Review of the EMC Aspects of Internet of Things

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***Abstract*—Wireless devices are the largest part of the Internet-of-Things (IoT) units. Radiated, such as specific absorption rate and spurious related issues are regulated by the standards bodies. The functionality performance will greatly influence IoT system stability, user experience, and cost. Radio receiver desensitization and coexistence aspects of IoT devices are discussed in this article. Measurement technologies are briefly reviewed for transmit/receive mode only of single-input single-output (SISO), and multiple-input multiple-output (MIMO) devices, to provide a means of device performance evaluation and electromagnetic interference troubleshooting. An understanding of the electromagnetic compatibility aspects of the IoT and its measurement methods can help ensure the best user experience for ubiquitous wireless systems.**

***Index Terms*—Coexistence, desensitization, electromagnetic compatibility (EMC), specific absorption rate (SAR), Internet of Thing (IoT), wireless communications.**

I. Introduction

MANY of us have experienced the disruption of a 2.4 GHz Wi-Fi or cordless phone voice call and simultaneously turning on a microwave oven. The experience of an in-car GPS prompting a turn after missing the turning point is also a regular occurrence. These are typical electromagnetic interference (EMI) problems in the Internet-of-Things (IoT) devices. Not all IoT devices are wireless, but a large percentage of them are [1]–[3].

Radio regulation is enforced to prevent EMI problems. Regulatory bodies, such as the Federal Communications Commission (FCC), states that manufacturers, importers, distributors, and sellers of radio apparatus, interference-causing equipment or radio-sensitive equipment must ensure that the equipment they provide guarantees electromagnetic compatibility (EMC) between other radio apparatus and services such as broadcasting, air traffic control, security services and communications with satellites. The radio equipment must also minimize interference between devices that use intended radios and other equipment that may be unintentional radiators. These types of interferences are categorized as spurious or immunity related intersystem EMC problems. The spurious and immunity EMC measurement is a mandatory measurement for the IoT devices and system through regulatory bodies [4].

For wearable wireless devices, the specific absorption rate (SAR) is also a mandatory requirement for human safety reasons. SAR has been extensively researched for decades. But reducing SAR is still an ongoing effort for the device makes [4], [5].

Interference and noise in the radio receiver can cause radio receiver desensitization commonly referred to as desense. Desense and coexistence of radiating systems is among the primary challenges in design and engineering of wireless systems, and research in this area is going to be of significant importance as wireless devices and the IoT proliferates. There are a lot of desense and coexistence problems especially in the IoT devices where the devices are generally not tightly controlled for functionality-related performance. For example, a Wi-Fi device could easily have as large as 20-dB total isotropic sensitivity (TIS) difference among different commercial available units. A ZigBee system communication range can extend from as few as 15 m to as many as 100 m depending on the device design, and the sensitivities of commercial GPS devices are often 20 dB higher than the minimum sensitivity that can be theoretically achieved.

For most of the IoT devices, quality or performance-related issues are left to be verified by the manufacturers, vendors, or deployment companies. The radio desensitization and multiradio coexistence are the EMC-related issues that can largely influence the IoT user experience, IoT system deployment stability, and cost. Most of the IoT connectivity technologies use a portion of the frequency spectrum defined by regulatory bodies allocated in many cases such that they do not have overlapping spectrum between technologies in order to avoid interference from one technology to the other. However, for regulatory reasons, a large portion of IoT technologies are using industrial, scientific and medical (ISM) frequency bands, where several different technologies are sharing the frequency band. Long-term evolution

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(LTE) Band 7 (FDD) and ISM bands of operation for wireless local area network (WLAN) work at the adjacent frequencies, but current state-of-the-art filter technology may not provide sufficient rejection that results in the concept of in-device coexistence (IDC) [15].

