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Shared Impedance Noise Coupling in Radio Receivers

YIHONG QI [1,2,3,4] (Fellow, IEEE), AND YUNLONG LUO [1,4] (Member, IEEE)

[1]Pontosense Inc., Kitchener, ON N2H 5G5, Canada
[2]Link-E Technologies, Zhuhai 519000, China
[3]General Test System, Shenzhen 518000, China
[4]School of Information Science and Technology, Southwest Jiaotong University, Chengdu 611756, China
CORRESPONDING AUTHOR: Y. QI (e-mail: yihongqi@gmail.com)

ABSTRACT Radio sensitivity serves as a commonly used parameter in wireless receiver systems. When excess antenna noise is introduced into the system, it results in a reduction of radiated sensitivity. This phenomenon, referred to as radiated sensitivity desensitization, occurs upon connecting antennas. This paper elucidates a shared impedance noise coupling mechanism, which sheds light on how passive antennas can introduce excess noise into the wireless system. To address this apparent contradiction, the paper introduces the general theory of antenna noise temperature, providing an explanation for the mechanism of noise coupling through a shared impedance path. Additionally, a mathematical expression for radiated sensitivity is presented in this paper. An understanding of this noise coupling mechanism holds significant implications for various fields, including antenna technology, electromagnetic compatibility, radio science, remote sensing, and wireless communication systems.

INDEX TERMS Antenna temperature, noise, antenna brightness, noise coupling mechanism, radio radiated sensitivity, sensitivity.

I. INTRODUCTION

IT IS known that radio receiver could have further sensitivity degradation when an antenna is connected to the radio systems [1], [2], [3]. How could a radio receiver have sensitivity degradation after connecting to a passive antenna? In the fields of antenna theory, radio transceiver design, and electromagnetic compatibility research, the concept of radio radiated sensitivity is extensively utilized. Radio radiated sensitivity refers to the minimum power that a wireless receiver system with an attached antenna can detect. The sensitivity of the wireless radio system is evaluated using a wireless over-the-air setup, which is referred to as radiated sensitivity. This is done to distinguish it from the sensitivity measurement obtained by connecting a cable directly to the receiver, known as conducted sensitivity measurement. Although the concept of radiated sensitivity is well understood, a precise mathematical expression for it is currently unavailable. This is primarily because the mechanisms and mathematical models for noise coupling have not been fully elucidated.

How the sensitivity of a wireless radio receiver can differ when an antenna is attached compared to when no antenna is connected. In fact, the sensitivity of the radio receiver can be compromised and become worse when an antenna is present. This phenomenon is referred to as radio radiated desensitization (RRD). RRD is a common occurrence in various wireless systems, including communication systems, radar, wireless sensors, microwave radiometry, satellite communications, and more. Troubleshooting RRD problems is a crucial task for antenna and radio engineers [2], [3]. Understanding radio radiated sensitivity is a fundamental aspect of research in the fields of antennas and electromagnetics.

The sensitivity reduction is due to excess noise introduced into the radio system. The radiated desensitization is caused by antenna attachment. The antenna output noise is the root cause of the desensitization. While most of the antennas are passive components, how do passive components introduce excess noise? To solve this paradox, the theory of antenna noise temperature is investigated. Antenna

