Unified Antenna Temperature

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***Abstract*—In discussions of radio noise analysis, the noise coupled from radio to its connected antenna is generally neglected. This coupled noise can degrade signal to noise ratio of the radio receiver and it is the root cause of the radio receiver's radiated desensitization, which is a very common electromagnetic interference problem for compacted radio receivers. A unified antenna noise temperature definition is presented in this paper. With the general definition, the overall receiver noise analysis has theoretical integrity. The overall antenna temperature for tightly coupled radios such as cellphones can be measured using the unified antenna noise temperature definition in conjunction with radio conducted, radiated, and a real environment test. The unified antenna noise temperature definition allows the radio engineer to understand the mechanisms of the receiver-radiated desensitization. With the unified antenna temperature definition, radio radiated sensitivity, effective isotropic sensitivity, and total isotropic sensitivity can be mathematically defined.**

***Index Terms*—Antenna brightness, antenna temperature, effective isotropic sensitivity (EIS), noise, noise coupling mechanism, noise figure, radio radiated sensitivity, total isotropic sensitivity (TIS).**

I. Introduction

ANTENNA temperature is a widely used concept in radio astronomy, microwave radiometer, satellite communications, and general radio technologies [1]–[7]. The concept of antenna temperature is a part of antenna theory and radio science to define radio system parameters and conduct system noise analysis [8]–[9]. Antenna temperature is defined as a measured power at the antenna output port and it consists of two terms: the temperature due to the environment surrounding the antenna and the temperature due to the physical temperature of the antenna. In the conventional and classic textbook antenna temperature definition, the noise contribution from the sources surrounding the antenna only includes atmospheric galactic noise, precipitation statics, and blackbody radiation from the earth, ground, city noise, etc. [10]–[14]. The noise from other parts of the system, such as the radio receiver and its attached subsystems, are of no concern. The theory was developed based on the system calibration concept; when the antenna was placed in an ideal anechoic chamber in a thermal equilibrium condition, the background noise was considered isolated from the antenna. The power received at the antenna port was considered as the only noise because of the Brownian motion of the molecules due to the antenna's physical temperature, as shown in Fig. 1(a). For the thermal noise measurement, if the antenna is replaced by a resistor at the same temperature, the same output power at the antenna port can be measured. This practice has been largely used for microwave passive remote sensing as shown in Fig. 1(b). When the antenna was placed in a working environment, the power that was higher than the antenna's physical temperature at the port was the contribution of antenna brightness. The antenna brightness temperature is caused by the signal or noise environment surrounding the antenna and received by the antenna as shown in Fig. 1(c).

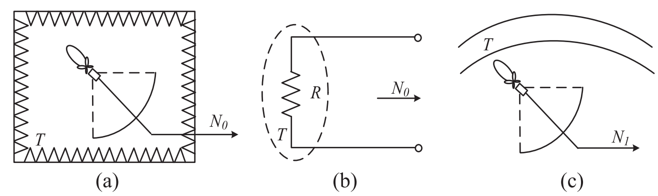

Fig. 1. Conventional antenna noise calibration.

The classic antenna temperature definition plays an important role in radio astronomy, radiometer, radar, satellite communication systems, and large antenna systems where the antennas are quite large and there is good isolation between the antennas and radio receiver subsystems. In the conventional antenna temperature definition, the electromagnetic interference and thermal noise that is higher than the antenna thermal noise from radio transceivers are of no concern. Those noise sources input into receiver from the antenna are also not included in the receiver noise analysis [15], [16] because those noise sources are generally well controlled in the above mentioned applications to maximize the system performance. However, in compact radio systems like wireless handheld, portable, and wearable devices, the radio/electronics printed circuit board (PCB) or body is part of the antenna and some antennas are directly integrated into the chip [17], [18]. The radio frequency (RF) and digital noise can couple to the antenna directly and cause radio desensitization [19], [20]. The antenna temperature measurement steps as shown in Fig. 1 would be hard to execute since the antenna and radio receiver are tightly coupled to each other and not physically separable without changing the antenna, receiver, and the noise coupling mechanisms between them. The noise coupled to the antenna will change the measured power at the antenna output port. Since this noise power is not included in the noise figure of the receiver, it is logical to include this noise power in a more general form in the antenna temperature definition. The radio internal interferences are known and some attempts are made to consider the radio internal noise in the antenna temperature [8], [9]; our unified antenna temperature definition clearly defined the relationship of overall antenna temperature with physical temperature, antenna brightness, and internal noise. The antenna efficiency and the noise coupling mechanism are defined so that it can be factorized for electromagnetic

