Automatic Restriction of Radiated Power in 5G Handsets based on Proximity Detection to Comply with Exposure Limits

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***Abstract* — Several strategies for limiting the radiated power in 5G handsets to meet regulatory limits are surveyed, with focus on an approach wherein the proximity of a human is sensed through built-in power measurements of the handset's transmitted signal and its reflections. The measurement system is based on directional couplers and power detectors that are placed in the transmission paths leading to the device's multiple antennas. The employment of such strategy is intended to ensure that the transmitted power is restricted only when there appears to be a human at risk, while otherwise allowing unrestricted transmission power and uncompromised up-link performance.**

***Index Terms* — ICNIRP, EMF exposure, specific absorption rate (SAR), power density (PD), regulatory compliance, body proximity sensing (BPS).**

I. Introduction

The multi-GHz wide millimeter wave (mmW) frequency bands made available to fifth generation (5G) cellular networks and user equipment (UE) in the range 24.25 - 52.6 GHz, known as Frequency Range 2 (FR2), have provided networks with higher overall capacity, and allowed mobile devices to reach higher data throughputs per user. To support the high data-rate communications in the up-link (UL), mobile devices may need to transmit at relatively high effective-isotropic-radiated-power (EIRP), for their signal to be received at a sufficiently high SNR by the base-station. This is typically achieved through the use of multiple transmit paths that are coherently summed in a phased-array, a structure that allows for beam-steering towards the optimal direction, effectively achieving higher power density in the desired direction, i.e., directionality. This is highlighted by equation (1), where N represents the number of coherent paths, P_{TX} represents the output power produced in each of them, given in dBm, and G_{TX} represents the gain of the antenna element terminating each of them, given in dBi.

$$EIRP = P_{TX} + G_{TX} + 10 \cdot logN^2 = P_{TX} + G_{TX} + 20 \cdot logN \qquad (1)$$

The N^2 gain factor is achieved through the combination of the coherent addition of N signals and the increase in directivity of the resultant beam when compared to that of a single element. For example, a beamforming transmitter based on N=4 paths that each produce P_{TX}=16 dBm (40 mW) into an antenna element of G_{TX}=2 dBi could create a beam of $EIRP$=30 dBmi. (The dBmi unit is used to distinguish the EIRP from conducted power, measured in units of dBm, as suggested by NIST in [1]).

While beamforming offers advantages in addressing propagation challenges and in reducing interference, phased-array transmitters pose various challenges associated with their testing and characterization, including measurements intended for regulatory compliance verification. Contrary to the testing of legacy transmitters, based on a single output and antenna element, which could rely on 'conducted' measurements, where the output power was measured directly at the transmitter's output and the antenna gain was accounted for separately, the testing of phased-array based systems requires over-the-air (OTA) measurements of greater complexity. This also includes regulatory tests that are performed for the purpose of verifying that the emissions from the device can be considered safe.

A common measure associated with this risk is the specific-absorption rate (SAR), expressed in W/kg, which is typically measured with the use of standardized models of the human head and body that are filled with liquids having absorption characteristics similar to those of different human tissues [2]. For 5G devices operating in the FR2 mmW bands, where lower penetration and absorption in human tissue is experienced, regulatory limits have been set on the average power density (PD), expressed in W/m^2, that a user may be exposed to over a specific time period.

II. Meeting the PD Regulatory Limit

In the realistic example from the previous section, with the handset's beam of 30 dBmi, the limit of 43 dBmi allowed for handsets as per the 3GPP standard is met with a significant margin [3]. This limit, specified in the 3GPP standard for Class 3 UE (i.e. handheld devices), is derived from Part 30 of the Code of Federal Regulations of the United States' Federal Communications Commission (FCC), specifying the allowed limits for mobile devices [4]. However, despite meeting this limit, when placed close enough to the body, this beam could exceed the power-density (PD) limit of 10 W/m^2 (equivalent to 1 mW/cm^2) for exposure to electromagnetic fields (EMF) in this frequency range, which was set forth by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the FCC [4]-[6]. Since this limit is specified for continuous emissions, whereas the transmission of a cellular handset typically has a duty cycle of operation that is well below 100%, higher instantaneous power may be transmitted, as long as the average power within any 4-second interval does not exceed that limit. Therefore, to be able to correctly adjust the device's EIRP to within the *maximal permissible exposure* (MPE), while minimizing degradation in the performance of the communications link, it must consider its output power setting at all transmission instances, as well as their total durations. This capability is provided by a time-averaging-SAR (TAS) algorithm, which ensures that the regulatory limits are met while also allowing dynamic control of the transmission power that is driven by the needs of the communications link.

