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Inverse Matrix Autosearch Technique for the RTS MIMO OTA Test

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***Abstract*—An inverse matrix autosearch algorithm for radiated two-stage (RTS) multiple input and multiple output (MIMO) over-the-air (OTA) tests is proposed in this article. The RTS is one standard technique for the MIMO OTA test provided by the Cellular Telecommunication and Internet Association and the Third Generation Partnership Project. A basic step in the RTS test procedure is to solve the inverse matrix at a combination of measurement antennas and device orientation. The automatic solving algorithm proposed in this article is based on two parts: the technique for selecting an appropriate combination for inverse matrix solving and the method for solving the inverse matrix at a fixed combination. The technique proposed in this article makes the RTS test procedure automatic and fast, which improves the test user experience. In fact, only 2 min are required for the whole process of the appropriate combination calculation and the inverse matrix solving at the selected combination, while several hours might be needed using the traversal method.**

***Index Terms*—Multiple-input and multiple-output (MIMO), over-the-air (OTA), radiated two-stage (RTS), throughput.**

I. Introduction

OVER-THE-AIR (OTA) test has been standardized by the Cellular Telecommunication and Internet Association (CTIA) and the Third Generation Partnership Project (3GPP) for many years to evaluate the end-to-end performance of multiple input and multiple output (MIMO) devices. As defined in the standards [1], [2], the primary parameter for the MIMO OTA performance evaluation is throughput, which depends on a number of factors, including self-desensitization, baseband processing, the propagation channels, the antenna system performance, etc. [3]. The major test challenge for the MIMO OTA test is creating a repeatable test environment, which accurately reflects the standardized wireless propagation environment.

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Different MIMO OTA test methods have been proposed by CTIA and 3GPP in the past decades, which fall into three categories: the multiple probe anechoic chamber (MPAC) method [4], the reverberation chamber (RC) test method [5], [6], and the radiated two-stage (RTS) method [7], [8]. The MPAC technique uses a hardware-enabled environment to simulate the mathematical multipath environment, which is straightforward and correct in theory. However, accurately implementation of the MPAC may face many challenges because of the complexity of the hardware and calibrations. A proposal showed that for three MPAC systems under the same configurations, the test difference could be up to 7.31 dB [9]. The RC is a statistical test solution without absorbers, which is widely used for single-input and single-output (SISO) wireless system performance evaluations. For the MIMO test, the RC method can build up some special multipath channel models (via the reflections inside the chamber), which are helpful for MIMO throughput evaluations, especially for the large-size wireless equipment. However, RC may face challenges to achieve the standard mathematical channel models, such as the spatial channel model and the spatial channel model extension [10].

The RTS method is based on the first stage of antenna pattern measurement via the antenna test function inside the device under test (DUT), which is used to report both the reference signal antenna power (RSAP) and the reference signal antenna relative phase (RSARP) [11], followed by the second stage of throughput measurement by combining the device antenna patterns with the channel models. The throughput test signals are sent to the corresponding receivers, respectively, in a radiated working mode, with an inverse matrix applied [7], [8]. RTS is a fast, cost-efficient, and promising method for the throughput test. By using the RTS method, the radiated sensitivities of MIMO device's receivers can be measured, respectively, which is quite important in the electromagnetic interference analysis of MIMO systems since the radiated sensitivity is an efficient metric for evaluating the receiver sensitivity degradation caused by the noise and interference generated by the wireless device's hardware circuit. The RTS is wisely utilized for MIMO performance evaluations. However, currently directly adopting the RTS MIMO test for the DUT with beam-forming technique may still face challenges since the DUT will dynamically change the radiation patterns according to the dynamic channel characteristics.

The RTS method was first proposed in [7], where, instead of using RF cables for signal transmissions, an inverse matrix technique was applied so that the desired throughput test signals

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could be delivered into receivers OTA. This way, the OTA measurement could include the actual effects of the self-interference of the DUT, which were incorrectly avoided by using RF cables. The self-interference reflected as the noise generated by the internal modules of the DUT, then coupled to the antennas, and eventually delivered into the receivers, could seriously degrade the receiver sensitivities. In the wireless device design, this phenomenon is categorized as a desense problem and is an emerging issue with increasing importance. Like other EMC problems, desense is closely related to the system-level design of the wireless device. The MIMO OTA test, when it is conducted properly to include the effects of the self-interference, not only is the ultimate method to quantify the desense performance of the DUT but also provides useful insights for the desense-related debugging and design optimization of the DUT [12].

