Project: **SEAWave**

Report on Preliminary End-User Device Evaluation

Work Package: WP 4

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Abstract

Deliverable No. 4.1 is the first deliverable of work package 4 (WP4) with the objective to provide early input data for WP5–7 with respect to exposure signal characteristics through theoretical considerations and experimental evaluation of FR2-enabled devices. This report documents the completion of Deliverable 4.1. The signal characteristics are chosen for the exposure setups in the *in vitro* studies, *in vivo* studies, and human studies in Work Packages 6, 7, and 8, respectively. Justification for the signal characteristics are provided based on the a review of commercially available 5G NR FR2 devices on the market. To provide the necessary background for this Work Package, the regulatory and standards framework are laid out, and the fundamentals of 5G NR FR2 and techniques for exposure control are described. A preliminary exposure evaluation study has also been conducted.

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Contents

1 Introduction

1.1 State-of-the-Art

Exposure from handheld and body-mounted devices dominates the overall average exposure of users and bystanders across 2G - 4G technologies regardless of network topology [11]. Knowledge of end-user device exposure is critical not only for demonstrating compliance with the regulation, but also for understanding of population exposure as a function of network topology and device use. The tools and procedures for determining maximum exposure and demonstrating compliance of handheld and body-mounted mobile devices and base stations operating below 6 GHz have been successfully developed and standardised; they are widely used and can be directly applied to FR1 [44], [45]. However, to date there is no standard for demonstrating compliance with the new basic restriction of absorbed power density (APD). There are also no established procedures for assessing exposure from devices with second-generation exposure managing features, such as time-averaged absorbed power density (TAPD) and proximity sensors. While the joint working groups of IEC and IEEE (JWG- IEC/IEEE), of which P4, P3, P12, P13, P14 are active members, have begun to develop standards, there is still a lack of publicly available specifications and technical reports to demonstrate compliance of 5G devices. WP4 will provide a fundamental contribution to the standards. CENELEC is eagerly awaiting the completion of the IEC standards, and without them the EU cannot harmonize the standards for FR2 devices. Yet, harmonized standards, with which all devices must comply, remain an important pillar of meaningful risk communication.

1.2 Objective

WP4 will provide the necessary instrumentation, test and validation procedures required to demonstrate compliance of FR2-enabled 5G devices with the latest safety guidelines [8], i.e., for (i) measuring APD; (ii) assessing the maximum exposure case for MIMO transmitters; (iii) demonstrating that the TAPD operates as indented in any device configuration. The results will be disseminated to the corresponding JWG-IEC/IEEE while SEAWave is still in progress to facilitate timely adoption by IEC/IEEE and later by CENELEC and the EU. Equally important, WP4 will provide the necessary input for WP5–8 and is essential for risk assessment and risk communication (WP9–10).

1.3 Methodology

In WP4, new probe technologies and test methods will be developed to determine the maximum exposure of beamforming antennas in experimental phantoms without having to measure all beam configurations. This will require not only magnitude but also phase information of the induced field. In addition, input from WP5 will be needed to develop the appropriate experimental phantom. WP4 can build on the published research results of P1 and P4 [46]–[49] and the 'Module APD' project funded by Innosuisse (Switzerland) but requires additional R&D effort to be applicable to devices with MIMO transmitters. Novel test procedures will also be required for a comprehensive evaluation of TAPD features, which can be combined with power, beamforming, antenna tuning, antenna selection, and proximity management. First, a prototype instrumentation will be developed and tested. Second, the zero-series probes and phantoms will be built and integrated in the DASY8 dosimetric measurement platform which will be validated using generic sources and sources obtained from leading manufacturers of advanced proximity sensing and transmitter modules (Semtech (Switzerland), Qualcomm Inc. (USA), MediaTek Inc (Taiwan)). The developed measurement system and procedures will be made available to government agencies, industry and test laboratories before the end of SEAWave. In parallel, results will be disseminated to IEC and, indirectly, to CENELEC early in the process to facilitate timely adoption with the ultimate goal of achieving a harmonised EU standard.