The frequency overlapping can also increase ambient noise for the in-band receivers in the same environment causing coexistence problems among devices. For the coexistence among devices between wireless networks, the transmit energy of one device may become an ambient noise of another receiver in the same environment. Providing adequate frequency separation or reduce channel occupancy will decrease the possibility of packet data collision rate. If the receiver network has narrow bandwidth, a proper filtering at the receiver RF front end can reduce the wide band noise that can potentially jam the low-noise amplifier (LNA) [6]. Although deploying the network with sufficient large distance between devices is a brute-force method for coexistence between wireless networks, but it is the most effective way to increase signal to interference ratio at each receiver. For example, if Bluetooth piconet is farther than 5 m away from a microwave oven the receiver degradation can be ignored [7].

The radio transmitter performance is tightly regulated by regulatory bodies. However, the receiver sensitivity can be severely degraded by intrasystem interference. For example, in many current products, multiple systems are integrated in in a densely packaged device. These systems are generally controlled by a processor and system power supply that can be sources of interference for one or more of the wireless receivers in the device. For reliable IoT system operation, identifying desense and coexistence problems, and fixing them is essential for making the IoT system more robust and providing a good user experience.

Many of these aspects can be better managed with suitable EMC design [8]. EMC and over-the-air (OTA) tests are the first step in finding critical issues that compromise wireless performance, and the OTA measurements are very good diagnostic tools for trouble shooting. The EMC aspects related to IoT devices are reviewed herein, and an overview of OTA measurement technologies for different types IoT terminals is provided.

The relevance of this application field for the technical and scientific EMC community, and the importance of EMC aspects in the state-of-the-art design of the IoT devices has been recognized, and the IEEE EMC Society in 2015 initiated Technical Committee 12 [9] (TC12), which is focused, on "*the EMC design, analysis, modeling, measurement, and testing aspects of emerging wireless products, such as Internet of Things and 5th Generation of Wireless Communication.*" This review article is sponsored by this TC.

Three classes of IoT device categorization is discussed in Section II from the problem diagnostic point of view. Desensitization and coexistence problems of IoT devices are discusses in Section III. Immunity problems, with emphasis on security related immunity, which has not been well addressed to date are discussed in Section IV. OTA measurement methodologies focusing on desense diagnostic methods are addressed in Section V.

II. Internet-of-Things (IoT) Devices

The IoT will enable communication among an estimated 50 billion devices and information systems, integrating web-based and mobile business applications, and enabling intelligent interaction among people and automated devices to achieve unprecedented performance and power efficiency [3]. As the IoT is quickly transitioning from closed networks to the public internet, many unpredictable phenomena in the EMC world will be encountered.

The IoT connects an extraordinarily wide range of computing technologies, spanning computers and servers to smart devices. Sensors, actuators, radio frequency identification (RFID) tags, vehicular ad hoc networks (VANETs), low-power wide area network (LPWAN) [49], and microcontrollers equipped with radio frequency (RF) transceivers capture and communicate various types of data related to, for example, industrial and building control, e-health (e.g., from wearable devices embedded in our clothing), smart energy grid and vehicle system performance, and home automation (from internet-connected appliances in our increasingly smart homes, such as washing machines, dryers, and refrigerators). That data are transmitted through the internet via wireless, wired and/or a hybrid to back-end business application/integration servers or cloud that receive and process it into meaningful information. However, the sensitivity of each of those IoT devices is tested individually, and has not considered the compound effect of multiple transmitters and receivers sending and receiving within the same frequency band, which can be considered as unintended jamming to an intended Rx or interference from other devices. For example, the LPWAN technology achieved a long-range communication with low power and low cost, but unexpected interference may adversely affect its communication range and performance [50].

According to the complexity of Tx/Rx structures, we may classify the IoT devices or cyber physical devices [10] into three classes.

1) Single Tx/Rx pairs, such as GPS receivers, RFID tags [11], etc.
2) Single-input single-output (SISO) devices, such as Bluetooth or Bluetooth Low Energy (BLE) [12], ZigBee [13], [14], Narrowband IoT [15], etc.
3) More complicated structures (i.e., multiple-input multiple-output (MIMO) devices such as Wi-Fi, 4G-LTE, 5G and beyond, Wi-MAX, etc.