The step for the inverse matrix solving is essential in the RTS test procedure. However, there are at least two issues, which significantly affect the measurement period, accuracy, and user experience of the RTS method for the MIMO OTA test. The first issue is solving the corresponding inverse matrix on the condition that the source matrix has several unknown factors. The other issue is selecting an appropriate combination of measurement antennas and DUT orientation to do the inverse matrix solving so that the uncertainties on the final throughput results contributed by the interference can be neglected [2], [13].

For the first issue, a feasible traditional way for the propagation matrix measurement is the conductive approach, which uses a vector network analyzer connected between the chamber antenna feedings and the DUT receiver input ports. Theoretically, the measured S parameters are the calibration matrix. However, besides its inconvenience, the conductive measurements for the calibration matrix may introduce uncertainties since the cable may impact the DUT antenna radiation pattern. For the second issue, a conventional method for selecting a combination is the traversal method, which conducts the inverse matrix solving at every combination to find an appropriate one. The traversal method is extremely time-consuming.

For solving the two issues, an automatic solving algorithm is proposed in this article, which is based on two parts: the technique for selecting an appropriate combination for inverse matrix solving and the method for solving the inverse matrix at a fixed combination. The technique makes the RTS test procedure automatic and fast. In fact, only 2 min are required for the whole process of the appropriate combination calculation and the inverse matrix solving at the selected combination, while several hours might be needed using the traversal method.

The rest of this article is organized as follows. In Section II, the two problems will be detailed. In Section III, the method for solving the inverse matrix at a fixed combination is discussed. In Sect IV, while the search process of the appropriate location for inverse matrix solving is described. In Section V, the throughput test procedure is presented. Finally, Section VI concludes this article.

II. Problem Description

Both the conducted two-stage (CTS) method and the RTS test method were presented in [7]. In the throughput test stage

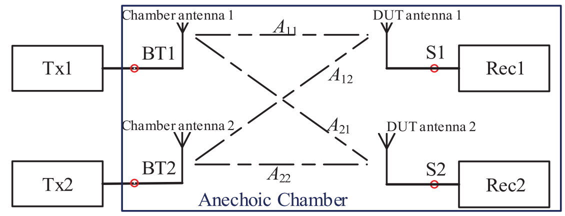

Fig. 1. Feeding the stimulus signals over the air inside an anechoic chamber.

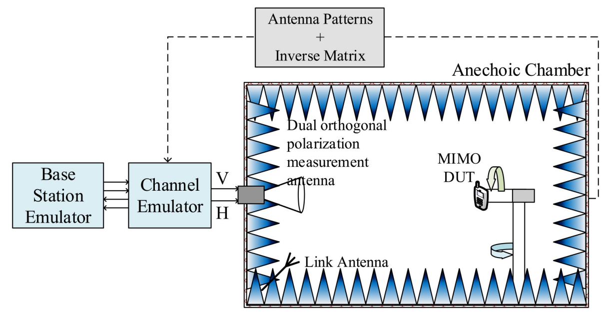

Fig. 2. RTS implementation.

of RTS, instead of using RF cables to deliver the throughput test signals (marked as $S1$ and $S2$) to the MIMO receivers directly, two transmit antennas are used to deliver the signals BT_1 and BT_2 OTA to the MIMO DUT antennas, in a way that the signals fed into the MIMO receivers equal the throughput test signals $S1$ and $S2$. As shown in Fig. 1, the DUT is located in an anechoic chamber. BT_1 and BT_2 are fed into the transmit antennas in order to get $S1$ and $S2$ at the input ports of receiver 1 and receiver 2, respectively.

Then $S1$ and $S2$ are related to BT_1 and BT_2 as

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} * \begin{bmatrix} BT_1 \\ BT_2 \end{bmatrix},\ A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \tag{1}$$

where S_x is the power received at the receiver input port x; BT_x is the power transmitted to the measurement antenna x in the chamber; A_{ij} is the power path loss and phase offset from the transmit power BT_j to the received power S_i. We named the transmission matrix A as the calibration matrix in the rest of this article for convenience.

The calibration matrix A is a function of the gains of the measurement antennas, the gains of the DUT antennas, the free-space propagation path loss values, and phase offsets between the measurement antenna feeding points and the DUT antenna feeding points. It is always possible that the DUT can be rotated to an orientation such that the matrix A is nonsingular. Then, the required signals to the reference antennas can be determined as

$$\begin{bmatrix} BT_1 \\ BT_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}^{-1} * \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \tag{2}$$

In summary, the RTS method, as shown in Fig. 2, can be described as follows. First, measure the DUT antenna patterns. Then, calculate the inverse matrix of the calibration matrix A and generate BT_1 and BT_2 based on formula (2) in the emulator. Keep the DUT fixed in the anechoic chamber (both location and orientation relative to the transmit antennas) and feed BT_1 and

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BT_2 into the transmit antennas (measurement antennas in the chamber) to perform the MIMO throughput test.

