5G Internet of Things (IOT) Near and Far-Fields and Regulatory Compliance Intricacies

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Abstract—Internet of things (IOT) primarily consists of an instrumentation system that connects to the internet. Most modern applications of IOT would be integrated with wireless connectivity. Billions of sensing devices will be integrated with million types of wireless devices operating at varying frequency bands, power levels, and time intervals. Both intentional and unintentional radiations from the circuits of device instrumentation system, the collocated devices, and the operating environments can be higher than the operating sensitivity level of the wireless receivers. This paper reviews testability challenges of 5G IOT devices integrated with mmW and low frequency wireless. It also provides some insight on mmW near-field and far-field measurement challenges, and the necessity of radiated immunity evaluation. Lastly, it describes the theory used to explain the observation that the actual near-field or far-field starting distance is smaller than the calculated distance based on the overall dimensions of the massive MIMO antenna system and discusses the supporting experimental data.

Keywords— 5G; EIRP; TRP; Radiated Immunity; millimeter Wave (mmW); massive MIMO; Near and Far-Fields

1. INTRODUCTION

Most large and complex localized instrumentation control systems will be soon integrated with the internet. To effectively collect and transmit the data with low latency close to optical fiber, the 5G network is required. To process large amounts of data, make fast decisions, and solve complex problems at a lower cost, the IOT would be connected to the edge cloud or cloud network and utilize artificial intelligence. Most regulatory compliance emission requirements are established to minimize interference to the licensed bands including broadcasting services. The colocation and coexistence emission requirements are hardly considered. Coexistence is the ability of two or more spectrum-dependent IOT devices including other devices or networks to operate without harmful interference. Unlike preceding wireless technologies, in-network 5G will be deployed in a more coordinated manner. Established solutions such as a self- organizing network (SON) with self-healing and self-optimizing features will be used. These features include switching to interference free channels, coordinated transmit power reduction, changing receive and transmit time and protocols, bandwidth adjustments for avoiding interference and frequent reuse of frequency [1]. Therefore, deployment situations that may lead to collocation and coexistence interference will be minimized. However, out-of-network, non-cooperative devices, and unplanned installations will still be subjected to interference. Furthermore, instrumentation systems should be hardened to operate in noisy electrical environments such as the electrical grid, automated factories, nuclear plants, automobiles, airports, shopping malls, healthcare facilities, smart homes and other mission critical installations. Low level in-band and out-of-band noise typically affects the quality of the received signals. High level noise can disrupt the operation of the instrumentation system, and possibly cause permanent damage. Therefore, considering the low receiver sensitivity levels, intentionally generated wireless transmit levels, and the operating electrical noise environment, it is critical that immunity hardening must be considered not only at the compliance verification stages but also early in the design concept stage. This paper reviews the adequacy of present regulatory compliance requirements, test challenges, test chamber requirements and provides far-field distance validation methods.

II. GENERAL INSTRUMENTATION SYSTEM WITH WIRELESS CONNECTIVITY

While billions of devices and applications will be controlled or monitored through the internet using the wireless connectivity option, this could be limited by latency, availability of spectrum, radiated power restrictions, coverage distance and data handling capability. Some of the current open loop systems could be in the sleep mode most of the time and these would send a few small messages (up to 12 bytes) per hour or day. The 5G network is inherently built for the IOT [1] and backward compatibility. Therefore, the older connectivity technologies will be eventually phased out and replaced with newer cost-effective technologies such as 5G. The 5G network will be able to communicate with a large range of objects that have the capability for sensing and performing mechanical action. The 5G network will be designed to work not only with massive data transfers, but also with short-burst sessions of small packet transfers that do not consume significant network signalling and power resources. Large scale manufacturing and optimizable common platforms will render 5G IOT less costly over time.