The communication protocols, operation frequencies, multiple access methods, and possible applications for these classes of devices are provided in Table I [48]. For a more detailed list of IoT devices, the reader is referred to [10], [16], and [17].

III. IoT Device Desensitization and Coexistence

In modern wireless devices, different radio functions are now integrated into a small, lightweight, and ergonomic designed device as shown in Fig. 1. For example, LTE smart phones always have cellular, Bluetooth, Wi-Fi, and GPS wireless functionalities, all fitting in one small form factor.

TABLE I
IoT DEVICES CATEGORIES

Communication protocol		Spectrum	Trans. range	Transmission rate	Multiple access	Applications
Simple Tx/Rx IoT Devices	GPS	1575.42 (L1), 1227.6 (L2), 1176.45 (L5) MHz				Location service
	NFC	13.56 MHz	< 20 cm	106-424 Kb/s	Single device coupling	Mobile commerce, bootstrap setups, social networking, identification
	LoRa	different in different countries, e.g., 863-870 MHz (Europe), 902-928 MHz (US)	variates	variates	FDMA	IoT long range
	RFID tags	866-960 MHz	~ 2-7 m	~115 Kb/s	CSMA/CA	Ultrahigh frequency: vehicle ID, supply chain, indexing, access/security
		13.56 MHz	~ 1 m	~106 Kb/s	F-TDMA	High: antitheft, supply chain, indexing
		125-135 kHz	< 50 cm	5-98 Kb/s	Pure Aloha	Low: smart cards, ticketing, tagging, access control
SISO IoT Devices	Bluetooth 3.0	2.4 GHz	~ 10 m	~ 25 Mb/s	TDMA	Wearable electronics, peripherals, device pairing, vehicle entertainment
	BLE	2.4 GHz	> 100 m	~ 1 Mb/s	TDMA	Medical devices, wearable electronics, sensor networks, electronic leashing
	ZigBee	2.4 GHz/ 866 MHz	~ 40 m	20-250 Kb/s	CSMA/CA	Smart home, physical security, medical devices (including implantable devices) smart meter, home automation
	UWB	3.1-10.6 GHz (bandwidth > 500 MHz)	~ 30 m	~ 100 Mb/s	TDMA, CDMA	Video streaming, wireless displays, wireless printing/scanning (WPS), file transfers, peer-to-peer (P2P) connections
MIMO IoT Devices	3G	700-3500 MHz (UMTS), 450-2100 MHz(CDMA)	5-70 km	< 2.4 Mb/s	TD-CDMA, CDMA	GPS services, high-speed data (e-mails, maps, directions, News, shopping, e-commerce, interactive gaming, etc.)
	4G-LTE	400 MHz-3.5 GHz	2-103 km	300 Mb/s (D), 75 Mb/s (U)	OFDMA (D), SC-FDMA (U)	Video streaming, mobile Internet, telecommunications, ubiquitous computing with location intelligence
	5G and beyond	up to 90 GHz	2–150 km	up to 20Gb/s	Various	Supporting IoT, smart city, industrial automation
	Wi-Fi	2.4/5.8 GHz	~ 100 m	50 - 320 Mb/s	CSMA/CA	Internet access points, video streaming, wireless displays, WPS, file transfers, P2P connections
	Wi-Max	2-11 GHz	~ 50 km	~ 70 Mb/s	OFDMA	Portable Internet AP, smart meters, air traffic communications, smart cities, VoIP

D: downlink; U: uplink; FDMA: frequency-division multiple access; CSMA: carrier-sense multiple access; TDMA: time-division multiple access; CDMA: code-division multipole access; OFDM: orthogonal frequency-division multiple access; UMTS: universal mobile telecommunications system.

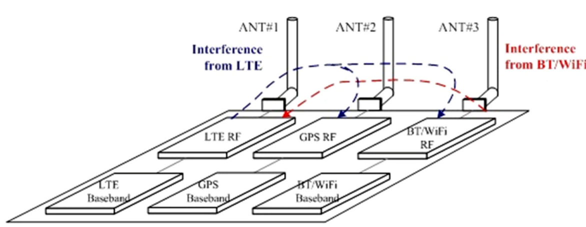

Fig. 1. 3GPP Frequency bands around ISM band (Source–3GPP spec 36.816 [18]).