As discussed above, one essential key step of the RTS method is solving the inverse matrix of the calibration matrix. However, the process for solving the inverse matrix has two challenging issues.

A. First Issue

As stated before, the calibration matrix contains the amplitude and phase changes between the transmitted signals at the emulator output ports and the received signals at the MIMO DUT receiver input ports. The amplitude and phase changes are mainly caused by the RF connections, cables, measurement antennas, free-space propagation (in the anechoic chamber), and receiver antennas. The amplitude and phase factors of the calibration matrix are rewritten as

$$A = \begin{bmatrix} a_{11}e^{j\Phi_{11}} & a_{12}e^{j\Phi_{12}} \\ a_{21}e^{j\Phi_{21}} & a_{22}e^{j\Phi_{22}} \end{bmatrix} \tag{3}$$

where a_{xy} and Φ_{xy} are the absolute amplitude and phase offsets from the transmitting signal *y* (at the emulator output port) to the received signal *x* (at the receiver input port), respectively.

In fact, the absolute amplitude offset a_{xy} can be obtained through the RSAP and RSARP reporting system, which can report the received power levels at all receiver inputs and the relative phase offset between any two received signals [13]. However, the absolute phase offsets Φ_{xy} cannot be calculated just using the RTS setups shown in Fig. 2. Since the OTA test system is nonintrusive, it is almost impossible to compare the phase offsets between the transmitting ports and the received ports. A feasible traditional way for the calibration matrix measurement is the conductive approach, which uses a vector network analyzer with connecting the emulator output ports and the receiver input ports. The measured *S* parameters are the calibration matrix. However, besides its inconvenience, the conductive measurements for the calibration matrix may introduce uncertainties since the cable may impact the DUT antenna radiation pattern.

The calibration matrix has several unknown factors. As a consequence, solving the inverse matrix through the calibration matrix is impractical, which is the first problem that needs to be resolved for the RTS test. As discussed above, in a fixed OTA test system, the matrix is only sensitive to the combination of measurement antennas and DUT orientation. Therefore, one combination corresponds to a calibration matrix. Then the first issue is solving the inverse matrix at a fixed combination of the measurement antennas and the DUT orientation on the condition that the corresponding calibration matrix is unknown.

B. Second Issue

Before introducing the second issue, several major performance benchmarks for the inverse matrix solving are presented here.

As stated above, with applying the inverse matrix, the throughput test signals can be transmitted to the receivers separately in RTS tests, as shown in Fig. 3. Then S_1 and S_2 are related to T_1 and T_2 as

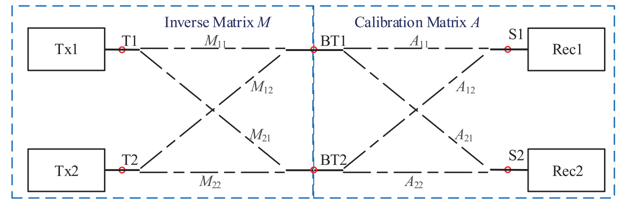

Fig. 3. Applying the inverse matrix.

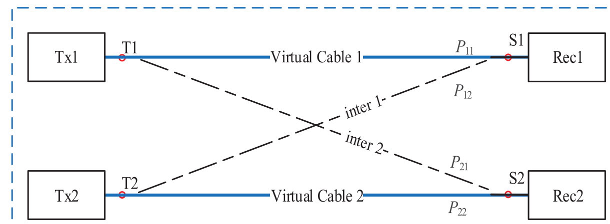

Fig. 4. Simplified diagram for Fig. 3.

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} * \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} * \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}. \tag{4}$$

Moreover, it is exactly that

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} * \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = I \tag{5}$$

where *I* is the identity matrix.

From (4) and (5), it follows

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}. \tag{6}$$

Fig. 3, then, is simplified as Fig. 4. By applying the inverse matrix, the signals can reach the receivers directly and, respectively, without crossing, similar to the conducted working mode. We named this propagation way as "virtual cables," as shown in Fig. 4, for the solid lines.

However, in the practical application of the RTS method, the interference from each other is always existent (mainly caused by reflecting from the absorbers inside the anechoic chamber, coupling between receiver circuits, accuracy of inverse matrix calculation, and implementation in the RF instrument, etc.) as well as in the CTS method where the real cables are used for signals transmission. In fact, the isolation of the real cables can be larger than 60 dB so that the interference between the real cables can be negligible.

The isolation of the virtual cables is a key performance benchmark to evaluate the uncertainties on the throughput test contributed by the applied inverse matrix.

