Objective Total Isotropic Sensitivity Measurement

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***Abstract*—The characterization of the performance of wireless devices plays a significant role in developing radio products that meet the demands of the latest standards and deliver a satisfying user experience. With current standard total isotropic sensitivity (TIS) measurement, the transmitters are set to work at their maximum transmission power level. However, the standard TIS test procedure is unable to accurately reflect a receiver's performance because in actual usage transmitters are rarely working at their maximum power level. In measurements, different kinds of devices hold different maximum power levels. The measured radio sensitivity depends on the instantaneous local temperature of the radio, and the local temperature depends on the heat generation (power levels), the heat dissipation, and time. So the power levels and the thermal conditions could affect their radio sensitivity and, hence, the TIS. With standard TIS methods, the maximum power level and the radio's thermal condition cause ambiguity in the measurements. However, this paper proposes a new objective TIS method. With this new TIS method, the measured TIS is a function of the transmitter power level at its thermally stable condition. The proposed method resolves the ambiguity of the TIS measurement.**

***Index Terms*—Desensitization, effective isotropic radiated power, effective isotropic sensitivity (EIS) radio transmitter power, electromagnetic interference (EMI) and electromagnetic compatibility (EMC), over-the-air (OTA), radio sensitivity, total isotropic sensitivity (TIS).**

I. Introduction

RADIO transmitterand receiver (T/R) performance plays an important role in the coverage and capacity of wireless networks. The over-the-air (OTA) test is a systematic way to evaluate radio T/R performance standardized by the cellular telecommunications and internet association (CTIA) and the third generation partnership project (3GPP) [1], [2]. In the OTA test, the receiver's overall performance is evaluated by total isotropic sensitivity (TIS) [3]–[6]. The OTA TIS measurement provides the means for electromagnetic interference (EMI) troubleshooting in the radio's development stage by measuring conducted sensitivity and TIS. With the test of radio radiated sensitivity and TIS, the antenna gain information can be obtained. If TIS measurement is not accurate, then system engineers cannot know who should work to improve subsystem performance, antenna engineers or radio engineers?

The TIS is a single figure of merit that quantifies a mobile device's capability of receiving a weak signal that determines the downlink performance of the terminal. Poor TIS can result in a low quality voice signal, and it can also alter coverage maps. There are two main methods for TIS measurement. One is a classic method from CTIA and 3GPP, which is an integration of measured effective isotropic sensitivity (EIS) from all of the sampling angles in a sphere [1]. Another method is to measure the radio's radiated sensitivity and then divide it by the measured average antenna gain, which is also a CTIA alternative test procedure with reasonable measurement accuracy and test speed improvement [3]–[5].

In the standard OTA TIS measurement, the radio transmit power is set to its maximum to evaluate the worst possible TIS value. However, the maximum power may bring in uncertainties due to thermal effects and nonlinear effects. With the maximum radio transmit power, the radio receiver part can be heated up to a temperature that may adversely affect the performance of the radio receiver. This is a typical case of intrasystem electromagnetic compatibility (EMC) that makes, as it will be shown in this paper, the OTA TIS measurement a new frontier in the EMC domain. The temperature can also vary with the test time before it reaches a thermal steady state. The worst case scenario is that some device under test (DUT) that works at the maximum power may shutdown and be unable to reach its thermal steady state. Besides, maximum transmit power can also trigger nonlinear effects in the radio system and cause the increase of radio internal noise. EIS and radio radiated sensitivity are a function of the radio thermal temperature and radio internal noise [7]. Since the heating effect is a function of time and transmit power, the maximum transmit power setting may cause the measurement ambiguity of the TIS measurement. In application scenarios, the radio is hardly working at its maximum transmission power level. A TIS at a different power level can provide an objective view of the radio's receiver performance.

In addition to the temperature, the measurement time when the radiated sensitivity is measured will also alter the

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measurement results due to the impact of the thermal condition. The time, which causes ambiguities, includes the initial setup time for the radio to work and the test time that differs in anechoic chamber setups for OTA measurement and in TIS test methods.

An anechoic chamber has two fundamental setups, one is the great circle test setup and the other is the conical cut test setup. The conical cut test method with electrical selection of the measurement antenna is generally faster than the great circle test [1]. Similarly, the two different TIS measurement methods also result in different measurement times that in turn generate uncertainty. For the alternative TIS method, even with the fast measurement algorithm, it will take about 30 minutes. The radio with maximum power can generate heat and cause different measurement results if the radiated sensitivity is measured at a different time slot before reaching a thermal steady state.