The spectrum allocation by regulatory bodies of respective technologies, in most cases, is set in such a way that overlapping spectrum is avoided as much as possible in order to prevent interference from one technology to another. However, due to the ever growing applications of wireless technologies, some frequency overlapping is unavoidable. For example, the UWB transmitter frequency band can spread over several gigahertz. And, rapidly growing number of devices are using technologies such as WLAN, Wi-Fi, Bluetooth, and Zigbee in the ISM band at 2.4 GHz. Although the UWB transmitter power is low, when it is physically close to other systems it can have a significant impact on other system receivers such as IEEE 802.11 a/b. Another case is LTE Band 7 (FDD) and the ISM bands of operation for WLAN. They work on the adjacent frequencies as discussed in Section I.

The solutions to solve this kind of IDC issues include the following.

1) *Controlling the Power Level:* One of the IDC problems is due to the overpowering of one system transmitter jamming the receiver of another system. Reducing the transmitter power is a straightforward solution. UWB transmitters generally have very low transmitter power, so that only when the UWB transmitter is physically close to other receivers, will inference occur. Adding a surface acoustic wave filter in the receiving chain could prevent the LNA in the receiver from generating saturating noise [6]. When an LTE signal acts as the interferer to a Wi-Fi receiver, lowering the LTE uplink signal power using power control mechanisms in LTE is an effective method. The user equipment (UE) power can be adjusted to a lower value when Wi-Fi operation is detected in a nearby channel in the same UE. Another means to reduce the IDC problem is by making the antenna orthogonally polarized or separating the antennas physically [19].
2) *Relocating Interference Frequency:* Relocating the frequency of an interfering source can largely resolve the IDC problem. For example, the LTE operating band can be relocated to a different channel that is further away from the Wi-Fi channel being used by performing a handover like operation.

3) Time-division multiplexing of LTE and Wi-Fi operation is another option.

In addition to the IDC problems, receiver desensitization is another common aspect of RF interference in IoT devices. This type of problem is manifested by a radio receiver being overloaded by interfering noise and unable to receive a weak radio signal that it might otherwise be able to receive without interference [20]. Typical interferences that can result in receiver desensitization may include noise from digital circuits, power/ground noise, other wide spectrum noise, and interference from other radios. With the continuous increase of data rate and bandwidth due to performance requirements, digital circuits used in the IoT devices such as processor, memory, I/O buffer, switch-mode power supply/converter tend to generate more noise due to device switching. Further, IoT devices often have a small form factor resulting in high design density. Thus, digital noise, often called platform noise, becomes the major source of interference that causes RF receiver desensitization.

Digital noise can couple to the RF antenna through various coupling paths or mechanisms. For example, the common mode of the liquid crystal display (LCD) signal from printed circuit board (PCB) to drive the LCD assembly though a flex PCB has a discontinuity in the return-current path at the flex PCB. This discontinuity can be modeled as a magnetic dipole moment, whose radiation is received by an RF antenna causing receiver desensitization [21]. This is a typical example of coupling through radiated paths, most likely in the near field region of the receiving antenna. In another example, the harmonics of a digital clock generated by a processor integrated circuit (IC) is radiated when it passes through a flex PCB where the return current is not well controlled, and the radiation is picked up by the FM antenna [22].

Digital noise can also couple to the RF antenna directly through conducted paths. For example, the harmonics of a digital clock generated by a processor IC, when coupled to the adjacent traces that are designed to carry audio signals and are connected to the FM antenna conductively, directly induce noise voltage in the antenna [22]. In many cases, the PCB ground plane is part of the RF antenna and carries antenna currents. In such designs, any noise current flowing in the ground plane can potentially induce noise voltage at the antenna [23].