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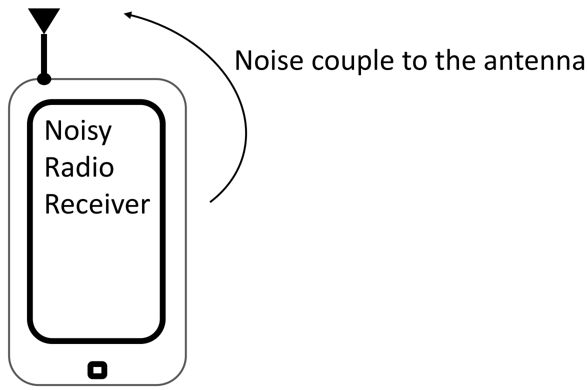

Fig. 2. Receiver noise coupled to the antenna.

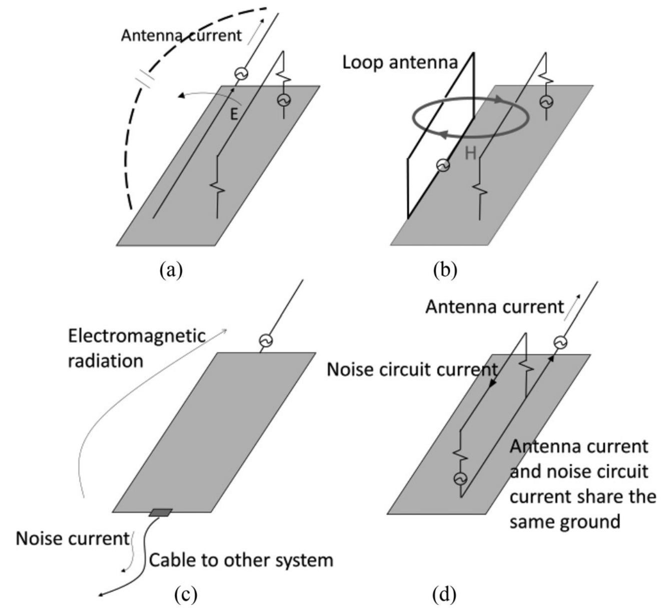

Fig. 3. Noise coupling mechanisms. (a) Electricfield coupling, (b) Magnetic-field coupling, (c) Electromagnetic field coupling and (d) Common impedance coupling.

compatibility analysis. It is also a standard practice in radio receiver design to measure the radio performance both with and without the antenna so that the noise from the receiver coupled to the antenna can be identified. The noise from the radio coupled to the antenna causes radio radiated desensitization [21]. The desensitization can be measured through radio conducted and radiated sensitivity test [22].

To make the antenna temperature definition applicable to tightly coupled radio systems, a unified antenna noise temperature is presented in this paper. The unified definition is not only more general, but also keeps the integrity of the overall receiver system noise analysis. With the unified definition, the technical terms such as radio conducted sensitivity, radio radiated sensitivity, effective isotropic sensitivity (EIS), and total isotropic sensitivity (TIS) can be mathematically well defined.

Noise coupling mechanisms are discussed in Section II, antenna temperature definitions are given in Section III. The antenna noise temperature test methods for wireless devices and the definitions for conducted sensitivity, radiated sensitivity, EIS, and TIS are provided in Section IV, and examples of antenna temperature applications are given in Section V.

II. Noise Source and Coupling Mechanism

In a tightly coupled system, the internal noise can feed back to the antenna and contribute to the overall noise level of the receiving system as shown in Fig. 2. There are four coupling mechanisms that a radio system noise can couple to the antenna: electric field coupling, magnetic field coupling, electromagnetic field coupling, and common impedance coupling, as shown in Fig. 3 [23]–[26]. One example of the electric field coupling is the coupling between two dipole types of antennas, one of the antennas is the real antenna we used for communication and the other antenna might be the unintentional radiation structure in the radio system that behaves like a dipole antenna. The magnetic field coupling might take place between a noisy loop structure in the PCB and the loop antenna or near-field magnetic field coupling. The electromagnetic field noise coupling might become serious when the radio is attached to another system (such as a car charger) or the system is separated for a larger distance in terms of wavelength; the radiated noise can get into the radio antenna and cause interference. Common impedance coupling occurs when the antenna current and radio noise current share the same path. The common impedance coupling could be the dominating noise coupling mechanism in tightly coupled radio receivers, in which the radio PCB is designed as a part of the antenna. In general, all of these coupling mechanisms can be denoted with an antenna coupling efficiency η_c, which is introduced to represent the coupling between the system and the antenna, as shown in Fig. 2.