The uncertainty in the TIS measurement is $\pm$ 2.6 dB, which is too large considering that antenna engineers and radio engineers are generally trying to improve something as small as a fraction of a decibel in a system's performance. The large TIS uncertainty could mislead the development engineers in the direction of problem solving. For example, if the antenna has reached its maximum efficiency, then the large uncertainty will confuse radio engineers, causing them to conclude that either the sensitivity is too good to be true or the sensitivity is not good enough. In either case, they will not know what does or does not need improvement. The large uncertainty also causes disputes in carrier acceptance of devices and problems in the radio's round robin test. The standards committee continuously strives to reduce measurement uncertainties.

The goal of this paper is to minimize the measurement uncertainty due to transmission power level and measurement time. In the alternative TIS measurement, the antenna gain measurement is generally stable and the measurement uncertainties are better described, while the radiated sensitivity or the EIS measurement could be ambiguous if a thermal stable condition has not been reached during the measurement process. Since the EIS measurement could be ambiguous during this process, the EIS is better measured at its thermal steady state to limit its uncertainty due to varied temperatures. Furthermore, this measurement ambiguity is mainly caused by high transmit power related effects. At a low transmit power level, it is very quicker to reach the thermal stable condition. Thus, in low power transmission (TX) measurement, the TIS measurement uncertainty will be smaller. From the TIS definition, we know that the radiated sensitivity variation will be reflected in TIS. Radiated sensitivity changes with the radio's physical temperature and its thermal condition, hence the TX power and time. A TIS is, thus, a function of the TX power and time. In this paper, we propose an objective TIS measurement method. A TIS is measured at a low TX power level in a thermally stable condition. Then the radiated sensitivities at different power levels are measured to illustrate the relationship between the TX power and TIS. The TX power is not an ambiguous factor, but a part of the radio receiver's performance related parameter.

The radio sensitivity theory with regard to the transmit power level is discussed in Section II, TIS measurement technologies are addressed in Section III, the objective TIS measurement method is presented in Section IV and the measurement results are shown in Section V and this paper is concluded in Section VI.

II. Receiver Sensitivity

Radio radiated sensitivity can be expressed as follows [7]:

$$P_{\mathrm{signtmin}} = FkB\mathrm{SNR}_{\mathrm{outmin}}\left(T_r + \eta_{\mathrm{rad}}\eta_c T_i\right) \tag{1}$$

where F is noise figure, B is the bandwidth, $\mathrm{SNR}_{\mathrm{outmin}}$ is the minimum detectable output signal to noise ratio, and k is Boltzmann's constant $(1.38 \times 10^{-23}$ J/K$)$. T_i is the radio interference temperature. η_{rad} is the antenna efficiency and η_c is the noise coupling efficiency. T_r is the receiver temperature, and it is expressed as follows:

$$T_r = T_p + T_{ci} \tag{2}$$

where T_p is the receiver's physical temperature and T_{ci} is the conducted interference temperature. From (1), it can be seen that the radio radiated sensitivity is associated with the radio's physical temperature and the radio's interference temperature.

The power level is essential to the radio radiated sensitivity due to its significant impact on the radio's physical temperature and the radio's interference temperature. In CTIA and 3GPP standards, the TIS is measured at the maximum transmit power level to illustrate the worst case performance of the TIS. When the radio is transmitting at the maximum power, it will generate heat directly and may contribute to noise due to nonlinear effects. The heat can directly raise the radio's physical temperature T_p and the radio radiated sensitivity, and it may also lead to some nonlinear effects. The nonlinear effects may affect the conducted interference temperature T_{ci}, if the noise couples into the radio receiver. Those thermal and nonlinear effects can change the radio radiated sensitivity and, hence, alter the TIS and cause ambiguities in the TIS measurement.

When the radio is starting to heat up, the process follows the heat transfer equation [8]

$$\frac{\partial\left(\rho T\right)}{\partial t} + \frac{\partial\left(\rho u_i T\right)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{K}{c_p}\frac{\partial T}{\partial x_i}\right) + S + Q \tag{3}$$

where ρ is the density, T is the temperature, and t is the time. x_i is the Cartesian coordinate system components, K is the thermal conductivity. c_p is the constant-pressure specific heat. u_i is the convection velocity vector, S is the source that generates heat, and Q is the radiated heat term.