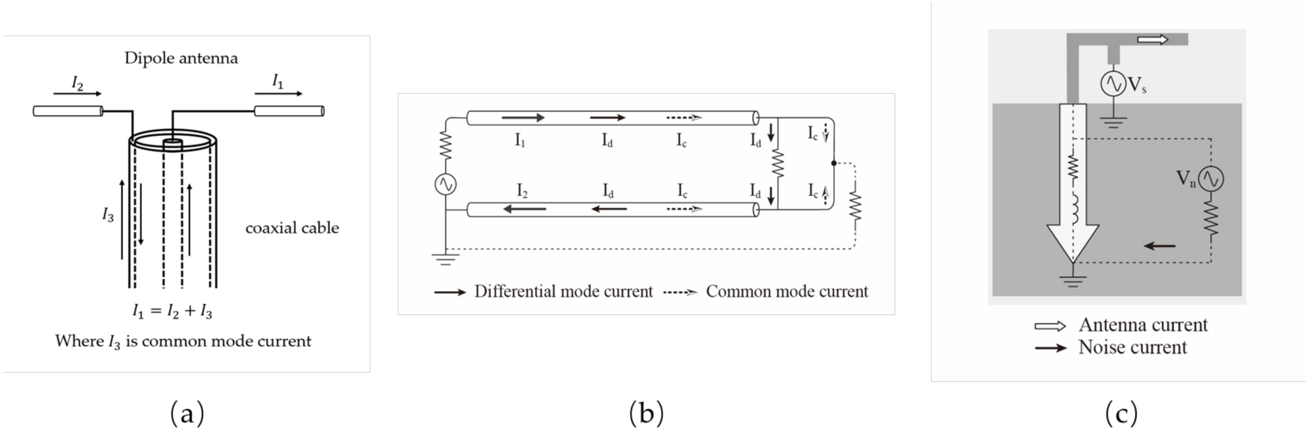

FIGURE 1. Common mode concept and shared impedance concept.

noise temperature is the measured noise power from the antenna output port [1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. Antenna noise temperature is a fundamental aspect of radio science and engineering [11], [12]. In the conventional definition of antenna noise temperature, there are two noise sources, one is thermal noise and the other is the noise contribution from surrounding sources including environmental noise, and all the natural and man-made noise in the radio frequency band [13], [14], [15], [16], [17], [18], [19].

In the conventional definition, the antenna temperature is expressed as the combination of antenna physical temperature and antenna brightness factored by antenna efficiency as shown in equation (1):

$$T_A = \eta_{rad} T_b + (1 - \eta_{rad}) T_P \tag{1}$$

where η_{rad} is the antenna radiation efficiency; T_b is the background brightness temperature of the antenna; T_P is the thermal noise temperature. But equation (1) cannot explain why in a radio system, a passive antenna system connected to an active system may desensitize the radio system.

In this paper, we first demonstrate that when there is shared impedance in the antenna and radio system, the noise from the radio subsystem or transceiver can couple to the antenna, leading to an increase in output noise from the antenna. With the shared impedance noise coupling mechanism, a general antenna noise temperature equation is presented. Then we proved theoretically that RRD is a direct result of the shared impedance system noise coupling through antennas. And finally, the radio radiated sensitivity equation is presented mathematically for the first time.

II. ANTENNA NOISE TEMPERATURE ANALYSIS

A. ANTENNA COMMON MODE CURRENT

When a balanced antenna is connected to an unbalanced coaxial transmission line, a common mode current is induced on the outer surface of the coaxial cable. Fig. 1(a) provides an illustration of the common mode current in a coaxial cable feeding a dipole antenna [20]. In a broader sense, an imbalanced transmission structure also has a certain amount of common mode current as shown in Fig. 1(b) [21]. An unbalanced antenna connected to an unbalanced feeding structure will also generate a common mode current flowing on the grounding structure as illustrated in Fig. 1(c) [22]. In the case of a mobile phone antenna integrated into a mobile system, the system's ground plane is typically part of the antenna. Due to the common mode effect, the accuracy of passive antenna measurement methods may be compromised [23]. The common mode current path in a radio receiver system is not easy to be accurately defined, the simulation of the antenna common mode current path needs detailed information on the printed circuit board, components information, and materials around the entire system.

If the antenna current passes through a section of the noisy circuit, it creates a shared loop with the noisy circuit, as illustrated in Fig. 1(c). This common section of the circuit is referred to as the shared impedance component. The shared impedance not only possesses resistance but also exhibits partial inductance or capacitance. The measurement demonstration of shared impedance coupling is investigated on the antenna common mode current influence [24].

B. ANTENNA TEMPERATURE

Antenna temperature refers to the power received by an antenna from various noise sources, including thermal noise. It serves as a measure of the noise power received by the antenna and is a significant concept in antenna theory and radio science.