We define the virtual cable isolation as (in the format of real)

$$\begin{aligned} \mathrm{Iso}_1 &= |P_{11}/P_{12}| \\ \mathrm{Iso}_2 &= |P_{22}/P_{21}| \\ \mathrm{Iso}_t &= \min(\mathrm{Iso}_1, \mathrm{Iso}_2) \end{aligned} \tag{7}$$

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where P_{ij} is the power level received by the receiver i from the signal T_j, Iso_1 is the isolation of the virtual cable 1 against T_2 and is expressed as P_{11}/P_{12}, Iso_2 is the isolation of the virtual cable 2 against $T_1$and is expressed as P_{22}/P_{21}, and Iso_t is the minimum one of the two.

Furthermore, the parameter Iso_t is regarded as the final performance benchmark of the calculated inverse matrix at the corresponding combination of the measurement antennas and the DUT orientation. The powers P_{21} and P_{12} are the crossing power levels between the different receivers.

In practice, the isolations of the two virtual cables are required to reach a certain large value so that the crosstalk between the two virtual cables would not seriously impact the throughput test result. More importantly, it is better to obtain a large isolation value as much as possible to ensure the throughput test repeatability and accuracy.

As stated above, in a fixed test system, one combination of measurement antennas and DUT orientation corresponds to a calibration matrix. There are many combinations in a multiple test antenna chamber, where we can choose two single-polarized test antennas and one DUT orientation for the throughput test. The second issue is how to select a combination for solving the inverse matrix, which can ensure that the achieved isolation Iso_t is large enough to neglect the uncertainties on throughput contributed by crosstalk.

The above-mentioned two problems have significant influences on the RTS method.

For problem 1, the inverse matrix-solving step at a fixed combination is an indispensable and essential step for performing RTS MIMO OTA tests.

Problem 2 is also troublesome. A conventional method for selecting a combination, which can ensure the achieved isolation Iso_t being large enough, is the traversal method. In this method, the inverse matrix-solving process is conducted at every combination to find the appropriate one. It is a seriously time-consuming process. With a step of 15° in both the θ axis and φ axis in Fig. 2, there are 266 combinations in total. It may require several hours for just the process of performing the inverse matrix at the 266 combinations, which is intolerable (the DUT battery also might not last for several hours).

Therefore, an innovative inverse matrix autosearch technique is proposed in this article. The technique can be divided into the following two parts.

1) The method for solving the inverse matrix at a fixed combination.
2) The method for selecting the appropriate combinations of measurement antennas and DUT orientation for inverse matrix solving.

The technique proposed in this article can make the RTS test procedure automatic and fast, which greatly improves the user experience. The most mentionable advantage of the technique is that only 2 min are required for the whole process, including the appropriate combination calculation and the inverse matrix solving at the selected combination, while several hours might be needed using the traversal method.

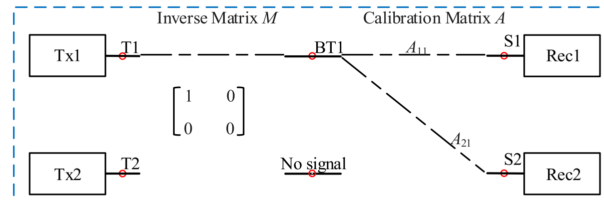

Fig. 5. Step 2 for solving the inverse matrix at a fixed location.

III. Method for Solving the Inverse Matrix at a Fixed Combination

An effective method for solving the inverse matrix at a fixed combination is proposed and detailed in this section. By using the method, the inverse matrix can be obtained quickly and conveniently.

In the inverse matrix-solving process, the DUT RSAP and RSARP reporting techniques are required to report the information about the signal strengths at the receiver input ports and the related phase offsets between any two signals at the receiver input ports.

The inverse matrix-solving process at a fixed location can be divided into the following steps. It is worth mentioning that practically the inverse matrix is implemented in an RF module in the instrument and then remains unchanged during a whole throughput test process. A general RF circuit of the instrument has a limited gain, which indicates that the dynamic range of the amplitudes of the elements in the inverse matrix is limited. In this article, we assumed that the gain limitation is one (in the format of real).

1) Select a combination. The combination is achieved automatically using the proposed technique, which will be detailed in Section IV.
2) Set the inverse matrix as

$$\mathrm{M} = \begin{bmatrix}1 & 0\\0 & 0\end{bmatrix} \tag{8}$$

and then get the report from the DUT. At this step, we can get the module of A_{11} (recorded as $|A_{11}|$), the module of A_{21} (recorded as $|A_{21}|$), and the related phase offset between vector A_{11} and A_{21}. The step is shown in Fig. 5.

3) Set the inverse matrix as

$$\mathrm{M} = \begin{bmatrix}0 & 0\\0 & 1\end{bmatrix} \tag{9}$$

and then get the report from the DUT. At this step, we can get the module of A_{12} (recorded as $|A_{12}|$), the module of A_{22} (recorded as $|A_{22}|$), and the related phase offset between vector A_{12} and A_{22}. The step is shown in Fig. 6.