In a radio system, when the transmitter and receiver are working, the battery's chemical energy is converted into thermal energy. In the radio's OTA test, this heat energy will make the radio hotter than the environment and the heat will dissipate into the environment by conduction through the DUT holder, simulated hand or head phantom, convection of air drawn by fans in the chamber, and radiation.

After a certain time, the radio receiver's physical temperature will be stable due to the balance of TX heat generation and its dissipation by conduction, convection, and radiation. This time varies with different radio heat sink designs, electronics circuits, material used, overall radio mechanic design, etc. When the overall radio design and test environment are fixed, then the time to reach a stable radio temperature is a function of radio transmitter power level. Then the radio sensitivity is a function of the receiver's physical temperature and, hence, the transmitter power level.

$$P_{\mathrm{signtmin}} = f\left(t, P_{tx}\right) \tag{4}$$

where P_{tx} is the transmitter power level. Constant receiver physical temperature T_p can be reached after a certain period of time, which is also transmitter power level related. At high transmit power level, T_p, T_{ci}, and T_i can all be changed.

III. TIS of the Radio Receiver

The CTIA has a standard "test plan for mobile station over-the-air performance." In this test plan, TIS is obtained by performing the integration of the measured EIS over a spherical surface as

$$\mathrm{TIS} = \frac{4\pi}{\oiint \left[\frac{1}{\mathrm{EIS}_{\theta}(\theta,\varphi)} + \frac{1}{\mathrm{EIS}_{\varphi}(\theta,\varphi)}\right] \sin\theta d\theta d\varphi}. \tag{5}$$

The above formula describes a standard CTIA TIS test procedure, which measures EIS at each and every angle. The standard EIS measurement is determined by power stepping, which searches the EIS by gradually reducing the power of the base station emulator until it reaches the receiver's threshold. Generally, this is a very time consuming process.

The measurement time can be significantly reduced by using the curve invariance method [3]–[5]. During the EIS-based method, the radio sensitivity is always measured in conjunction with receiving antenna gain.

Another method of measuring the TIS is to measure radio sensitivity once and then measure the average antenna gain. The formula for the method is as follows.

Considering that

$$\mathrm{EIS}_x\left(\theta,\varphi\right) = \frac{P_{\mathrm{signtmin}}}{G_x\left(\theta,\varphi\right)} \tag{6}$$

where x stands for θ or φ polarization of the wave. Hence, we have

$$\mathrm{TIS} = \frac{P_{\mathrm{signtmin}}}{G_{\mathrm{ave}}} \tag{7}$$

where G_{ave} is the antenna average gain of the DUT. And

$$G_{ave} = \oiint \left[G_{\theta}\left(\theta,\varphi\right) + G_{\varphi}\left(\theta,\varphi\right)\right] \sin\theta d\theta d\varphi. \tag{8}$$

This method in CTIA is called the alternative method. The original version of this method is a quick test with limited accuracy. Its modified version can achieve time efficiency with high accuracy performance [1]– [9].

The TIS measurement can be significantly impacted by the transmitter power level and test procedures, because TIS is strongly related to the radio radiated sensitivity, and the radio radiated sensitivity is a function of the transmitter power level and test time. With this alternative method, the average antenna gain is not affected by the radio's working temperature and the radio sensitivity can be measured at any time during the measurement process. This will result in different TIS values if the thermal stable condition of the radio receiver is not reached. For example, if the radio radiated sensitivity is measured at the beginning of the test and the radio's physical temperature is lower, the TIS is better than when the radio radiated sensitivity is measured at the end of the test process.

Neither low TIS nor high TIS reflect the overall characteristics of the radio. From the current discussion, we know that the TIS values are determined by the radio radiated sensitivity and antenna average gain. The radio radiated sensitivity is a function of the radio receiver's physical temperature. The radio temperature is mainly affected by the radio transmit power. Hence, the TIS expressed as a function of the radio transmit power provides a better picture for the receiver's characteristics.

IV. Objective TIS Measurement

In order to provide an objective measurement for TIS, the transmitter power issue should be considered. Including the transmitter power, the TIS is as follows:

$$\mathrm{TIS} = \frac{f\left(t, P_{tx}\right)}{G_{\mathrm{ave}}}. \tag{9}$$

This means that the TIS is not only the function of transmitter power, but also the time. Evaluation of the relationship between the TIS and these two factors will make the measurement time too long and the results will be confusing. In this paper, an orthogonal test method is proposed to provide a full picture of overall TIS with a manageable measurement time.