When a resistor is placed inside an anechoic chamber, the thermal noise power resulting from the random motion of electrons can be measured. If we replace the resistor with an antenna that has a radiation resistance in the same anechoic chamber, the noise power available at the antenna terminal is equal to the noise power of the resistor. This implies that the antenna has a noise power, denoted as P_0 (as shown in Fig. 2(a)).

Subsequently, the antenna is taken out of the chamber and pointed towards the sky to measure the sky temperature. By comparing the noise temperature of the antenna with that

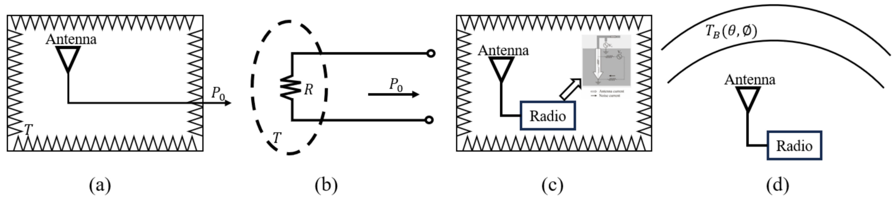

FIGURE 2. Conventional Antenna Temperature Definition.

of a resistor at an adjustable temperature, we can calibrate the sky temperature. This technique of using an antenna to measure a temperature at a distant location is known as passive remote sensing (as depicted in Fig. 2(b)). Antenna temperature is a widely used concept.

However, when a wireless receiver is connected to an antenna that has a common mode current in an anechoic chamber, the shared impedance between the antenna and the noise circuit can lead to noise coupling into the radio system. This can lead to decreased sensitivity in the radio compared to when no antenna is attached, as depicted in Fig. 2(c). This phenomenon, known as RRD, occurs due to the excess noise coupled from the antenna to the radio.

Radio sensitivity pertains to the capability of a radio receiver to detect weak radio signals. It is termed "radiated sensitivity" because the sensitivity measurement is conducted using over-the-air radiated means. In order for the radio sensitivity to deteriorate, there must be an excessive amount of noise output emanating from the antenna. In the case of a passive antenna that solely exhibits thermal noise, there must be additional noise coupled to the antenna and subsequently fed into the receiver.

When the radio receiver is placed in a real working environment, the ambient noise is received by the antenna. This environmental or ambient noise is denoted as T_b (Fig. 2(d)).

When an antenna with a common mode current is connected to a radio transceiver or any other system that introduces in-band equivalent noise temperature T_i along the shared impedance path. In the shared impedance path, a noise coupling efficiency to the antenna is η_c, which means the amount of $\eta_c k T_i B$ noise coupled to the antenna, where B is the channel bandwidth, k is the Boltzmann's constant (1.38×10^{-23} J/K).

In physics, the noise in the circuit couples through the shared impedance and applies to the antenna as illustrated in Fig. 2(c). The shared impedance is a common part that a noise can couple to the antenna through conducted means, which increases antenna temperature resulting in receiver RRD.

When the radio receiver is in a real working environment, it will receive environmental noise on top of the thermal and shared impedance coupled noise, as shown in Fig. 2(d). The environmental noise is distributed in all directions in proportion to the antenna pattern response. These noises are radiated noise sources in nature, which is also called background brightness. The background noise temperature varies with the angles, time, and frequency which is denoted as $T_B(\theta, \phi)$. The total background brightness temperature of the antenna is expressed as:

$$T_b = \int_0^{2\pi} \int_0^{\pi} T_B(\theta, \phi) D(\theta, \phi) sin\theta d\theta d\phi / 4\pi \tag{2}$$

where $D(\theta, \phi)$ is the directivity of the receiving antenna.

This antenna brightness noise temperature will present a power of $\eta_{rad} T_b$ at the antenna output port due to antenna efficiency.

C. SHARED IMPEDANCE COUPLING

Shared impedance interference can be verified by conducted and radiated measurements when the device under test is positioned in an anechoic chamber. The conducted and radiated sensitivity difference is caused by shared impedance noise coupling.