4) Set the inverse matrix as

$$M = \begin{cases}\begin{bmatrix}1 & 0\\ -\frac{|A_{21}|}{|A_{22}|}e^{jx} & 0\end{bmatrix}, & (\text{if } |\mathrm{A}_{22}| \geq |\mathrm{A}_{21}|)\\ \begin{bmatrix}-\frac{|A_{22}|}{|A_{21}|}e^{jx} & 0\\ 1 & 0\end{bmatrix}, & (\text{if } |\mathrm{A}_{22}| < |\mathrm{A}_{21}|)\end{cases} \tag{10}$$

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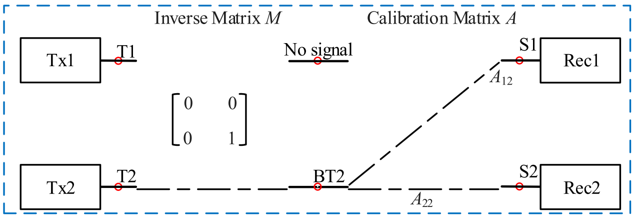

Fig. 6. Step 3 for solving the inverse matrix at a fixed location.

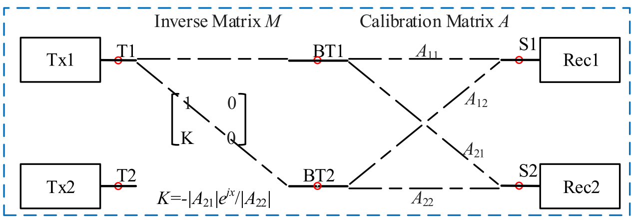

Fig. 7. Step 4 for solving the inverse matrix at a fixed location.

and get the report from the DUT, where x is an unknown factor and required to be calculated in this step.

In the rest of this article, we take the condition of $|A_{22}| \geq |A_{21}|$ as an example for the deviation of the method (since the deviation process in the condition of $|A_{22}| < |A_{21}|$ is the same). The setups are shown in Fig. 7 and the process for calculating x is described in the following part.

With the inverse matrix applied, the received signals at the two receivers can be expressed as

$$S_1 = \left(A_{11} - A_{12} \frac{|A_{21}|}{|A_{22}|} e^{jx} \right) T_1$$
$$S_2 = \left(A_{21} - A_{22} \frac{|A_{21}|}{|A_{22}|} e^{jx} \right) T_1. \quad (11)$$

Theoretically, with this inverse matrix applied, the power level at the second receiver input port should always be zero with an appropriate x value applied in the setups in Fig. 7 (since the signals from Tx_1 should not be received by the second receiver with this half-inverse matrix applied). Although the absolute phase offset of A_{21} is unknown, it is a constant value at a fixed combination. Therefore, we can adjust the x in formula (11) step by step from 0° to 360° and record the wanted value as α, which minimizes the power level at the second receiver. It is worth mentioning that theoretically the minimum power level value is zero. However, in reality, it is a nonzero value mainly caused by reflected noise, self-interference, and bandwidth. For convenience, we named this constant as the canceled power level (CPL) in the rest of this article.

Mathematically, the α obtained in this step enables the following expression:

$$A_{21} = A_{22} \frac{|A_{21}|}{|A_{22}|} e^{j\alpha}. \quad (12)$$

From (1), (3), and (12), it is easy to get

$$\alpha = \Phi_{21} - \Phi_{22}. \quad (13)$$

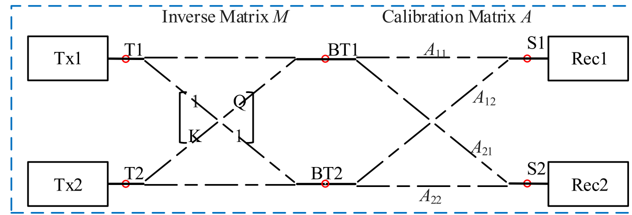

Fig. 8. Step 5 for solving the inverse matrix at a fixed location.

Following the same processes from steps 1–4, β is expressed in the following expression:

$$A_{12} = A_{11} \frac{|A_{12}|}{|A_{11}|} e^{j\beta}. \quad (14)$$

From (1), (3), and (14), it is easy to get

$$\beta = \Phi_{12} - \Phi_{11}. \quad (15)$$

5) Set the inverse matrix as

$$M = \begin{bmatrix} 1 & -\frac{|A_{12}|}{|A_{11}|} e^{j\beta} \\ -\frac{|A_{21}|}{|A_{22}|} e^{j\alpha} & 1 \end{bmatrix} \quad (16)$$

and get the report from the DUT. The step is shown in Fig. 8.