Some coupling mechanisms are very complicated. For example, the transmitting RF signal coupling to the LCD driver IC, and then the baseband LCD noise is modulated with this RF signal, resulting in sidebands that fall into the receiving bands and then received by the RF antenna [24]. Passive intermodulation can also contribute to RF desensitization, so mechanical designs in IoT devices may need to be carefully investigated.

Debugging and fixing desensitization problems in IoT devices follow the general guidelines of typical interference problems. The underlying physics such as noise sources and coupling paths usually need to be fully understood before meaningful solutions can be developed. The desensitization problems can be mitigated by reducing the noise at its source, eliminating the noise coupling paths or making the coupling less effective, and making antenna designs less sensitive to noise. In addition, noise cancelling methods can be used, but the interference needs to be known in advance or in real time.

Digital noise may be generated by device switching. It can be categorized into radiated noise and conducted noise. The time-varying voltages and currents inside an IC can produce radiated fields. These kinds of radiated emissions from an IC can be mitigated by optimizing the IC layout and packaging design. Alternatively, shielding or package-level shielding [25] can be used to reduce the effect of IC radiated emissions. Noise can also propagate out from IC at the I/O and power/ground pins. These conducted emissions, when they couple to effective radiators or are directly connected to antenna structures, can also result in desensitization issues. Attention should be given to rise/fall times, and avoid using unnecessarily short rise/fall times when feasible. In addition, filters and careful circuit layout (ensuring return-current continuity and reducing crosstalk) can reduce the possibility of RF interference due to conducted emissions.

To model the desensitization problems, noise sources need to be characterized and represented in a manner so that they can be included in the simulation tool. The radiated emissions from ICs are often modeled as Huygens' equivalent sources [26], [27] or dipole moments [28], [29]. The conducted emissions are often modeled as an equivalent source with equivalent impedance based on their Norton or Thévenin equivalent [30]. After the noise sources are characterized, either full wave simulations of the PCB, chassis and antenna structures or a method based on reciprocity [31] can be used to estimate the RF interference received by an RF antenna. The received RF interference power will affect the IoT device in different ways. The degradation of the IoT device will depend on the interference characteristics and the IoT device technology.

For reliable IoT system operations, the regulatory bodies are still making effort to reduce the frequency overlapping among different radio systems. The current frequency allocation at the sub-6 GHz band for 5G system is a good example. By the definition of the ISM bands, several systems can use the same frequency band. In such cases, in the design of new IoT technologies, devices within the same IoT network shall use time-division multiplexing, power level controlling, and communication channel reallocation to reduce the interference to each other. Physical separation of different IoT systems is a brute force but effective way for reducing intersystem interference. Improving the sensitivity of the radio system can improve the coverage of the IoT system. The coverage improvement can possibly reduce the number of the IoT devices required in the covered area, and also reduce the interference among systems. Hence, receiver desensitization and IDC problems need to be identified and fixed in the design of IoT devices and the deployment of IoT system, to ensure a good user experience.

IV. IoT Immunity in Critical Environments

VANETs can enable communication among vehicles (vehicle-to-vehicle, V2V) and via roadside access points (vehicle-to-roadside, V2R) also called as Road Side Units. Intelligent VANETs use Wi-Fi IEEE 802.11p (WAVE standard) and WiMAX IEEE 802.16 for communication between vehicles with dynamic mobility. Those deployed communication technologies can be enabled as efficient methods to track automotive vehicles. Autonomous cars use a variety of techniques to detect their surroundings and navigation, such as radar, lidar, GPS, odometry, and computer vision. Advanced control systems will be employed for analyzing the sensory data for identifying appropriate navigation paths, as well as obstacles and relevant signage.

The automotive EMI sources can be unintentional RF sources inside and outside the vehicle, and intentional RF interference originated from RF transmitters. Lightning and background noises are broadband unintentional EMI sources. Intentional EMI sources may come from a ZigBee sensor's signal, cellular signal, or Wi-Fi signal from either a passenger in the car, or the vehicle's communication system for collecting traffic information through V2V or V2R, or the crosstalk from the active RF transmitter [47] (note that the carrier frequency may be the same or different depending which communication protocols are used). The overall composite thermal noise component, yielding from the vehicle's high data processing operations including digital signal processing, visual operations, and authentication computing for guaranteeing what received traffic information is authentic, is overlooked by any classic method, since it contributes little for detecting the intended signal in current applications. However, it cannot be ignored in the environment of the IoT.