The radio board or surrounding structures generally contain other radios, processors, digital circuits, and other unintentional noise sources as part of the system. Those circuits may have frequencies that are in the receiver signal band, for receivers these frequencies power is the interference noise. Once the antenna shares the impedance with the noise circuit, then this shared impedance will form a noise coupling mechanism as illustrated in Fig. 3. This shared impedance can couple radio or its connected subsystem noise into antenna, which can cause higher antenna noise output. The consequence of this higher antenna output noise power results in RRD. Shared impedance noise coupling refers to a conducted pathway through which noise can enter the radio receiver system via antenna.

The shared impedance path contains resistance and partial inductance resulting from the shared noise circuit loop with the antenna's current loop. The capacitive shared impedance can also introduce noise into the antenna, but it is typically not the dominant factor and is omitted from our equivalent circuit illustration. Instead, we focus on demonstrating the shared inductance and resistance, which are generally the primary contributors to shared impedance coupling. To illustrate the concept of the noise coupling, a simplified equivalent circuit of shared impedance coupling is shown in Fig. 3. When the antenna is in a resonance state, the antenna can be modeled as a resistance. In antenna circuit I_{ant} is the antenna current, R_{rad} is the antenna radiation resistance, V_{ant} is the antenna voltage, V_{sa} is the antenna source voltage and R_{sa} is the antenna source resistance. In the noise circuit, I_{noise} is the noise current, V_{noise} is the noise circuit voltage, and R_{noise} is noise circuit resistance and R_{sn} is the noise source resistance. R_{share} and L_{share} are the shared resistance and inductance. Shared inductance at higher frequencies might be the bigger impedance contributor. With the shared impedance, the

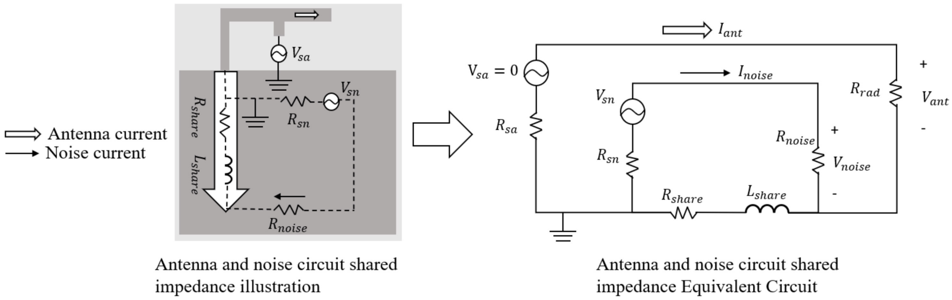

FIGURE 3. Shared impedance illustration.

noise voltage source V_{sn} can introduce noise in antenna circuit. The coupling efficiency of coupled noise power from noisy circuit to antenna can be defined as

$$\eta_c = 20log\left|\frac{V_{ant}}{V_{noise}}\right|_{V_{sa}=0} \tag{3}$$

η_c is the shared impedance coupling efficiency. For the equivalent circuit, the η_c is expressed as

$$\eta_c = 20log\left|\frac{R_{share} + j\omega L_{share}}{R_{sa} + R_{rad} + R_{share} + j\omega L_{share}}\frac{R_{rad}}{R_{noise}}\right| \tag{4}$$

Based on equation (4), it is evident that the shared impedance coupling efficiency becomes zero when both the shared resistance and inductance are equal to zero. Although the resistance in the shared impedance may be very small, the contribution of partially shared inductance is typically not insignificant. In this specific situation, the condition for T_i to be equal to T_p in the antenna circuit is that only the shared impedance path remains free from interference noise, which is in band power from unintentional subsystem such as harmonics of processor and so on.