With the abovementioned inverse matrix applied, the signals received by the two receivers are

$$S_1 = \left(A_{11} - A_{12} \frac{|A_{21}|}{|A_{22}|} e^{j\alpha} \right) T_1$$
$$S_2 = \left(A_{22} - A_{21} \frac{|A_{12}|}{|A_{11}|} e^{j\beta} \right) T_2. \quad (17)$$

Equation (17) indicates that the signal received by the first receiver only from sources from Tx_1, and the signal received by the second receiver only from sources from Tx_2. There is no signal crossing, which is exactly the definition of the RTS method. Moreover, the two virtual cables' S_{21} values are $(A_{11} - A_{12}\frac{|A_{21}|}{|A_{22}|}e^{j\alpha})$ and $(A_{22} - A_{21}\frac{|A_{12}|}{|A_{11}|}e^{j\beta})$, respectively, and these S_{21} values are known and easy to modify exactly.

Therefore, using the steps presented above, the inverse matrix is solved efficiently and accurately.

In the following section, the method for searching the appropriate combinations for solving the inverse matrix is proposed.

IV. Method for Searching Appropriate Combination of Measurement Antennas and DUT Orientation for the Inverse Matrix Solving

As defined before, the second issue is how to select an appropriate combination for solving the inverse matrix, which can ensure that the achieved isolation Iso_t is large enough to neglect the uncertainties on throughput contributed by crosstalk. For a fixed MIMO DUT and a fixed test system, there may be few combinations making the isolation Iso_t suitable, especially when the DUT antennas are high correlated. In order to accommodate all the circumstances, this article presents a method for calculating all the isolation values without any extra test steps. Thus, the desired combination can be selected just through calculations.

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In the calculations for isolation values, only the information about the antenna patterns is required, which is already achieved in the first stage in the RTS method. So no additional measurement steps are carried out.

There are three parts of the derivation for the isolation values calculations: the expressions of the parameter Iso_t, the relationship between the antenna pattern achieved in stage 1 in the RTS method, and the parameter Iso_t and the final Iso_t calculation.

A. Expressions of the Parameter Iso_t

By applying the inverse matrix, the received power levels at the receiver input ports are shown in (17) and the crossing power level, named as the CPL, can be regarded as a constant for two reasons. First, the CPL is caused by reflections, receiver coupling, and calculation errors. It is an angle independent factor. As shown in Fig. 4, CPL indicates the power level of crosstalk. Second, the isolation defined in (7) indicates the ratio of the gain of the virtual cable and the gain of the cross-coupling path. So although the value of CPL is unknown, we can select a combination corresponding to the largest gain of the virtual cable. Based on the facts, CPL can be regarded as a constant.

Iso_t is the minimum value of Iso_1 and Iso_2, as defined in (7). By applying the inverse matrix, the gains of the two virtual cables are the same in theory so that only the bigger CPL value (two CPL values for Iso_1 and Iso_2) is associated with Iso_t. Then one constant value C is used in the article for representing the two CPL values.

Furthermore, formula (7) can be rewritten as

$$\begin{aligned}\mathrm{Iso}_1 &= |P_{11}/C| \\ \mathrm{Iso}_2 &= |P_{22}/C| \\ \mathrm{Iso}_t &= \min(\mathrm{Iso}_1, \mathrm{Iso}_2)\end{aligned} \tag{18}$$

where P_{11} is the power level received by the receiver 1 from the signal T_1, P_{22} is the power level received by the receiver 2 from the signal T_2, C is the CPL (a constant for the fixed test setups). By applying the inverse matrix, P_{11} and P_{22} just correspond to S_1 and S_2 in (19). Therefore, we can have

$$\mathrm{Iso}_t = \min\left\{\begin{array}{l}\left|A_{11} - A_{12}\frac{|A_{21}|}{|A_{22}|}e^{j\alpha}\right|/C \\ \left|A_{22} - A_{21}\frac{|A_{12}|}{|A_{11}|}e^{j\beta}\right|/C\end{array}\right. . \tag{19}$$