A simplified electrical block diagram of a typical IOT application instrumentation [2] is provided below which consists of digital, wired and wireless parts. The compliance

assessment of the digital part may not be as complex as the wireless part. The digital compliance assessment must be carefully performed to make certain that any emanating radiation is not within range of the wireless operational frequencies of the device or collocated devices.
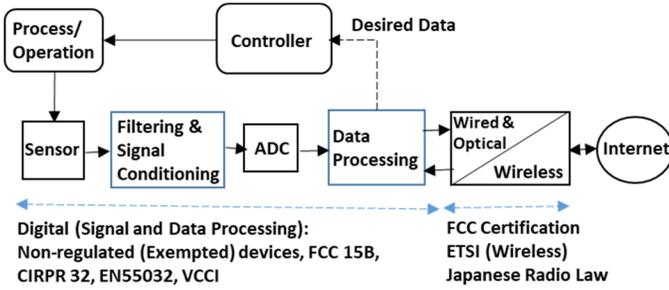

Fig. 1. Simplified Block Diagram of an IOT Instrumentation System

Most digital devices are evaluated up to 40GHz for FCC compliance, however, CE and VCCI (Japan) compliance evaluations are limited to 6GHz. Digital device radiations could be narrow or broadband. Although the digital devices may meet the most stringent class B limits, this does not guarantee interference free operation of a wireless device. For example, at 5 GHz, the CISPR 32 Class B limit is 54dBµV/m/MHz at 3m distance which is equivalent to an EIRP level of -41.2dBm/MHz at the digital device. A typical wireless device can operate at a sensitivity level of -95dBm/MHz [3]. If a digital device just meets the class B requirements at 5GHz, then it should be installed at 489m away from the wireless device operating at 5GHz, to avoid potential interference. In most countries, wireless integrated instrumentation systems are evaluated using less stringent wireless device emission requirements. In Japan and USA, digital device compliance and RF immunity hardening are voluntary [4]. However, both digital and wireless emission and RF immunity hardening requirements (up to 6 GHz) must be met for CE marking.

III. MILLIMETER WAVE (mmW) DEVICE COMPLIANCE AND NEAR-FIELD CHALLENGES

IOT devices will use mmW frequencies because they would be physically small, a larger number of small antennas can be used which facilitates easier beamforming, consume less power, can be configured to operate at large and small bandwidths, can have variable beam patterns and can accommodate data rates comparable to optical fiber. Because the wavelength is very small when compared to the overall size of the antenna system, a general presumption is, characterizing them at the far-field within a typical anechoic chamber would be difficult. The following paragraph describes the theory with experimental data that proves the near-field or far-field starting distance is smaller than the calculated distance based on overall dimensions of the MIMO antenna system.

A. Near-Field and Far-Field:

Beyond the near-field regions, the free-space angular distribution of radiating fields is independent of the distance from the antenna and is called the far-field region. The

boundary of this region is not strictly defined; however, it is commonly accepted that the radiating near-field extends to

$$2D^2/\lambda \qquad\qquad \text{——— (1)}$$

where,

D is largest dimension of either the transmitting or receiving antenna aperture

The largest linear dimension of a typical patch antenna used in massive MIMO is $\lambda/2$. If the largest linear aperture dimension (D) of measurement antenna is $\leq \lambda/2$ of path antenna, then, the far-field distance of a single patch antenna occurs at

