test complexity and reduces the test period. Therefore, it is of great value to the RTS MIMO OTA test.

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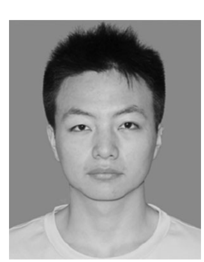

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