In the absence of information on the location of humans in the device's proximity, it must assume a worst-case scenario of human proximity to the emitting element, within a distance that is only as large as the separation provided by the device's housing (i.e. a few millimeters). This is demonstrated in the measurement setup shown in Fig. 1, which is used during regulatory testing, and in Fig. 2, showing that the probe used for such testing is capable of measuring the field within 2 mm from the device's housing (the probe's tip is 0.5 mm from the device's boundary, and the sensor is located 1.5 mm from the probe's tip).

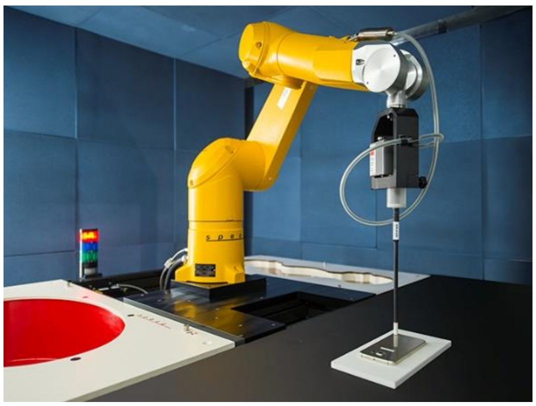

Fig. 1. Power density (PD) measurement setup based on robotic arm holding near-field EM probe (EUmmWV2, offered by SPEAG) for measurement of a device's emissions (from speag.swiss website).

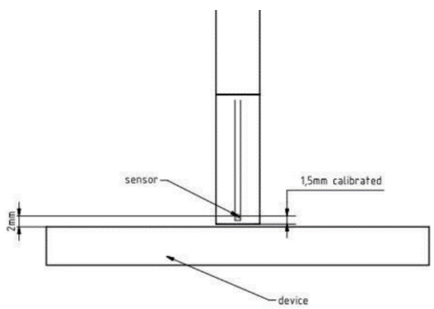

Fig. 2. Sensor of near-field probe measures the electric field within 2 mm distance from the boundary of the device-under-test (DUT).

At such proximity, to comply with the PD limit of 1 mW/cm^2, i.e. 40 dBm/m^2 (averaged over an area of 4 cm^2), the average EIRP of the device may have to be limited to below 15 dBmi, which in some scenarios, depending on the required throughput and distance from the base-station, could potentially compromise the link performance. However, if the device were capable of reliably determining the absence of humans within a range of about 20 cm, it could allow its transmitter to operate at full power (30 dBmi in each polarization in this example) and at a duty cycle of up to 100%, for which it would still maintain about 5 dB of margin from the FCC limit, as shown in Fig. 3. As can be seen in Fig. 3, at the minimal distance of 2 mm, the FCC limit is exceeded by about 15 dB for EIRP=30 dBmi, requiring a reduction of 15 dB in average power for compliance. Slightly beyond the distance of 10 cm this transmitter is shown to be compliant with the limit.

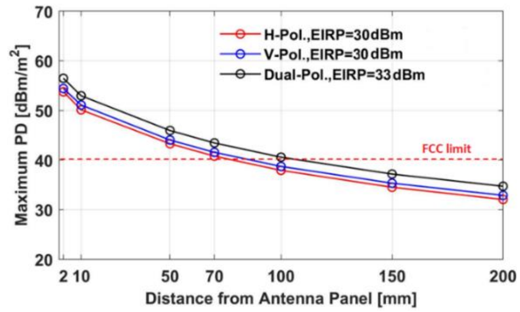

Fig. 3. Estimated power density (PD) versus distance for a device operating in FR2 capable of reaching EIRP=30 dBmi in both horizontal and vertical polarizations, adding up to a total of 33 dBmi.

With the implementation of a solution for body-proximity detection, the measurement of PD, performed via a patch of 4 cm^2 area, may assume a greater separation distance d_{sep} to the phantom representing the human, as shown in [6].

For a device having beamforming capabilities, compliance would have to be validated for all possible beams, as demonstrated in [10]. If, for example, a beamformer is capable of steering to 3 different angles spaced 22.5° apart in both directions from the boresight, then a total of 7 different beams would have to be considered, as shown in Fig. 4. When considering that a module may support transmission in both horizontal and vertical polarizations, as well as their combined operation, a total of 21 beams would have to be evaluated. In order to reduce the overall regulatory testing time that this requires, the FCC may accept simulation results in place of some of the compliance verification measurements.