$$2D^2/\lambda = \lambda/2 \qquad\qquad \text{-------- (2)}$$

The electric field termination in a massive MIMO antenna system is a complex matrix. In-phase power of several individual antenna beams must be combined to increase the EIRP of a MIMO antenna system. The overall linear dimension of the antenna system is typically used for calculating the far-field distance.
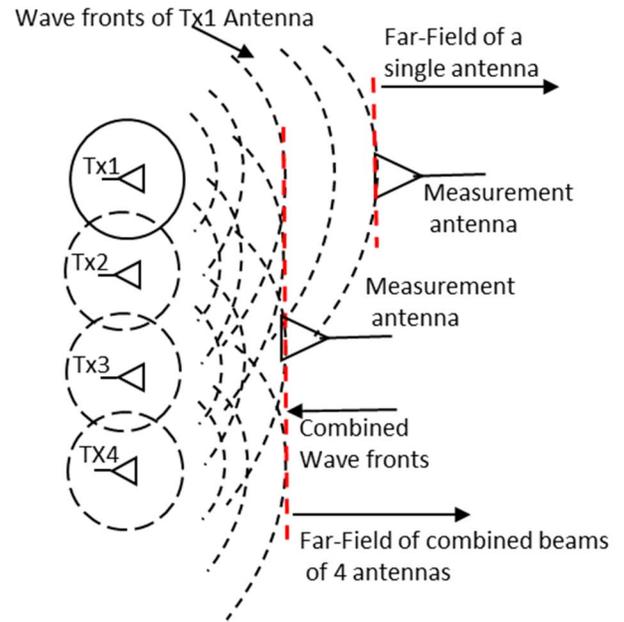

Fig.2. Near-field and Far-field Starting Distance of a MIMO Antenna System

B. Schelkunoff Equivalence Theorem for Massive MIMO Far-Field Distance:

According to the Schelkunoff equivalence theorem, the field on an imaginary closed surface can be obtained by placing a small equivalent electric and magnetic densities on the surface [5]. This principle is based on Huygens theorem which states that each particle in any wave front acts as a new source of disturbance, sending out secondary waves, and these secondary waves combine to form the new wave front. In a beamforming of MIMO antenna system, each individual antenna can be considered as small equivalent sources which would produce individual secondary waves. Using the converse of Schelkunoff equivalence theorem, the in-phase overlapping secondary

waves should combine to form a new larger wave front. A measurement antenna would intercept the less angular (flatter) field when the wave front is large (larger circumference).

As shown in Figure 2, for a measurement antenna larger than the individual antenna, each standalone MIMO antenna produces less angular (flatter) fields at a larger distance. However, the combined wave front produced by a group of antennas yields a flatter wave front at a distance closer than the standalone antenna. However, for a typical n x n matrix massive MIMO antenna system, the elements are separated by a distances of $\lambda/2$ to $(2n-1)\,\lambda/2$. The interaction of field is much greater between adjacent elements than it is for more distant elements. Additionally, the largest linear dimension of measurement antenna is typically greater than the single patch antenna element [6]. Therefore, the far-field is expected to be much smaller than the distance calculated from the overall dimensions of the n x n antenna but not smaller than the distance calculated from the single element.

A far-field occurs when a receive antenna intercepts a flatter field. Since antenna gain and Friis free-space propagation loss equations are valid only for the far-field, the EIRP of a device antenna must be constant at any far-field distances.

EIRP at the device antenna = Level at the measurement antenna + Free space propagation loss (L)   ----------- (3)

$L = 20\log_{10}$ (measurement distance (D) from the device antenna in meter) + $20\log_{10}$ (frequency in MHz) – 27.56 dB   --- (4)
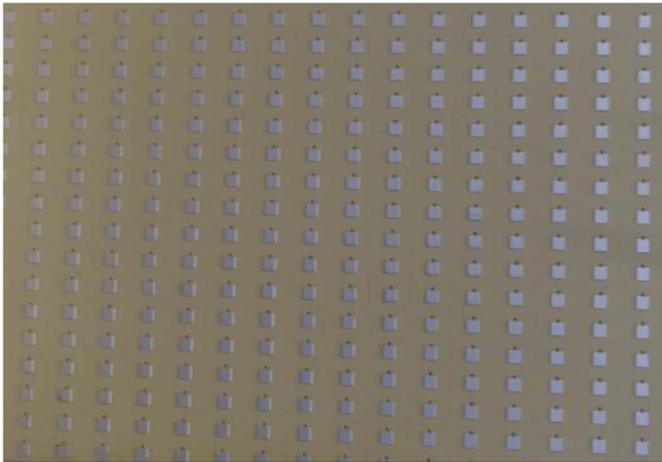

Fig. 3. Photo of Patch Antenna Evaluated

C. Far-Field Measurement on a 16 x16 Patch antenna system

The far-field distance of a micro Base Transceiver Station (BTS) equipped with a16x16 patch antenna system (see Fig. 3) having an overall dimension of 13.4 cm (L) x 8.3 cm (W) was tested at 28 GHz using a 1.8 cm x 1.4 cm standard gain antenna.