The electromagnetic disturbance can interfere with sensors and electronic control units at the vehicle platform, and the V2V and V2R communication. A critical environment includes hospitals, with wireless signals for remotely monitoring patient conditions. These environments are similar to the current situation that passengers are requested to turn OFF their electronic devices when airplanes take-off or land in order to prevent interference to the navigation signals of the airplanes. IoT systems and networks amplify this scenario in much more grand scales and much more severe critical environments. Nevertheless, this should be considered as a challenge to the EMC community. In other words, how one can measure and test the compound interference from multiple IoT devices where each of them individually passes the FCC requirements. This can provide some guidance to other sectors and technical areas, which make IoT systems available and secure.

V. IoT OTA Measurement

OTA measurements are the standard methods to evaluate radio performance, including desense and coexistence, in IoT production stages (research and development, certification, mass production, etc.). EMI issues in system design such as interference, modulation, receiver desensitization, and coexistence need to be carefully addressed in the OTA measurement methodology for system level performance evaluations. The Cellular Telecommunication and Internet Association (CTIA) and the Third Generation Partnership Project (3GPP) have adopted OTA testing for total radiated power (TRP), TIS and throughput tests to evaluate 2G, 3G, 4G, 5G, and GPS device under tests (DUTs) [32], [33]. Besides TRP, TIS and throughput, OTA measurements can provide intermediate results for debugging and identifying EMC issues.

TRP is a figure of merit that characterizes the overall radiated performance of SISO DUTs [32]. It can be measured and calculated by integrating the effective isotropic radiated power (EIRP) sampled on a spherical surface surrounding the DUT according to the CTIA test plan, while the transmitter is working at its maximum radiated power. The EIRP values are the directional power levels emitted by the DUT, captured by the measurement antenna and measured with a high-precision instrument.

TIS is a figure of merit that quantifies a mobile device's capability of receiving a weak signal and determines the overall downlink performance of the terminal. Several TIS measurement methods are provided in [32]. The power-stepping method is the standard TIS test method. In this method, the TIS is obtained by performing the integration of the measured effective isotropic sensitivity (EIS) over a spherical surface surrounding the DUT. This measurement process is very time consuming, because the cumbersome bit error rate (BER) threshold searches are required at each sampling angle and polarization [32]. Besides the power-stepping method, the alternate TIS measurement methods improve the test efficiency by separating the TIS measurement into the receiver sensitivity and the antenna pattern measurements [34]. The receiver sensitivity is measured by the power-stepping method at only one sampling angle. The antenna pattern can be obtained by the RSSI techniques [34], the cofrequency-based method [40], or the BER curve-based method [38]. Since the time-consuming power-stepping process is only conducted once, and antenna pattern with finer scanning intervals can be acquired in fast and accurate processes, the alternate TIS measurement methods are more time-efficient and accurate.

Throughput is a figure of merit to evaluate the OTA performance of a MIMO device. It is measured in a multipath fading model established in a MIMO OTA test system. 3GPP approves only two standard methods for qualifying the MIMO performance: the multiprobe anechoic chamber (MPAC) method and the radiated two-stage (RTS) method [33]. In CTIA [32], MPAC is the only standard method and the RTS standardization is still in progress. Throughput tests are essential to evaluate MIMO devices, but ineffective to identify underlying EMC problems that compromise MIMO performance. The RTS method, reported in [35] and [43], is a more cost-efficient way for MIMO tests, and provides the foundation for a decomposition method to provide RF designers with the TIS value, desense, coexistence, the multiantenna patterns, the ECC, the antenna imbalance, and the radiated sensitivities. The RTS method only requires a SISO anechoic chamber, and its hardware implementation is simpler, compared to the MPAC method. Therefore, the RTS method has less test uncertainties, and the repeatability is less than ± 0.5 dB [45], [46].