In this method, the radio radiated sensitivity is measured against the transmitter power level in thermal stable conditions, from its lowest possible power level to the maximum. Then the TIS is the radio radiated sensitivity divided by the measured three-dimensional (3-D) antenna average gain. Since the 3-D antenna average gain is irrelevant to the power level and time, this measurement method can be time efficient because it separates the average gain measurement from power-and-time dependent sensitivity measurement. Generally, it is much quicker for the receiver to reach its radio thermal stability points at low transmitter power in a standard anechoic chamber with controlled ambient temperature. Moreover, at a very low transmit power level, a low-noise amplifier may be needed to compensate for path loss in large chambers and to ensure the radio connection of radiated sensitivity measurement. A temperature sensor can be used to measure the radio temperature. The criteria of thermal stability can be described as follows:

$$\frac{\partial T}{\partial t} = \frac{T_2 - T_1}{t_2 - t_1}. \tag{10}$$

In the given $\Delta t = t_2 - t_1$ time, if the temperature change is less than ΔT degree (which has been calculated based on the TIS measurement uncertainty caused by this ΔT degree, which is less than 0.1 dB), then a standard TIS measurement can be conducted.

Then, the radiated sensitivity changes versus the transmitter power level

$$P_{\mathrm{signtmin}} = f\left(P_{tx}\right). \tag{11}$$

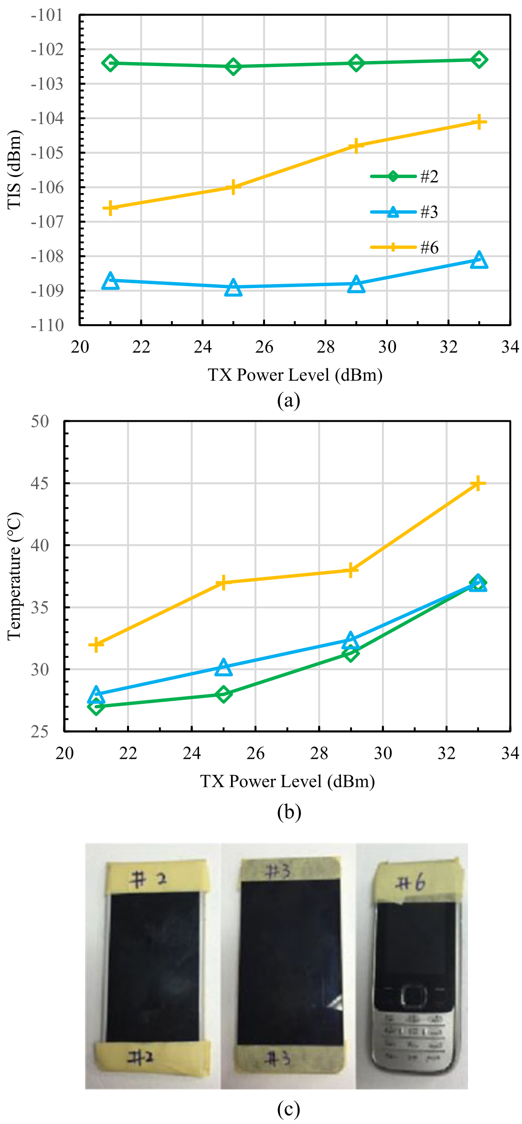

Fig. 1. Objective TIS measurement in different samples at GSM 850 band. (a) TIS versus transmitter power levels. (b) Local temperature of DUT versus transmitter power levels. (c) Test samples.

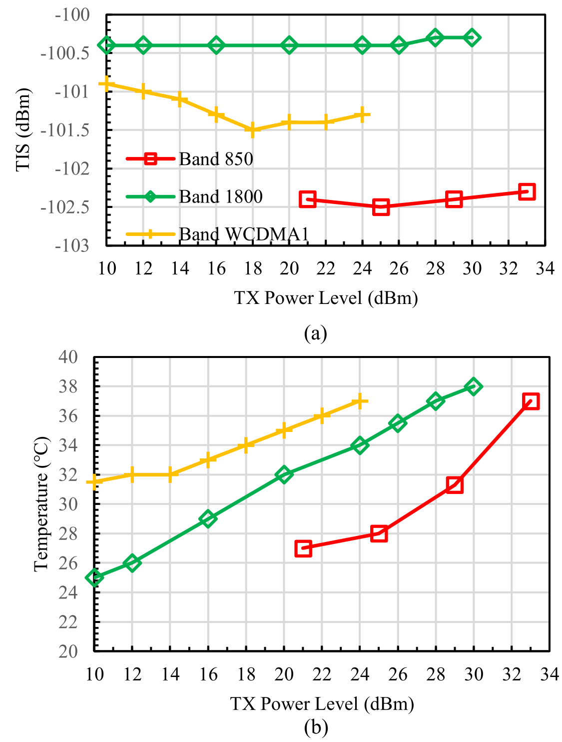

Fig. 2. Objective TIS measurement of sample #2 in different frequency bands. (a) TIS versus transmitter power levels. (b) Local temperature of DUT versus transmitter power levels.