III. Antenna Temperature

Every object with a physical temperature above zero $(0\mathrm{K} = -273^\circ\mathrm{C})$ radiates energy. In our conducted measurement as shown in Fig. 1(b), the Brownian motion of electrons in the resistor produces small random voltage fluctuations at the antenna output terminal. This voltage has zero average value but a nonzero rms value. This noise power per unit bandwidth is proportional to the resistor's temperature and is given by the Nyquist relation

$$n_0 = kT_p, \quad \mathrm{W/Hz} \tag{1}$$

where T_p is the environmental temperature or the physical temperature of the resistor in kelvin; and k is Boltzmann's constant $(1.38 \times 10^{-23}\ J/K)$.

For RF and microwave frequencies, the Brownian motion of electrons can generate noise power that is independent of the frequency. Such noise has its power evenly distributed in a certain frequency band B and is referred to as white noise. For wireless communication systems, if we assume that the overall noise power is distributed across the communication channel bandwidth, B, the total mean square power is

$$N_0 = kT_pB, \quad \mathrm{W}. \tag{2}$$

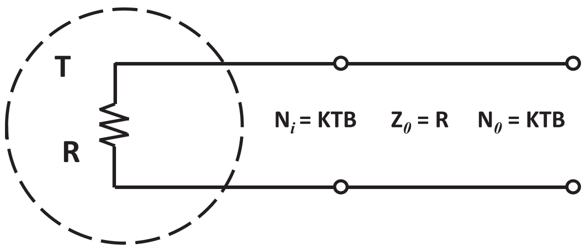

Fig. 4. Antenna thermal noise.

If the receiver antenna has a loss, its radiation efficiency is less than unity, and the power at the antenna output port is reduced by a factor of η_{rad}

$$\eta_{\mathrm{rad}} = \frac{R_{\mathrm{rad}}}{R_{\mathrm{rad}} + R_{\mathrm{loss}}} \tag{3}$$

where R_{rad} is the radiation resistance of the antenna and R_{loss} is the loss resistance.

A lossy antenna can be modeled as a lossless antenna and an attenuator having a power loss of $1/\eta_{\mathrm{rad}}$, as shown in Fig. 4. If the antenna is replaced by a resistor, for the thermal only case, and the thermal noise is referenced to the antenna input, the input and output noise are all kT_pB, and the following will be obtained:

$$N_0 = kT_pB = \eta_{\mathrm{rad}}kT_pB + \eta_{\mathrm{rad}}N_{\mathrm{add}}, \tag{4}$$

where N_{add} is the noise added by the attenuator

$$N_{\mathrm{add}} = \frac{1-\eta_{\mathrm{rad}}}{\eta_{\mathrm{rad}}}kT_pB. \tag{5}$$

N_{add} is the thermal noise contribution added to the antenna overall noise output.

The natural and man-made noise sources are distributed across all the angles that antenna covers. The background noise temperature T_B is defined as the equivalent temperature of a resistor required to generate the same background noise as the actual environment seen by the antenna. The background noise temperature varies with the angles, time, and frequency. When the antenna beam width is wide with high-side lobes, the effective brightness of the antenna seen by the antenna includes two parts, one is the received power from the background temperature weighting by the antenna pattern function; the other is the received power from internal noise source coupling into the antenna. The first part of the antenna brightness is expressed by the following equation:

$$T_b = \frac{\int_0^{2\pi}\int_0^{2\pi} T_B(\theta,\phi)\,\mathrm{D}(\theta,\phi)\sin\theta d\theta d\phi}{\int_0^{2\pi}\int_0^{2\pi} \mathrm{D}(\theta,\phi)\sin\theta d\theta d\phi} \tag{6}$$

where $T_B(\theta,\phi)$ is the distribution of the background temperature and $\mathrm{D}(\theta,\phi)$ is the directivity of the antenna.