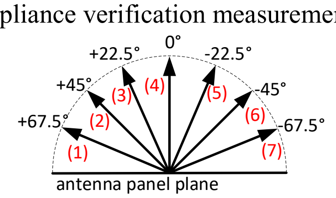

Fig. 4. Example of beamforming capability in a handset, showing 7 different possible directions for transmission in one plane (one-dimensional phased array shown with 22.5° steps).

It should be noted that high duty cycles for the up-link (UL) direction are not very common, as the use of high UL throughputs is limited to scenarios such as high-definition video streaming, or 'hot-spot' operation, where the UE serves as a gateway to the web, potentially for multiple users. The more common applications, involving voice or data/streaming have relatively low UL duty cycles. Based on the actual duty cycle, as well as the peak power being used, which depend on factors such as the data-rate and link losses at that particular scenario, the device may determine the appropriate extent of required maximum-power-reduction (MPR) for a particular proximity, as is shown in [9].

Table 1 shows an example of this, where MPR is required for all EIRP levels listed for a transmission duty cycle of 100%, but is only required in the higher ones when the more realistic duty cycle of 20% is assumed. Furthermore, for those higher power levels, the MPR required for the 5× lower duty cycle is 5× (7 dB) lower.

Table 1 – Estimated required MPR to comply with the 40 dBm/m^2 limit at a distance of 2 mm from the antenna plane

Peak EIRP [dBmi]	Required MPR [dB]	
	100% duty cycle	20% duty cycle
15	1	–
20	6	–
25	11	4
30	16	9

Since the average EIRP is determined over an evaluation period T_E (set at 4 s for MPE, as previously noted), it may be reduced not only through lowering of the transmitter's peak power, which may be impractical, but also through reduction in the duty cycle of the transmission. This is evident in the averaging integration operation representing the compliance condition expressed in inequality (2), where $PD(t)$ represents the instantaneous power-density and PD_{limit} represents the compliance limit (1mW/cm^2). While a lower UL duty-cycle results in lower UL throughput, it does not impact the link robustness as much as the reduction in UL peak power could.

$$\frac{1}{T_E}\int_{t-T_E}^{t} PD(t)dt < PD_{limit} \tag{2}$$

III. Reliance on Body Proximity Sensing (BPS)

The ability to accurately determine the proximity of a human, for example to within ±2 cm of error, could allow the implementation of MPR to be limited to what is necessary to meet the 40 dBm/m^2 limit, while minimizing unnecessary compromises in the UL performance that would result from an overly restrictive approach. The validation of a device that relies on BPS may require that different operating scenarios and proximities be considered/tested in order to verify proper operation of the proximity sensing mechanism and the associated MPR algorithm [7]-[8]. In practice, a device may employ a simplified strategy, wherein it distinguishes between only two proximity scenarios: close distances that may require MPR and 'safe' distances, where a device may be allowed to operate without restricting its EIRP. Such approach would have the drawback of potentially sacrificing more of the UL performance than is justified by the actual proximity, but it would be simple to implement and validate.

Various techniques may be employed for proximity sensing, including thermal sensors (as demonstrated by Motorola's IHDT56XL1 Mobile 5G MOD device), capacitive sensors, and radar. In the 3GPP submission from Apple, a pulse-based radar system is proposed, which could measure the distance to a nearby body [9]. In that proposal the transmitted sensing pulses are to be limited to gap instances during which the 5G FR2 radio would not be operating and would not experience interference, and the level proposed for those pulses was set below the limit allowed for spurious emissions. The assumption was that this limit was set such that no noticeable interference could be caused by emissions at such level. However, spurious levels set for intentional emissions consider practical implementation constraints and could therefore be somewhat lenient, with the assumption that these emissions would be present only during the transmission instances of the device, whereas the levels allowed for intentional emissions, as the BPS transmissions would be, are set with different considerations. Furthermore, spectrum allocation for cellular communications may not be assumed available for sensing purposes. In this context, it should be noted that following the FCC's Notice of Proposed Rule Making from 2021, the band 57-64 GHz, which has been allowed for license-exempt communication systems (such as WiGig) has recently been made available for radar/sensing applications as well [11].