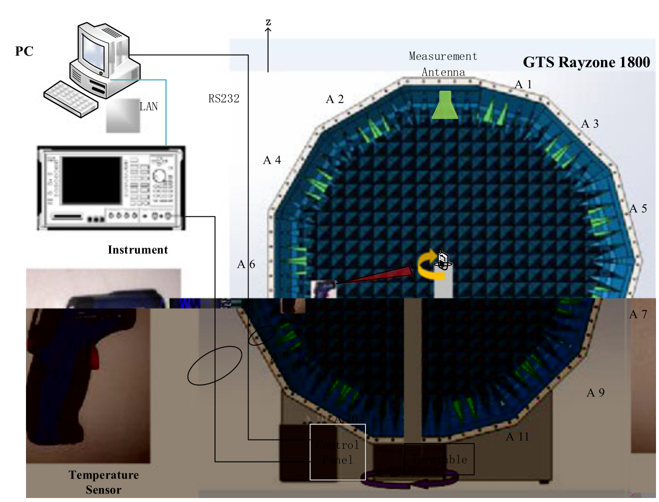

Fig. 3. Schematic view of the test setup.

Here, the physical temperature of the radio receiver is measured at the thermal stable condition we described above. For a different transmitter power level, the Δt for achieving a radiostable thermal condition is different. With the sensitivity curve and a TIS value, the objective TIS curve will be obtained.

V. Measurement

Three selected samples have been tested using the objective TIS measurement using MAXSIGN software and the Rayzone 1800 chamber from general test systems, Inc. The results are shown in Figs. 1 and 2, and the test setup is shown in Figs. 3 and 4.

As shown in Figs. 3 and 4, Rayzone 1800 is a compact multiprobe anechoic chamber. Compared to the large anechoic chamber with a single probe antenna, the compact multiprobe chamber has the advantage of a time-efficient measurement process and less path loss. In large anechoic chambers, during the objective TIS measurement, it may be difficult to establish radio connection without an adequate link margin. In this case, a low noise amplifier is required. In addition, a thermometer (DT-880 from CEM, Fig. 3) has been used to measure the local temperature of the DUT and to ensure the thermal stable condition in testing radio radiated sensitivity. A radio communication analyzer, Anritsu MT8820C, has been used to measure the TIS in the tests.

The measurement procedure is generally composed of four steps:

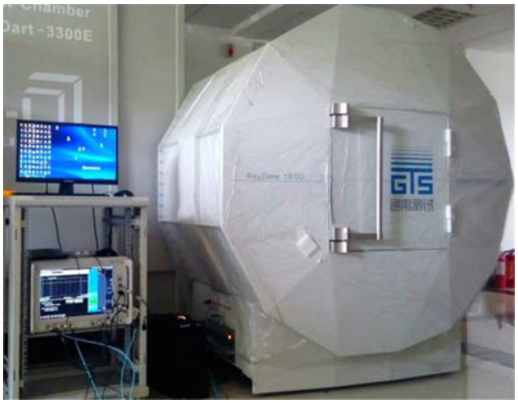

Fig. 4. Front view of the test setup.

TABLE I
DETAILS OF THE TIS VERSUS TRANSMITTER POWER LEVEL

Sample	Average TIS(dBm)	Ranges of TIS(dBm)
#1	−104.74	0.42
#2	−103.02	0.62
#3	−103.11	2.47

1) Initial setup. Before each test, the test systems and the DUT should be in their ready-to-test conditions. The ambient temperature of the anechoic chamber should be 20° C. The test instruments should be fully warmed up and in a normal working condition. The DUT should be reset, sufficiently charged, and cooled down to the ambient temperature.
2) Radio radiated sensitivity test versus power level.
   a) Set the transmitter power level to its lowest value with reliable radio link.
   b) Use the thermometer to test the temperature of the DUT until it reaches the thermal stable condition.
   c) Measure the radio radiated sensitivity.
   d) Increase the power level and repeat steps a) to c) until the DUT is working at its maximum power level or the DUT shuts down.
3) Average gain measurement. Measure the average gain from the 3D gain pattern of the DUT.
4) TIS calculation. Measure TIS at stabilized sensitivity stage, usually at a low transmit power level. Calculate the TIS using (7). Then get the results of TIS versus power level.