From (1), (3), (17), and (19), the parameter Iso_t is rewritten as

$$\mathrm{Iso}_t = \min\left\{\begin{array}{l}\left|\frac{a_{11}a_{22}e^{j\Phi_{11}} - a_{12}a_{21}e^{j(\Phi_{12}+\Phi_{21}-\Phi_{22})}}{a_{22}}\right|/C \\ \left|\frac{a_{11}a_{22}e^{j\Phi_{22}} - a_{12}a_{21}e^{j(\Phi_{21}+\Phi_{12}-\Phi_{11})}}{a_{11}}\right|/C\end{array}\right. \tag{20}$$

and then transformed as

$$\mathrm{Iso}_t = \min\left\{\begin{array}{l}\left|\frac{a_{11}a_{22} - a_{12}a_{21}e^{j(\Phi_{12}+\Phi_{21}-\Phi_{22}-\Phi_{11})}}{a_{22}}e^{j\Phi_{11}}\right|/C \\ \left|\frac{a_{11}a_{22} - a_{12}a_{21}e^{j(\Phi_{21}+\Phi_{12}-\Phi_{11}-\Phi_{22})}}{a_{11}}e^{j\Phi_{22}}\right|/C\end{array}\right. \tag{21}$$

where $e^{j\varphi_{11}}$ and $e^{j\varphi_{22}}$ are the common phase-related factors, which have no contact with the modules.

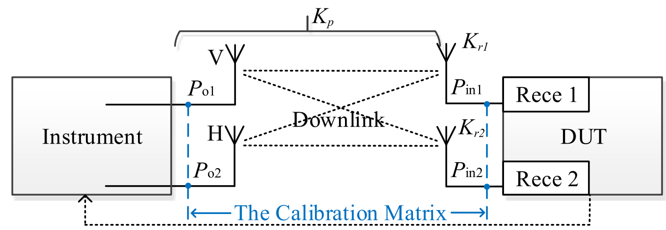

Fig. 9. Simplified diagram for the antenna measurement.

So (21) is equivalent to

$$\mathrm{Iso}_t = \min\left\{\begin{array}{l}\left|\frac{a_{11}a_{22} - a_{12}a_{21}e^{j(\Phi_{12}+\Phi_{21}-\Phi_{22}-\Phi_{11})}}{a_{22}}\right|/C \\ \left|\frac{a_{11}a_{22} - a_{12}a_{21}e^{j(\Phi_{21}+\Phi_{12}-\Phi_{11}-\Phi_{22})}}{a_{11}}\right|/C\end{array}\right. . \tag{22}$$

That is the expression for the isolation Iso_t.

B. Relationship Between Antenna Patterns Achieved in the First Stage in RTS Method and the Parameter Iso_t

In the first stage in the RTS test, the DUT antenna patterns were achieved. The related test setups are shown in Fig. 2, which is simplified as Fig. 9, where P_{ox} is the instrument output power (known); K_p is the total power path loss, including the range power path loss due to the range length, the gain of the reference antenna (the reference antenna contains the horizontal and vertical polarizations), and any loss terms associated with the cabling, connections, amplifiers, etc. (known); K_{rx} is the gain of the xth DUT antenna (unknown); and $P_{\mathrm{in}x}$ is the power received at the receiver input, which can be achieved through the RSAP and RSARP reporting.

From the diagram, the antenna gain at any combination is

$$K_{rx} = \frac{P_{\mathrm{in}x}}{P_{ox} * K_p} \tag{23}$$

and the related phase offset at this orientation is achieved through the reporting from the DUT directly. Therefore, the antenna gains (both horizontal and vertical polarizations) and the phase offset at every orientation can be obtained in the first stage in the RTS tests.

In summary, at every orientation, six data can be obtained as follows.

1) V polarization gain of antenna 1 (recorded as G_{V1}).
2) H polarization gain of antenna 1 (recorded as G_{H1}).
3) V polarization gain of antenna 2 (recorded as G_{V2}).
4) H polarization gain of antenna 2 (recorded as G_{H2}).
5) V polarization phase offset between antenna 1 and antenna 2 (recorded as Φ_V).
6) H polarization phase offset between antenna 1 and antenna 2 (recorded as Φ_H).

Comparing Figs. 9 and 1, with using the horizontal and vertical polarizations of the reference antenna as the two measurement antennas, the relationship between P_{ox} and $P_{\mathrm{in}x}$ is

$$\begin{bmatrix}P_{\mathrm{in}1} \\ P_{\mathrm{in}2}\end{bmatrix} = A' * \begin{bmatrix}P_{o1} \\ P_{o2}\end{bmatrix}, A' = \begin{bmatrix}a_{11} & a_{12} \\ a_{21} & a_{22}\end{bmatrix} \tag{24}$$

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where a_{xy} is the power change between the *x*th output port of the instrument and the *y*th receiver input of the DUT since only power levels are considered in the antenna gains tests.

Therefore, at each orientation, the relationship between the antenna pattern information and the corresponding calibration matrix *A* can be described as

$$\begin{aligned} |G_{V1}/K_p| &= a_{11} \\ |G_{H1}/K_p| &= a_{12} \\ |G_{V2}/K_p| &= a_{21} \\ |G_{H2}/K_p| &= a_{22} \\ \Phi_V &= \Phi_{21} - \Phi_{11} \\ \Phi_H &= \Phi_{22} - \Phi_{12}. \end{aligned} \tag{25}$$

This formula is the primary foundation for the Iso_t calculation at every combination.