D. GENERAL ANTENNA TEMPERATURE EXPRESSION

All objects, when not at absolute zero (0 = −273 °C), emit radiation that can be detected by a wireless radio receiver. In the scenario shown in Fig. 2(b), we have a simple case of a resistor at temperature T_P. The thermal molecule motion of electrons within the resistor results in the generation of noise power at the output terminal of the antenna. This voltage fluctuation is random and has a non-zero root mean square (rms) value. At radio frequency and microwave frequencies, this thermal noise power, known as white noise, is independent of frequency. According to the Nyquist relation, the thermal noise power at the output port of the antenna is expressed as follows:

$$P_0 = kT_P B, \;\; W \tag{5}$$

where B is the channel bandwidth, k is the Boltzmann's constant (1.38×10^{-23} J/K).

A resonant antenna can be effectively modeled as a resistor, with no distinction between the terminals of the antenna and the resistor. The total antenna resistance is composed of two components. The first component is the antenna radiation resistance, denoted as R_{rad}, which represents the power radiated into space. The second component is the antenna ohmic loss, expressed as R_{loss}, which accounts for losses resulting from imperfect conductivity or dielectric losses within the antenna. Generally, antenna radiation efficiency can be expressed as

$$\eta_{rad} = \frac{R_{rad}}{R_{rad} + R_{loss}} \tag{6}$$

For a receiving antenna, this implies that the power at the output port of the antenna is attenuated by a factor of η_{rad}.

The total output noise power from the antenna is the contributions of thermal noise, antenna background brightness and shared impedance noise coupling to the receiver. The noise behavior of the antenna can be represented by modeling it as a resistor at a temperature T_A, which accounts for the total contribution of all noise sources. The antenna temperature, in this context, does not correspond to the actual physical temperature of the antenna. Instead, it is an equivalent temperature that generates the same level of noise power as the antenna operating in a real radio system and environment. The antenna temperature mathematical expression needs to include all extreme cases. If the antenna loss is considered as a lossy network having a power loss of $1/\eta_{rad}$. At extreme case, the entire system is in thermal equilibrium at temperature T_P, the output noise power must be same as input noise power [14].

$$P_0 = kT_P B = \eta_{rad} kT_P B + \varsigma_{rad} N_{add} \tag{7}$$

where N_{add} is the noise added by the network loss:

$$N_{add} = \frac{1 - \eta_{rad} - \eta_{rad}\eta_c}{\eta_{rad}} kT_P B \tag{8}$$

The term N_{add} refers to the rational thermal noise contribution to the overall noise output of the antenna. This happens when we put the radio in an anechoic chamber and there is no noise source on the shared impedance path. Considering the thermal noise power $kT_P B$, the antenna background brightness noise power $kT_b B$ and the shared impedance noise power $\eta_c kT_i B$, the total noise at the radio antenna output is

$$\begin{aligned} P_{total} &= kT_A B \\ &= k[\eta_{rad} T_b + (1 - \eta_{rad} - \eta_{rad}\eta_c)T_P + \eta_{rad}\eta_c T_i]B \end{aligned} \tag{9}$$

Then the antenna temperature is:

$$T_A = \eta_{rad} T_b + (1 - \eta_{rad} - \eta_{rad}\eta_c)T_P + \eta_{rad}\eta_c T_i \tag{10}$$

TABLE 1. Wi-Fi device sensitivity test results.

Channel: Frequency (GHz)	Conducted Sensitivity	Radiated Sensitivity
1: 2.401 – 2.423	-86.85dBm	-83.97dBm
6: 2.426 – 2.448	-87.15dBm	-82.62dBm
11: 2.451 – 2.473	-87.84dBm	-86.19dBm
36: 5.16 – 5.20	-90.60dBm	-88.61dBm
44: 5.20 – 5.24	-91.50dBm	-88.83dBm
100: 5.48 – 5.52	-90.30dBm	-81.48dBm
136: 5.66 – 5.70	-92.10dBm	-86.83dBm

If the radio is tested in the anechoic chamber, the antenna background brightness temperature equals the thermal temperature, resulting antenna temperature.

$$T_A = ((1 - \eta_{rad}\eta_c)T_P - \eta_{rad}\eta_c T_i) \tag{11}$$

This happens when the radio is measured in an anechoic chamber, a typical case for radio development or certification test.