In the measurement results, shown in Fig. 1 and Table I, the TIS of some samples barely changes with the power level, while some TIS increased as much as 2.5 dB as the power level goes up. This has a lot to do with the radio's power amplifier design, heat dissipation, and noise control in the device system. The measurement results provide information on the TIS and transmit power relationship.

As shown in Fig. 2, the performance of the TIS versus the power level varies in different frequency bands, so evaluation of the TIS versus the power level in different bands is also necessary. These variations may result from the performance of the heat dissipation and the EMI design. Due to the high band and low band antenna current distribution difference, the TIS influence is also different. Although the radiated sensitivity is very sensitive to the temperature, if the heat sink of the receiver dissipates enough heat to maintain the safe working temperature of the receiver, the radiated sensitivity may not be greatly influenced by the transmitter power level. If the EMI design of the DUT isolates interference noise due to the nonlinear effects, the radiated sensitivity may almost stay the same as the power level scales up.

VI. CONCLUSION

An objective TIS measurement is presented and a better picture of TIS measurement is given in this paper. With the measurement of the TIS versus the transmitter power level, radio engineers can fully evaluate the receiver performance, and the ambiguities resulting from the power level and the thermal condition of the DUT have been cleared up. The test procedure of the objective TIS measurement is defined by measuring the TIS as a function of the transmit power level in the thermal stable condition of the DUT with the modified alternative TIS measurement method.

Solving radio desensitization problems is a major task for most RF-related device manufacturers. The TIS tests are performed in certification, research and development (R&D), and mass production phrases. Narrowing TIS uncertainties is of great importance. For certification, the TIS value is a merit of figure that can affect radio coverage. The radio desense is a typical EMI problem affecting the user experience related device performance, device time to market, and quality control of mass production. The narrowed TIS measurement uncertainty is not a continuous effort that standard organizations are pursuing. Since the TIS has two contributing factors, antenna gain and radio sensitivity, the objective TIS measurement is also able to help R&D engineers to identify the root cause of the TIS degradation and find the right solution for troubleshooting. Determining the right transmit power is also important in setting the right limits for combined radio final tests in the mass production stage.

REFERENCES

[1] CTIA. 2017. [Online]. Available: http://www.ctia.org
[2] 3GPP. 2017. [Online]. Available: http://www.3gpp.org
[3] P. Shen, Y. Qi, W. Yu, F. Li, and J. Fan, "Fast and accurate TIS testing method for wireless user equipment with RSS reporting," *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 3, pp. 887–895, Jun. 2016.
[4] Z. Liu, Y. QI, F. Lin, W. Yu, J. Fan, and J. Chen, "Fast band-sweep total isotropic sensitivity measurement," *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 4, pp. 1244–1251, Aug. 2016.
[5] P. Shen, Y. Qi, W. Yu, F. Li, and J. Fan, "Fast method for OTA performance testing of transmit-receive cofrequency mobile terminal," *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 4, pp. 1367–1374, Aug. 2016.
[6] W. Yu, Y. Qi, K. Liu, Y. Xu, and J. Fan, "Radiated two-stage method for LTE MIMO user equipment performance evaluation," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 6, pp. 1691–1696, Dec. 2014.
[7] Y. Qi and W. Yu, "Unified antenna temperature," *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 5, pp. 1425–1431, Jun. 2016.

[8] S. V. Patankar and D. B. Spalding, "A calculation procedure for heat, mass and momentum transfer in the three-dimentional parabolic flows," *Int. J. Heat Mass Transfer*, vol. 15, no. 10, pp. 1787–1806, 1983.

[9] Y. Qi, P. Jarmuszewski, Q. Zhou, M. Certain, and J. Chen, "An efficient TIS measurement technique based on RSSI for wireless mobile stations," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 9, pp. 2414–2419, Sep. 2010.

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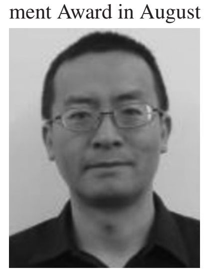

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Dr. Yang received the 2016 IEEE Electromagnetic Compatibility Society Technical Achievement Award.