Test conditions & procedure:

- The tests were performed in a 10 m anechoic chamber.

- The BTS was installed 1.5 m above the ground plane.

- All patch elements were excited to transmit on a single distinct beam at a maximum EIRP level of 22.5 dBm/MHz.

- Initially, the measurement antenna was positioned at 450 cm from the transmit antenna. RF absorbers were placed at the measurement area ground plane to create near free-space. The measurement antenna was bore sighted to the transmit antenna.

- Measurements were made using a spectrum analyzer that was connected to the measurement antenna. The EIRP level was calculated from the spectrum analyzer reading.

- EIRP = Spectrum Analyzer Reading + Measurement antenna cable loss + Free space path loss – Measurement Antenna Gain.

- The measurement antenna was then moved towards the transmit antenna in several increments of decreasing distance to a final position of 20 cm. For each of the distances, the measurement antenna was bore sighted to the transmit antenna and the analyzer reading was recorded. The calculated EIRP was plotted in Graph-1.

Based on the patch antenna system length (L) = 13.4cm, the far-field should occur at 3.35m (335cm), and if the patch antenna system diagonal distance is considered, the far-field should occur at 4.6m (460cm). The plotted EIRP with respect to the measurement distance in Graph-1 shows that the measured EIRP is constant beyond 90 cm. Therefore, the far-field starts at approximately 90 cm based on the measured data, and is shorter than the calculated theoretical distance based on the overall dimensions of the massive MIMO antenna system.

IV.   FAR-FIELD VERIFICATION METHOD

The measurements in the near-field of real a product is more complex than the measurement antennas. The field pattern may vary from point to point. Consequently, the measurement accuracy in the near-field is questionable. The measurement-antenna factor and gain that are calibrated at the far-field cannot be used for the near-field. The radiated emissions measurements for compliance are performed at either a 3m or a 10m distance. The field radiated from the device can be in the near-field or far-field depending on the measurement distance, radiation aperture and frequency. Neither the substitution method [7] nor direct measurement will provide near or far field information unless measurements are verified at distances other than the legal measurement distances. If the sum of the measured field value and propagation loss at different distances is approximately constant, then the measured value is in the far-field [8]. This procedure is only applicable for free space measurements and takes additional testing time. However, for emissions closer to the limit and identified as a potential for interference for IOT devices, using this far-field validation method would help in accurately analyzing its probability for interference.

A massive MIMO antenna system where antenna elements are typically arranged in a matrix is used in mmW 5G transmitters. Efficiency of RF components decreases with the increase of frequency. At the mmW frequencies, developing high power amplifiers would be expensive. Therefore, distributed low power amplifiers are used. The antenna system is permanently integrated into the distributed transmitter terminals to reduce interconnection losses. In addition to the conventional radiated emissions testing, the conducted emissions test that are performed on the antenna ports must be performed Over-The-Air (OTA). Traditionally EIRP levels were computed based on antenna port conducted spurious, in-band power levels, antenna beam width and beam pattern. EIRP levels can determine interference potential in a particular direction. Now, certain mmW frequencies, TRP [9] levels are the determining factors for FCC and EU compliance.

A radiator enclosed in a spherical shell having large radius r, the total radiated power

$$TRP = \int_0^{2\pi} \int_0^{\pi} \Phi\left(\theta, \phi\right) \sin\theta \, d\theta \, d\phi \qquad ----- (5)$$

Where $\Phi(\theta, \phi)$ radiated power at each angle, Watts/Steradian

Since r is assumed to be large, then Φ is independent of r. Therefore, distance r must be in the far field.