When the product of $\eta_{rad}\eta_c T_i$ is equal to thermal noise, the definition mentioned above is equivalent to the classic equation (1) for antenna temperature. This occurs when the noise source is completely removed or when the shared impedance coupling path is eliminated. The noise power without shared impedance noise contribution is

$$P_{total} = k[\eta_{rad}T_b + (1 - \eta_{rad})T_P]B \tag{12}$$

III. RADIO SENSITIVITY ANALYSIS

Radio sensitivity is a commonly employed concept in all applications related to wireless receivers. It signifies the minimum detectable power that a radio receiver is capable of decoding. When the radio received energy traverses through the networks in the radio front end, it experiences an increase in noise, leading to a reduction in the signal-to-noise ratio. The noise factor, F, serves as a measure of this reduction. Assuming the signal is uniformly distributed within the channel of interest, the noise factor is defined as

$$F = \frac{S_{sig} \; / \; P_n}{SNR_{out}} \tag{13}$$

where S_{sig} and P_n are the total mean square input signal and noise power. SNR_{out} is the total mean square output signal-to-noise ratio.

Identifying shared impedance paths can be challenging due to the lack of precise and detailed information in printed circuit board (PCB) layout, component modeling, and accurate clarification of the bill of materials (BOM) required for an accurate electromagnetic full simulation of the antenna, PCB, and the entire radio system. The over the air (OTA) measurement is the main method for identifying and troubleshooting shared impedance related RRD. Fig. 4 is an OTA measurement system for radio radiated performance test including desensitization.

Table 1 is a comparison of a Wi-Fi device conducted and radiated sensitivity measurement results. The test results of conduction sensitivity and radiation sensitivity shown in Table 1 are obtained in the anechoic chamber. The device under test (DUT) is a Wi-Fi router with two 2.4GHz channels and two 5GHz channels. The test system is calibrated before conducting the sensitivity measurement [25]. The working mode of the DUT during the 2.4GHz channel test is 802.11g 6Mbps, and the working mode of the device during the 5GHz channel test is 802.11a 6Mbps. The antenna used in the device under test is a dual-band antenna covering 2.4GHz-2.5GHz, 5.1GHz-5.9GHz. It can be seen in 1 that the radiated sensitivity measurement with antenna attached has more than 8dB of radiation sensitivity reduction. The conducted and radiated sensitivity measurements serve as diagnostic tools to identify shared impedance noise coupling.

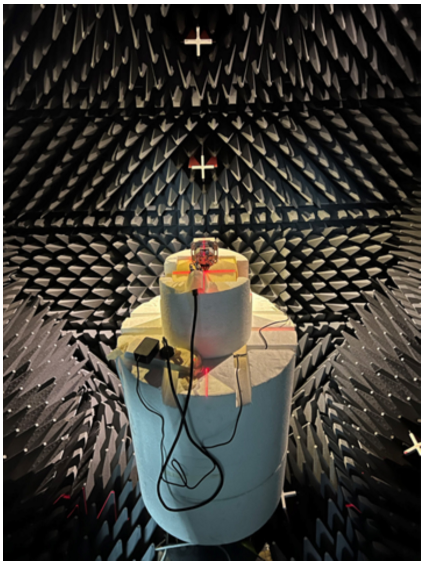

FIGURE 4. Wi-Fi 6 device OTA test.

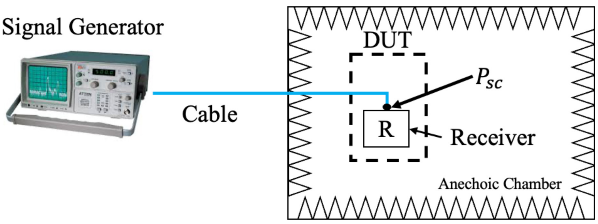

FIGURE 5. Conducted sensitivity measurement.

Radio conducted sensitivity pertains to a radio receiver's capability to detect and decode weak signals in the absence of an antenna attachment. It is utilized to determine the level of noise introduced by the front-end networks, including filters, low noise amplifiers, and mixers. This measure indicates the minimum power level of conducted signals that the receiver can reliably process, with a reference point typically located in the front of the radio input point, as illustrated in Fig. 5.