When the receiver is put in an ideal anechoic chamber in a thermal equilibrium condition, $T_B(\theta,\phi)$ equals the physical temperature T_p. Hence, we have the antenna brightness $T_b$equals T_p. This antenna brightness will be reduced by a factor of η_{rad} to the antenna output.

Assuming that the noise temperature in the receiver is T_i and the noise coupling efficiency is η_c, then, the noise at the antenna input due to radio system interference and radio system thermal noise is $\eta_c kT_iB$, and at the antenna output, the power output for internal noise contribution is $\eta_c\eta_{\mathrm{rad}}kT_iB$. The total output power from the antenna to the receiver is

$$N_{\mathrm{total}} = kT_AB = k\left[\eta_{\mathrm{rad}}T_b + (1-\eta_{\mathrm{rad}})\,T_p + \eta_{\mathrm{rad}}\eta_cT_i\right]B. \tag{7}$$

It follows that the antenna temperature is

$$T_A = \eta_{\mathrm{rad}}T_b + (1-\eta_{\mathrm{rad}})\,T_p + \eta_{\mathrm{rad}}\eta_cT_i. \tag{8}$$

When $\eta_{\mathrm{rad}}\eta_cT_i$ equals zero, the above definition is identical to the classic antenna temperature definition; this happens when the noise source is completely removed or the coupling path is eliminated.

IV. Noise Temperature Measurement

The coupled radio noise can be measured through conducted and radiated measurement, which are also the ways to identify whether or not the receiver has desensitization.

The noise figure of a receiver is defined as

$$F = \frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}} \tag{9}$$

where

$$\mathrm{SNR_{in}} = \frac{p_{\mathrm{sig}}}{p_n}, \tag{10}$$

where p_{sig} is the input signal power per unit bandwidth, p_n is the input noise power per unit bandwidth, $\mathrm{SNR_{in}}$ is the input signal to noise ratio, and $\mathrm{SNR_{out}}$ is the output signal to noise ratio.

The total mean square signal power P_{sigt} and mean square noise power P_{nt} can be obtained by integrating over the bandwidth of interest. Thus, for the total power in a channel, assuming signals are uniformly distributed and noise is white within the channel, we have

$$P_{\mathrm{nt}} = kT_pB. \tag{11}$$

In the radio-conducted test, the radio signal in a signal generator was fed into a transmission line and the transmission line loss was calibrated. When the input signal level was reduced, the radio output signal to noise level was also reduced. When the output signal to noise level reached its minimum decodable level $\mathrm{SNR_{outmin}}$, the input signal level P_{sigtminc} was the radio-conducted sensitivity. Radio-conducted sensitivity is the minimum signal level that a radio receiver can detect at the input of a radio receiver. The conducted sensitivity test setup is shown as shown in Fig. 5. The radio-conducted sensitivity can be expressed as

$$P_{\mathrm{sigtminc}} = T_{\mathrm{r}}FkB\mathrm{SNR_{outmin}} \tag{12}$$

where T_{r} is the radio receiver's conducted temperature which has two contribution terms, the radio thermal temperature and the temperature due to radio internal noise interference. If there is no radio internal noise interference or conducted radio receiver desensitization, T_{r} equals physical temperature $T_{\mathrm{p}}$of the

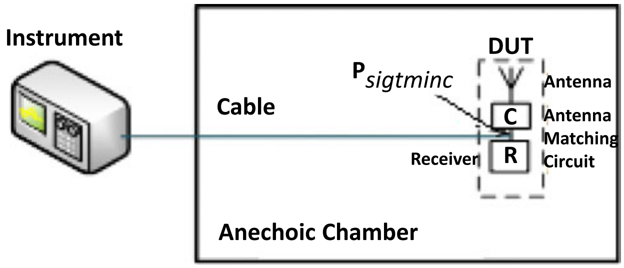

Fig. 5. Typical test set up illustration for conducted sensitivity measurement.