Based on three types of IoT devices, IoT OTA measurements on desense and coexistence can be categorized into three groups.

A. Receiver/Transmitter-Only IoT Devices Measurement

The performance of transmitter only (like RFID) IoT devices is characterized by the TRP test. Normally, the TRP test is a direct power measurement. According to the CTIA test plan, when the transmitter is working at its maximum radiated power configuration, its radiated power, received by the sampling antenna, is measured with a spectrum analyzer or a measurement receiver.

In order to measure the TIS value of receiver only IoT devices (like GPS carrier-to-interference ratio, C/I), an OTA assistant reporter is needed to provide the EIS value at a sampled angle/polarization. Wi-Fi or GSM technology can be used as the assistant reporter to indicate the value of the EIS, which is like a GPS test using the Wi-Fi module to send back the carrier-to-interference ratio measurement data. The desense and coexistence for receiver only IoT devices can be measured based on the TIS test.

Take a GPS C/I direct measurement as an example [32]

$$C/I\,[dB] = P + G_{Tx} - PL + G(\theta,\phi)_{Rx} - I \quad (1)$$

where P is the input power into the transmitting antenna, G_{Tx} is the gain of the transmitting antenna, PL is the free space path loss between the DUT and transmitting antenna, $G(\theta,\phi)_{Rx}$ is the gain of the GPS receiving antenna and related RF circuit with spherical coordinate (θ,ϕ) pointing to the transmitting antenna, and I is the interference signal received by the DUT.

The tests of desense and coexistence are based on the TIS test. The evaluation can be performed by measuring the TIS value while activating digital and power systems and applying jamming signals. The work status of the digital and power systems can be controlled by diagnostic programs. The jamming and interference signals can be generated by test instruments or a waveform generator and applied by conducted or radiated methods.

B. SISO Devices Measurement

The radiated performance of the SISO devices can be evaluated by TRP and EIRP at specific angles and frequencies, which is similar to the transmitter-only devices. A typical SISO OTA measurement chamber is illustrated in Fig. 2. Unlike the receiver only TIS measurement, SISO devices can also be tested by the alternative TIS measurement, which is based on RSSI reporting [34]. In this method, the TIS can be obtained as

$$TIS = \frac{P_{signt\min}}{G_{\text{ave}}} \quad (2)$$

where P_{signtmin} is the radio sensitivity, and G_{ave} is the antenna average gain of the DUT. The radio sensitivity is independent of the antenna radiation angle [36].

Since the conventional TIS test (the power-stepping method) is very time consuming, the IoT devices may not have enough battery power to conduct power-stepping TIS testing without connecting power cables or changing batteries, which can introduce additional interference to the TIS, TRP and its radiation pattern measurement or bring in unexpected measurement errors. An alternative TIS test method can be applied with greater time efficiency. The time-consuming radio sensitivity measurement is only needed to be performed once and antenna gain measurement can be very efficient [34]. While maintaining the same test efficiency, the measurement accuracy of the RSS-based TIS test can also be improved to the same level as the slow traditional TIS test, by eliminating nonlinear errors [37]. Conventional TIS testing only covers three channels in a band; however, an entire band-sweep TIS can be measured without losing efficiency and accuracy [38]. The CTIA test plan requires maximum transmit power to evaluate the TIS. An alternative TIS measurement which considers the transmitting power level and thermal stability of the devices has been proposed in [39]. The TIS test efficiency can be further improved by utilizing the TRP test value with cofrequency transmitter and receiver [40].