C. Final Iso_t Calculation

From (22) and (25), the calculation for Iso_t is

$$\mathrm{Iso}_t = \min \left\{ \begin{array}{l} \left| \frac{a_{11}a_{22} - a_{12}a_{21}e^{j(\Phi_V - \Phi_H)}}{a_{22}} \right| / C \\ \left| \frac{a_{11}a_{22} - a_{12}a_{21}e^{j(\Phi_V - \Phi_H)}}{a_{11}} \right| / C \end{array} \right. . \tag{26}$$

As discussed above, at each combination, the elements a_{11}, a_{12}, a_{21}, a_{22}, Φ_V, and Φ_H can be totally calculated just from the antenna patterns achieved in the first stage in the RTS method, as in (27). So the factor Iso_t is easy to be calculated at every angle. Reorder the combinations according to the factor Iso_t in the descending order. Then we can have all the isolation values. Actually, the combination, which corresponds to the largest isolation, is usually selected to complete the inverse matrix solving.

V. Throughput Test by Using the Proposed Method

The RTS MIMO OTA test procedure with the inverse matrix autosearch method applied can be divided into the following four steps.

1) Achieve the DUT antenna patterns.
2) Select the appropriate combination of the DUT for the inverse matrix solving.
3) Tuning the corresponding inverse matrix.
4) Do the throughput test with the inverse matrix applied.

It is worth mentioning that the DUT location should stay fixed at steps 3 and 4. Generally, the performance may differ while the DUT locates at different orientations related to the channel model. So it is required to perform throughput curve tests at all DUT orientations while keeping the channel fixed. In the RTS implementations, the DUT is fixed during all the throughput curve tests. For different DUT orientations (corresponding to different throughput curves), the antenna pattern is rotated in the channel emulator instead of rotating the DUT physically.

By using the proposed method, the inverse matrix was calculated in just 2 min (including steps 2 and 3). Generally, the isolation between the corresponding virtual cables, Iso_t, can reach 35 dB by adopting the proposed technique, which is enough to ensure the test accuracy and repeatability of the RTS MIMO OTA.

In fact, in the latest 3GPP standard [2], it is specified that the isolation should be greater than 15 dB to ensure that the error caused by the virtual cable can be negligible. Moreover, experiments in [13] illustrated a general relationship between the isolation and the throughput test errors. The results in [13] also indicated that any isolation greater than 15 dB is sufficient for the 2×2 MIMO OTA test. Additional test errors could be introduced when the isolation does not meet the standard specifications. Moreover, from April 2017 to July 2017, the 3GPP and CTIA held a harmonization comparison measurement for the MIMO OTA test standardizations, where both the MPAC method and the RTS method were introduced [14], [15]. There were total eight DUTs, four test bands, three test positions, and one channel model, resulting in 96 groups of throughput test results for the two methods (96×12 throughput test curves). The detailed setups for the DUT and instruments can be referred to as the 3GPP reports [14], [15]. Based on the measurement results, it is found that all the differences between the two methods under various conditions are within 0.92 dB. Several recommendations drawn from the study were proposed, including the following one that was recognized and accepted: "For the frequency-division duplex (FDD) bands tested in the MPAC/RTS harmonization, the harmonization cost varies between 0.5 and 0.92 dB. The harmonization cost is within the harmonization target for all bands and, therefore, harmonization between MPAC and RTS for bands 3, 5, 7, and 13 can be confirmed." In all these RTS measurements, the proposed algorithm was adopted although it was never revealed and published.

VI. Conclusion

An intelligent solving algorithm of the inverse matrix for the RTS MIMO OTA test method was proposed in this article, which is significant to reduce the RTS test period and ensure the measurement accuracy. The article first introduced the performance benchmarks of an inverse matrix according to the practical applications and then detailed the method to get the best combination for the inverse matrix solving just through calculations in PC in seconds, and finally, showed the detailed RTS test procedure with the proposed method applied. Compared with several hours, only 2 min are required for the whole process of the appreciate combination search and the inverse matrix solving by using the presented technique, which significantly improves the measurement user experience.

In addition, the method has become an indispensable part of the RTS test since it was proposed. Based on the inverse matrix autotuning technique, the RTS method has provided a series of reference results for 3GPP proposals [14], [15].

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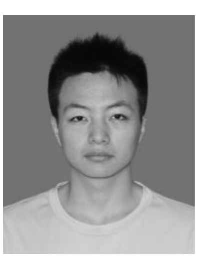

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