$\Phi_{average} = TRP/(4\pi)$ (averaged over the surface area of the sphere)

Expressing TRP in terms of EIRPs measured at several angles around the surface of the sphere, then

$$TRP = (1/4\pi) \int_0^{2\pi} \int_0^{\pi} EIRP\left(\theta, \phi\right) \sin\theta \, d\theta \, d\phi \qquad ---- (6)$$

Numerically,

$$TRP \approx \frac{\pi}{2NM} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \left(EIRP_\theta(\theta_n, \phi_m) + EIRP_\phi(\theta_n, \phi_m)\right) \sin\theta_n$$

Where, NM is total number of points evaluated around the EUT in the far-field in azimuth (ϕ) and elevation (θ) planes. It is obvious that there is a discrepancy between equation (5) and (6). If the radiation pattern of the small devices with near isotropic pattern as defined in CTIA [9], then the results of both equations would be equal. However, equation (6) has been adopted for licensed mmW devices.
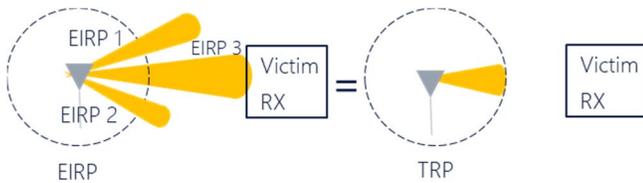

Fig. 4. EIRP and TRP Interference Potential Comparison

For example, TRP calculated from EIRPs of three beams as shown in Fig. 4 would yield a TRP level much lower than the maximum EIRP level. Based on the TRP data, potential for interference evaluation would be impossible.

## VI.	MILLIMETER WAVE RADIATED IMMUNITY

The 5G devices will be installed in a coordinated manner. However, devices that are not within a coordinated cluster, unplanned collocation installations, non-cooperative devices, damaged or inadequately shielded devices, and devices with uncontrolled wider receive bandwidths will be affected by the in-band noise sources. Radiated immunity test levels for 5G devices are first recognized and recommended in Telcordia GR 1089 [10]. Four radiated immunity levels are indicated based on receiver sensitivity and blocking ability; 5G devices with integrated antenna; and digital devices operating in 5G environment. The proposed levels are indicated in Table 1 below. At present, the test is limited to all FCC authorized frequencies up to 40 GHz only.

ETSI standards allow exclusion bands which are in-band frequency ±10%. However, GR 1089 does not have exclusion bands. The in-band immunity data is important for deciding coexistence capabilities and collocation distances of the spectrum sharing devices. For GR 1089, the test shall include in-band frequencies. However, throughput degradation is allowed and the threshold of failure shall be recorded in the test report.

Table 1: Test Levels

Severity Level	Immunity test Level (V/m)	Test Distance (m)	Notes (recommended Environment)
Level -1	0.1	1	Wireless devices with integrated antenna
Level -2	1	1	Wireless devices with detachable antenna
Level -3	3	1	Digital devices that uses or generate frequencies above 24 GHz
Level-4	10	1	Special request from the User

## VII.	CONCLUSIONS

Controlling emissions and RF immunity hardening of IOT devices must not only be considered during the device design concept stage, but also during installation. 5G will a use wide variety of licensed and unlicensed spectrum. Both electromagnetic emissions and immunity hardening data should be made available to installers for planning an interference free operation of the devices. For critical installations, an electromagnetic site survey must be performed. Based on the TRP data, potential for interference evaluation would be impossible. Far-field data can be reliably used for predicting an electromagnetic environment. This document provides some insight on predicting far-field distances of MIMO and massive MIMO devices and antennas. This document also provides theory and data to prove that the near-field or far-field starting distance is shorter than the calculated distance based on overall dimensions of the massive MIMO antenna system. Therefore,

large anechoic chambers are not required for evaluating massive MIMO antennas in the far-field.

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Graph -1