The conducted sensitivity measurement is typically conducted by connecting the input point of the radio receiver to a signal generator using a coaxial cable. The signal generator power is gradually reduced, employing a power stepping-down method, until the receiver's signal-to-noise ratio reaches a level where the receiver can no longer decode

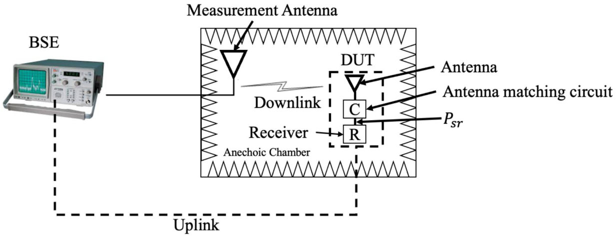

FIGURE 6. Radiated sensitivity measurement.

the signal. This signal level, adjusted for the calibrated coaxial cable loss, represents the minimum power at which the receiver can decode signals, commonly referred to as the conducted sensitivity. The minimum decodable $SNR_{outmin}$is determined by the receiver modulation scheme, channel condition error correction coding, and channel bandwidth. P_n is equals to kT_PB. Then according to equation (13), the radio conducted sensitivity S_c can be expressed as

$$S_c = F \times k \times T_P \times B \times SNR_{outmin} \tag{14}$$

During practical conducted sensitivity measurements, the physical temperature of the radio can exceed the ambient temperature due to the generation of excess heat by the radio transceiver and other components, such as the processor and DC-to-DC converters.

When a wireless device is equipped with an antenna, as discussed in previous sections, there is a possibility of shared impedance noise coupling, which can result in degradation of radio sensitivity. Various sources can contribute to radio noise, including the processor, DC-to-DC converters, nonlinearity of radio frequency components, and even saturated ferrite beads. In the presence of an antenna with common mode current, these noises can couple to the radio receiver through shared impedance paths. The sensitivity when an antenna is attached is referred to as radiated sensitivity. Radio radiated sensitivity is the radio's capability to detect a weak signal in the presence of the receiver's antenna. The radio signal is transmitted over-the-air, and the system takes into account the wireless path loss by calibration.

The setup for measuring radiated sensitivity is depicted in Fig. 6, where the integrated radio is placed within an anechoic chamber. The signal generator is connected to a probe antenna, establishing an OTA connection between the radio and the signal generator. When the anechoic chamber and the radio reach a state of thermal equilibrium, the brightness of the antenna corresponds to its physical temperature. Based on equation (11), the input noise from the antenna to the radio can be determined.

$$P_n = k((1 - \eta_{rad}\eta_c)T_P - \eta_{rad}\eta_c T_i)\ B \tag{15}$$

During radiated sensitivity measurements, the reference point is likewise positioned at the front of the receiver. By calibrating the path loss from the signal generator to the receiver, the minimum detectable output signal-to-noise ratio is determined as SNR_{outmin}. The radiated sensitivity $S_r$is achieved through a power stepping method, wherein the power of the signal generator is gradually reduced until the desired signal-to-noise level is reached.

$$S_r = F \times k \times B \times SNR_{outmin}((1 - \eta_{rad}\eta_c)T_P + \eta_{rad}\eta_c T_i) \tag{16}$$

Due to the noise temperature T_i being higher than the physical temperature of the radio T_P, the radiated sensitivity $S_r$is always equal to or higher than the conducted sensitivity S_c. By comparing equations (16) and (14), it can be observed that the radiated sensitivity will be higher than the conducted sensitivity and only equivalent to the conducted sensitivity when η_c equals zero or T_i equals T_P. This implies that if there is no shared impedance between the antenna and noise circuit or if there is no noise source present, the radio's radiated desensitization will not occur.

$$S_r = S_c \tag{17}$$

IV. CONCLUSION

Wireless devices and RF receiver systems heavily rely on receiver sensitivity, which serves as a fundamental metric impacting overall performance. RF engineers often troubleshoot radiated sensitivity desensitization, which is a significant aspect of their work. Radiated desensitization in radio systems can be puzzling, as it may appear that all individual components such as the antenna and RF frontend blocks are functioning correctly, yet the integrated receiver fails to meet the required specifications.