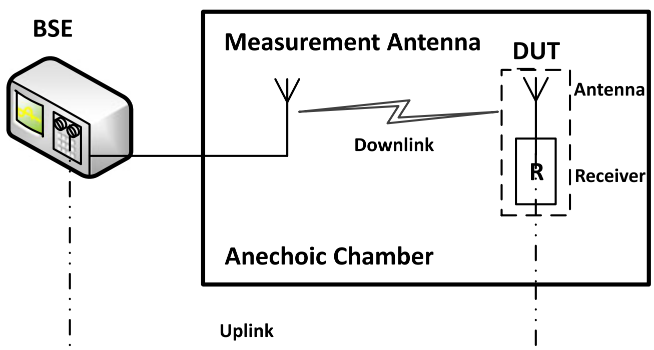

Fig. 6. Typical test set up illustration for radiated measurement.

radio. In conducted measurements, the receiver-conducted temperature can be determined

$$T_{\mathrm{r}} = \frac{P_{\mathrm{sigtminc}}}{FkB\mathrm{SNR}_{\mathrm{outmin}}}. \tag{13}$$

The receiver-conducted temperature is always equal or higher than the radio physical temperature. The physical temperature could be higher than the environment temperature due to the thermal heating effect of the radio transmitter.

The radio radiated sensitivity test is shown in Fig. 6, in which the integrated radio was set up in an anechoic chamber. The signal generator was connected to a measurement antenna so that the radio was linked to the signal generator over the air. If the anechoic chamber and the radio were in a thermal equilibria condition, the antenna brightness equals antenna physical temperature. The radio-radiated sensitivity is the minimum detectable at the radio receiver input with antenna connected to the radio receiver

$$P_{\mathrm{sigtminr}} = FkB\mathrm{SNR}_{\mathrm{outmin}} \left(T_{\mathrm{r}} + \eta_{\mathrm{rad}}\eta_c T_i\right). \tag{14}$$

T_{r} is determined by the radio receiver design. While $\eta_{\mathrm{rad}}\eta_c T_i$ is due to the contribution of receiver internal noise, noise coupling to the antenna, and the antenna efficiency. If there is no internal interference or the noise coupling path to the antenna is eliminated, the radiated sensitivity will be the same as the conducted sensitivity. For the receiver that does not have conducted and radiated desensitization, thermal noise is the only noise source that limits the radio receiver performance.

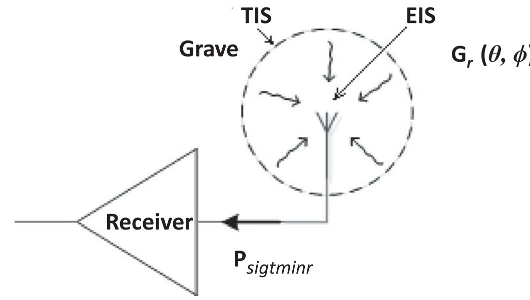

Fig. 7. TIS and EIS.

The EIS is a widely used concept in radio link analysis. It is defined as a minimum detectable radio signal in front of receiver antenna at a specific angle, as shown in Fig. 7. The EIS is due to the contribution of radio-radiated sensitivity and receiving antenna gain. Mathematically, EIS is defined as radio-radiated sensitivity divided by the receiving antenna gain G_r

$$\mathrm{EIS} = FkB\mathrm{SNR}_{\mathrm{outmin}} \left(T_{\mathrm{r}} + \eta_{\mathrm{rad}}\eta_c T_i\right)/G_r. \tag{15}$$

The TIS is another parameter that is used for wireless device performance evaluation; as shown in Fig. 7, it is the radio-averaged minimum signal receiving capability referenced to the front of the receiver antenna

$$TIS = FkB\mathrm{SNR}_{\mathrm{outmin}} \left(T_{\mathrm{r}} + \eta_{\mathrm{rad}}\eta_c T_i\right)/\eta_{\mathrm{rad}}. \tag{16}$$

From the radiated and conducted sensitivity measurement, the noise coupled to the antenna can be determined

$$N_c = kB\eta_{\mathrm{rad}}\eta_c T_i = \frac{P_{\mathrm{sigtminr}} - P_{\mathrm{sigtminc}}}{F\mathrm{SNR}_{\mathrm{outmin}}}. \tag{17}$$

η_{rad} can be determined by the standard antenna efficiency measurement. It is the antenna gain divided by the antenna directivity.

N_c and radio spectrum of$N_c$in different radio channels provide information for RF engineers trouble shooting the electromagnetic interference (EMI) problems.

In order to determine the overall antenna temperature in the real environment, the radio needs to be located in a real environment. The radio sensitivity in the real environment $P_{\mathrm{sigtminreal}}$ determines the antenna temperature in the real environment

$$T_A = \frac{P_{\mathrm{sigtminreal}}}{FkB\mathrm{SNR}_{\mathrm{outmin}}}. \tag{18}$$

Because of the real environment interference and noise fluctuation, the real environment antenna temperature test may not be very stable. For the cellular phone industry, the real environment sensitivity measurement is a way to find out the down link radio signal coverage. By recording the real environment sensitivity, the antenna temperature can be obtained.