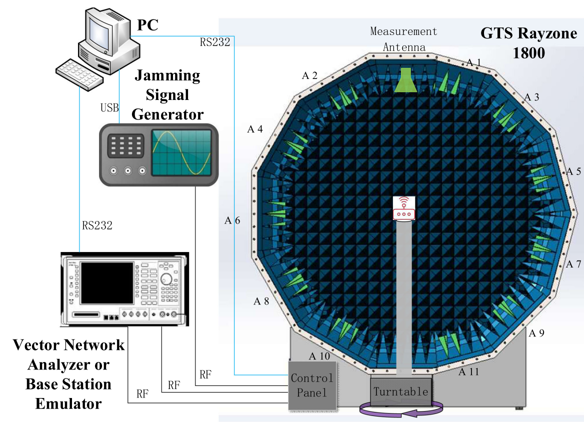

Fig. 2. Front view of a typical SISO test setup.

A general desense and coexistence measurement can be performed by the multiantenna chamber setup with suitable instruments and software illustrated in Fig. 2. Similarly, TIS is evaluated with digital and power systems functioning, and applied jamming signals. For SISO devices, this evaluation is time efficient by utilizing the improved TIS measurement methods mentioned above.

The work statues of digital and power systems are important in desense and coexistence testing. Taking Wi-Fi transmitter (2400–2497 MHz) interfering with LTE receiver (LTE TDD band 40, 2300–2400 MHz) as an example, simply connecting with a Wi-Fi access point may not have any adversely effect on the LTE TIS test. However, the TIS value may degrade while the DUT is downloading data via a Wi-Fi network.

C. MIMO Devices Measurement

In CTIA, throughput is a figure of merit for evaluating the OTA performance of MIMO devices, yet throughput is insufficient for desense and coexistence evaluation. Based on the RTS method for MIMO testing [35], [43], a decomposing MIMO OTA measurement method can be applied, and the TIS values for each corresponding antenna, and self-interference can also be measured. As shown in Fig. 3, this is a compact MPAC that

Fig. 3. Typical RTS MIMO test setup.

can perform RTS MIMO testing. With the improvement of the algorithm for determining the inverse matrix for the RTS MIMO OTA test in [41], and the elimination of reporting errors in [42], the diagnosis utility and measurement accuracy can be greatly improved.

The TIS calculated in [42] can be expressed as

$$TIS_x = \frac{4\pi}{\oint \left[\frac{G_{V\_x}(\theta,\phi)+G_{H\_x}(\theta,\phi)}{P_{rs\_x}}\right] \sin(\theta)\, d\theta d\phi} \tag{3}$$

where $G_{V\_x}(\theta, \phi)$ and $G_{H\_x}(\theta, \phi)$ are the xth antenna gains in two polarizations, and P_{rs_x} is the xth radiated sensitivity. The desense and coexistence can be modeled and measured based on (3) for MIMO devices.

In diagnostic measurements of desense and coexistence for MIMO devices, throughput may not directly reflect the performance of the receivers. However, the RTS MIMO test method can provide the TIS values for each antenna under specific test stress scenarios with digital and power system activity and jamming signals. This will effectively aid in diagnosing the desense and coexistence performance problems for MIMO devices. More details related to the RTS MIMO test method on IoT devices can be found in [44].

Besides an anechoic chamber measurement system, a reverberation chamber (RC) measurement system is also a fast and cost-efficient candidate for IoT OTA measurement. The RC is a shielded and highly reflective radiated test chamber. It is one of the standardized methods for measuring TRP and TIS of receiver/transmitter only and SISO IoT devices; however, it has not been included as the standardized method for the measurement of MIMO devices [33].

VI. Conclusion

The EMC aspects of IoT is reviewed in this article with emphasis on the receiver desense and system coexistence. The IoT devices are classified into three types of devices of transmit/receive only, SISO, and MIMO. The performance measurement methods for these three classes of devices are provided from the EMC diagnostic point of view. The high speed data processing operations including cryptographic computations add another dimension of interference in IoT systems.

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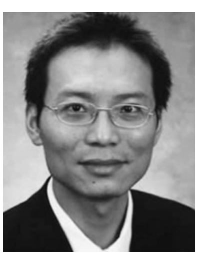

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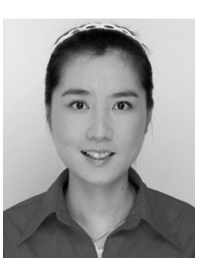

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