IV. BPS Based on Measuring Reflected RF Power

A. Principle of Operation

A BPS solution based on the detection of the reflected power from a nearby target was demonstrated in [12], where a 4-port bidirectional coupler was used in the transmit path, as shown in Fig. 5. The results presented there showed detection capabilities up to 10 mm, including some ability to distinguish between different types of targets. While this was demonstrated below 1 GHz, a similar system may be implemented in the FR2 band, based on the same structure. In the 4-port bidirectional coupler shown in the block diagram in Fig. 5, port 3 is intended to provide a sample of the incident (forward) power delivered from the PA to the antenna (fed through port 1), and its output signal is therefore denoted P_{fwd}, whereas port 4 is intended to provide a sample of the reverse power reflected from the antenna, which enters the coupler through port 2, and is therefore denoted P_{rev}. Depending on the proximity of the target, both these samples may be impacted, and their evaluation, preferably in complex form (i.e. including phase), could reveal the presence of a nearby object.

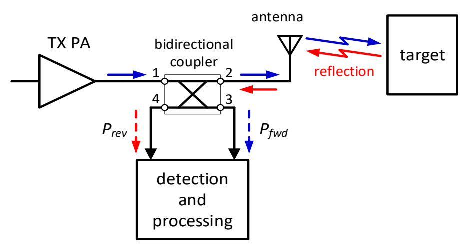

Fig. 5. Target detection system based on a bidirectional coupler providing samples of incident and reflected TX power.

The reverse power from the antenna, shown by the red arrow entering port 2 of the bidirectional coupler, may be represented as a vector sum of two signals: (1) the signal originating from the electromagnetic reflection from the target and (2) an electrical reflection from the antenna, which depends on the impedance matching at that point, i.e. the antenna's return loss. While the former is the signal of interest that the BPS system is intended to detect, the latter can be regarded as an interferer that would need to be separated from this sum as part of the detection algorithm. A similar concept is shown in [13], where two separate antennas are used for the transmission toward the target and the reception of the reflected signal from it. There the leakage signal from the TX to the nearby RX antenna (or 'spillover', in radar terminology) acts as the interferer, which is estimated and subtracted from the received signal so as to isolate the signal of interest, i.e. the reflection from the target.

B. *Experimental Results*

Several experiments were conducted with various targets placed at distances up to 30 cm from the boresight of a beam in the FR2 bands with EIRP below 30 dBmi. These have shown that based on the implementation of the detection circuitry (dynamic range, sensitivity) and the signal processing algorithm, the reflected signal from the target may be detectable, while also providing a sufficiently low probability of false positive detection. Such result was observed not only with a metal plate, which is naturally reflective, but even with human targets (hand and head), which reflect a portion of the incident signal back towards the UE, depending on the shape and position of the target. In an experiment setup, where a horn placed at a distance of ~1m was used for EIRP calibration, in addition to monitoring the signal reflected back at the device, the obstructed transmission was also recorded (shown in the dashed blue arrow in Fig. 6). In the scenario shown in this figure, where the human head was in the boresight of the antenna array at a distance of 30 cm from it, the signal level received in the horn antenna was reduced by about 20 dB. In an actual communications link, where such loss would be experienced not only in the UL direction but also in the downlink (due to reciprocity), this will likely trigger beam steering towards a preferred direction, where this obstruction would not be experienced. This adaptivity may also be viewed as a safety feature, although that's not its primary purpose and the device's regulatory compliance does not rely on it.

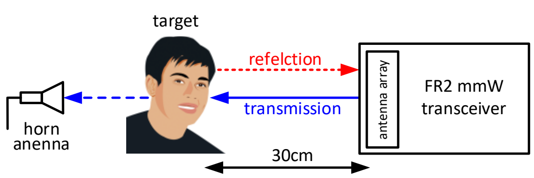

Fig. 6. Experimental setup with human head placed in boresight of a handset's mmW module, obstructing its reception in a horn antenna.

V. Conclusion

The EMF exposure limits set by the regulatory bodies for 5G cellular handsets operating in the mmW bands require that the power density averaged over an area of 4cm^2 within a duration of 4 seconds be limited below 1mW/cm^2. To ensure compliance with this limit, the device may limit its transmission power and duty cycle, thereby potentially sacrificing uplink (UL) performance. However, a handset may be permitted to operate at higher transmission power and duty cycle if it is capable of reliably determining that a human target is at a distance where the PD does not exceed the regulatory limit.

A possible cost-effective implementation for proximity sensing may be based on the detection of a reflected signal from the human target, allowing the device to distinguish between scenarios when it is held close to the body and scenarios where it is placed at a safe distance, where it may transmit at higher power and duty cycle to support high UL data throughputs.

The directional nature of the 5G handsets' mmW beamformed transmission, their ability to switch/redirect beams when obstructed, and their capability to detect the proximity of humans and to adjust their average EIRP accordingly, allow them to become more efficient and devices than their previous-generation predecessors, where omni-directional high-power transmission was used.

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