V. Examples of Application

The unified antenna temperature concept can be used in wide areas to identify internal noise interferences. In tightly coupled radio receivers, such as modern cellular phones and compact

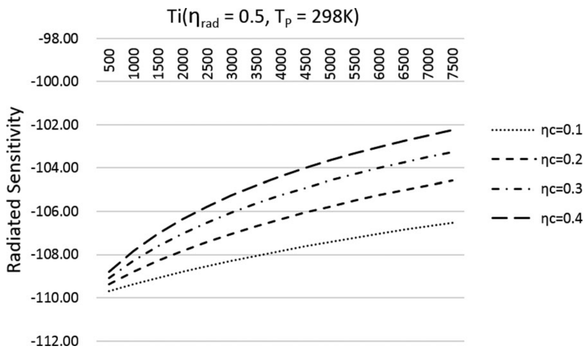

Fig. 8. Radio-radiated sensitivity and interference T_i.

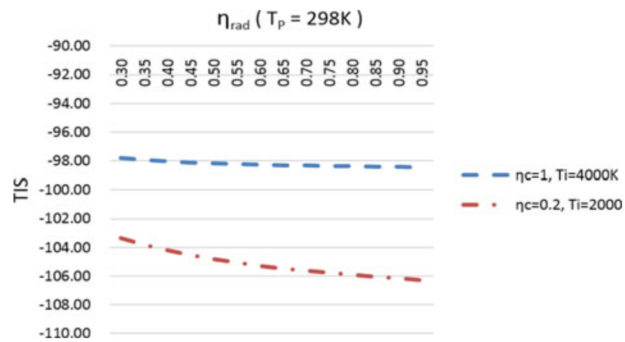

Fig. 10. TIS and antenna efficiency.

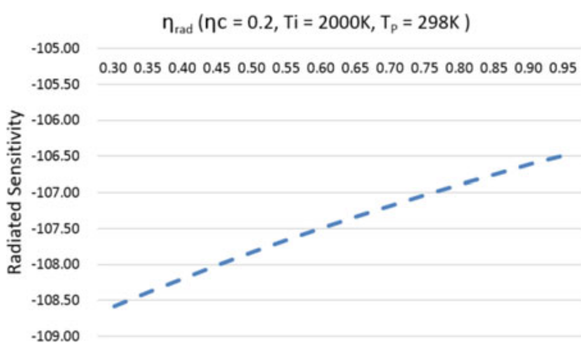

Fig. 9. Radio sensitivity and antenna efficiency.

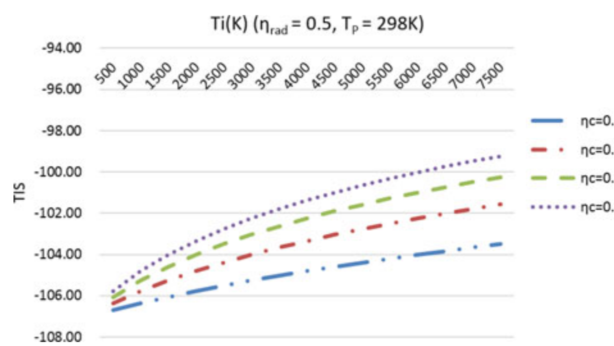

Fig. 11. TIS, noise power, and coupling efficiency η_c.

wireless devices, a lot of engineering phenomenal can be understood using the definitions presented in this paper.

A typical global system for mobile communication (GSM) cellular phone radio is used as an example. We have selected typical GSM radio parameters with a noise figure of 5.5 dB, demodulation signal to noise ratio of 6 dB, filter bandwidth of 170 kHz at radio working physical temperature of 298 K, this leads the conducted and radiated sensitivity to be –110.1 dBm without considering radio conducted and radiated interferences. Without radio internal interference, the conducted and radiated sensitivity are identical. It can be seen from (12) and (14). When there is interference, the radio-radiated sensitivity will be degraded, which is called radio receiver sensitivity desensitization. Assuming that the antenna efficiency is 50%, the desensitization changes when interference level charges. Fig. 8 shows the relationship between interference temperature T_i and radio-radiated sensitivity with different coupling efficiencies. It can be seen that when the noise gets higher the radio desensitization gets worse, which can be expected.