The mystery deepens when considering that antennas are primarily passive devices. It may seem perplexing that a passive device could contribute to excess noise. The antenna and radio noise circuit shared impedance coupling unveiled a noise coupling mechanism from antenna to radio receiver.

The shared impedance coupling mechanism is mathematically elucidated in this paper, leading to the derivation of a general antenna temperature. This concept finds wide application in various fields such as radio passive remote sensing, wireless communication, wireless sensing, and more.

The direct measurement of shared impedance path is very difficult due to the instrument dynamic range and probe sensitivity for ultra-low noise measurement. Simulation could also be challenging because of lacking components models for possible noise generation. The most direct measurement for the shared impedance noise coupling is through over the air RF measurement compared to that of the radio conducted measurement.

Although directly measuring and simulating shared impedance noise can be challenging, comprehending the noise coupling mechanism enables the design of antennas that minimize the flow of high antenna current through potential noise circuit loops. These loops might involve processors and DC-TO-DC conversion circuits, so considering this during the design stage is crucial.

During the research and development troubleshooting phase, one effective approach to address radio desensitization issues is to shield the antenna current from the noise circuit.

By doing so, potential problems caused by noise coupling can be mitigated.

Utilizing the general antenna temperature, the formula for radio radiated sensitivity can be formulated and presented.

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YIHONG QI (Fellow, IEEE) is an Engineer, a Scientist, an Inventor, and an Entrepreneur. He is a Founder of Pontosense Inc., Mercku Inc., Canada, Link-E, Zhuhai, China, and General Test Systems, Shenzhen, China. He is an Honorary Professor with Xidian University and Southwest Jiaotong University. He is also an Adjunct Professor with the EMC Laboratory, Missouri University of Science and Technology, Rolla, MO, USA, and Western University, Ontario, Canada. He was an Associate Professor with Southeast University, China, in 1992. From 1995 to 2010, he was with Research in Motion (Blackberry), Waterloo, ON, Canada, where he was the Director of Advanced Electromagnetic Research. He is an inventor of more than 500 published and pending patents. He has published 150 academic papers. His smartphone antenna design patent significantly reduced harmful radiowave radiation to the human head, which could potentially help billions of smartphone users reduce potential hazardous electromagnetic radiation. His invention also resolved the hearing aid compatibility issue; there are more than 20-million cell phone users who depend on hearing aid devices. His radio frequency measurement standards related inventions has have made the certification process for 4G, 5G, and potentially 6G wireless communications and autonomous cars more efficient and cost-effective.

Dr. Qi has received an IEEE EMC Society Technical Achievement Award. He is an Associate Editor of IEEE INTERNET OF THINGS JOURNAL and IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY. He is a Distinguished Lecture of IEEE Antenna and Propagation Society. He was a Distinguished Lecturer of IEEE EMC Society and a founding Chairman of the IEEE EMC Society TC-12. His inventions won the CES Innovation Awards in 2019 and 2020, the CES Network Product Award in 2021, the CES Wellbeing Product Award in 2022, the Red Dot Award, and the IEEE HI-TC Industrial Award. He is a Fellow of the Canadian Academy of Engineering and the National Academy of Inventors

YUNLONG LUO (Member, IEEE) received the B.E. and M.E. degrees in electronic engineering from Hunan University, Changsha, China, in 2016 and 2019, respectively. He is currently pursuing the Ph.D. degree in information and communication engineering with Southwest Jiaotong University, Chengdu, China.

He is a Chief Engineer with Pontosense Inc. From 2018 to 2011, he worked as a Hardware Director with Mercku Inc. His research interests include RF system design and wireless sensing. His inventions won the CES Innovation Awards in 2019 and 2020, the CES Network Product Award in 2021, the CES Wellbeing Product Award in 2022.