In radio receiver design, engineers have found when antenna efficiency reduces, the receiver-radiated sensitivity gets better. This happens when the radio noise coupling mechanism and internal noise sources have not been changed much. As shown in Fig. 9, in decibel chart, the radio sensitivity degrades almost linearly along with antenna efficiency increase. This lead people to think the overall radio performance might be improved by fine tuning the antenna. It is known that the overall radio receiver system performance is determined by the TIS. If the radio internal noise level is very high, the TIS will not be improved much without changing the noise coupling mechanism, coupling efficiency, and controlling system internal noise. If the noise level is low, then improving antenna gain can result in the improvement of the TIS. This can be seen in Fig. 10 and (16).

When antenna efficiency and antenna structure are fixed, TIS will improve by either reducing the internal noise or changing the noise coupling efficiency. This is part of the radio desensitization trouble shoot work. The relationship among TIS, noise power T_i, and coupling efficiency η_c is shown in Fig. 11. Fig. 11 is also very similar to Fig. 8 because the only difference in TIS and radiated sensitivity is that the antenna efficiency contributed in the TIS.

Measurements on conducted, radiated sensitivity, and TIS scan in GSM band were made for a Samsung S4 using general test systems' (GTS) MAXSIGN software and GTS Rayzone 1800 anechoic chamber as shown in Fig. 12 and the test setup is shown in Fig. 13. From the measured results, it can be seen that the conducted sensitivity was always better than the radiated sensitivity, this was due to the fact that there were some radio noise coupled to the radio through antenna. The TIS was worse than the radiated sensitivity due to the antenna loss. At some high interference frequencies, the peaks in the TIS and the radiated sensitivity were very similar, while some of the conducted sensitivity peaks were not shown in the radiated sensitivity scan. These were due to the fact that noise coupling mechanism for the TIS and the radiated sensitivity was

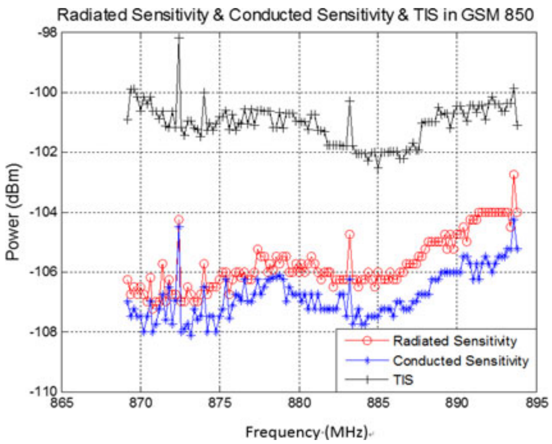

Fig. 12. Conducted, radiated sensitivity, and TIS scan.

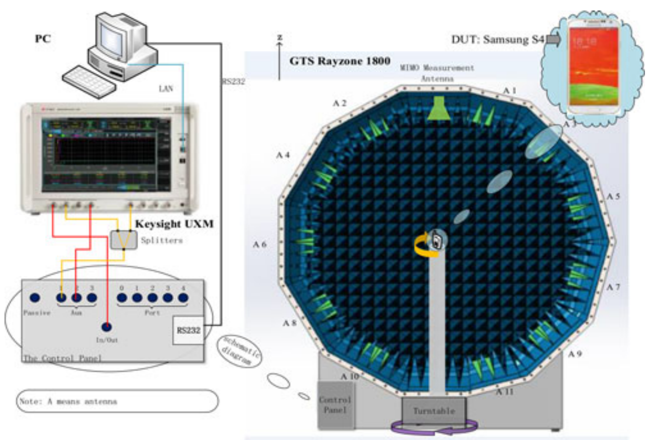

Fig. 13. Typical test set up illustration for radiated measurement.

same but noise coupling mechanisms for conducted and radiated sensitivity were different.

VI. Conclusion

The unified antenna temperature definition is presented in this paper and the antenna temperature measurement methodology for thermal, antenna brightness, and internal noise contributions can be determined through the radio sensitivity measurement. This definition and measurement methodology can help to identify the interference in radio design and calibrate radiometer for remote sensing. The conducted and radiated sensitivity measurements are the practical means to help radio engineers for EMI troubleshooting. With the unified antenna temperature definition, the widely used concepts such as radio-radiated sensitivity and EIS are mathematically defined.

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