1.4 Goal of Sub-Workpackage WP4.1

WP5–7 needs early input of signal characteristics, exposure and transmission of FR1 and FR2 enabled devices today and at end of the project. This information is needed at the beginning of the project, i.e., much before the instrumentation and methodology for exposure and up-link assessment according to the new guidelines is completed. Therefore the objective of WP4.1 is to perform a preliminary evaluation through theoretical considerations and experimental evaluations.

2 Basic Restrictions of Exposure Guidelines and Regulators

This section reviews the regulatory landscape for human exposure to electromagnetic (EM) fields at frequencies above 6 GHz. Limits for localized exposure are provided, as these are more relevant to this project than whole-body exposure. Regulatory limits for human exposure to EM fields typically follow international guidelines by IEEE ICES (International Committee on Electromagnetic Safety) [1] and ICNIRP (International commission on Non-Ionizing Radiation Protection) [2], although there can be delays their implementation by national regulatory bodies. These guidelines were revised in 2019 and 2020, respectively, incorporating novel and updated exposure limits for exposure in the millimeter wave frequency range.

The EM exposure limits are summarized in Table 1 for basic restrictions on absorbed power density (APD), Table 2 for reference levels on incident power density (IPD), and Table 3 for limits on energy density. The next sections describe the limits in international standards and the regulatory limits in EU/EFTA countries, Canada, and the USA. But first it is important to explain the power density definitions.

2.1 Definition of Incident Power Density (IPD)

IPD is measured in air at a distance from the device under test that is specified in the relevant regulation or standard. The IPD is spatially averaged over a surface area A_{avg} in the shape of a square or circle that is located on the evaluation surface, which is the area of the body or the phantom that is exposed to the incident field. It is temporally averaged over the averaging time t_{avg} (see Table 2 for the specifications of A_{avg} and t_{avg}).

The quantity that is averaged is the Poynting vector of the incident electromagnetic field $\mathbf{S}_{\mathrm{i}}(\mathbf{r}) = \frac{1}{2}\,\mathbf{E}_{\mathrm{i}}(\mathbf{r}) \times \mathbf{H}_{\mathrm{i}}^{*}(\mathbf{r})$, where $\mathbf{E}_{\mathrm{i}}$ and $\mathbf{H}_{\mathrm{i}}$ are the electric and magnetic time harmonic field vectors at the location $\mathbf{r}$ on the evaluation surface, respectively, and the asterisk indicates the complex conjugate. The joint IEC and IEEE standards on the experimental and computational assessment of the IPD [3, 4] specify three formulations as a function of the Poynting vector.

$$\mathrm{IPD}_{\mathrm{n+}}(\mathbf{r}) = \frac{1}{2}\Re\left\{\mathbf{E}_{\mathrm{i}}(\mathbf{r}) \times \mathbf{H}_{\mathrm{i}}^{*}(\mathbf{r})\right\} \cdot \mathbf{u}_{\mathrm{n}}(\mathbf{r}) \tag{1}$$

$$\mathrm{IPD}_{\mathrm{tot+}}(\mathbf{r}) = \frac{1}{2}\left|\left|\Re\left\{\mathbf{E}_{\mathrm{i}}(\mathbf{r}) \times \mathbf{H}_{\mathrm{i}}^{*}(\mathbf{r})\right\}\right|\right| \tag{2}$$

$$\mathrm{IPD}_{\mathrm{mod+}}(\mathbf{r}) = \frac{1}{2}\left|\left|\mathbf{E}_{\mathrm{i}}(\mathbf{r}) \times \mathbf{H}_{\mathrm{i}}^{*}(\mathbf{r})\right|\right|. \tag{3}$$

$\mathbf{u}_{\mathrm{n}}(\mathbf{r})$ is the normal vector of the surface area A_{avg}. The spatial average incident power density sPD at a location $\mathbf{r_0}$ on the evaluation surface is then defined as

$$\text{sPD}(\mathbf{r_0}) = \frac{1}{A_\text{avg}} \iint_{A_\text{avg}(\mathbf{r_0})} \text{IPD}(\mathbf{r})\, dA. \tag{4}$$

In Eqn. (4), IPD($\mathbf{r}$) is one of the expressions of Eqns. (1) – (3). Eqn. (1) only considers the real (i.e., the propagating) part of the component of the Poynting vector that is perpendicular to the evaluation surface, whereas Eqns. (2) – (3) take into account all propagating components of the Poynting vector or its modulus, respectively. The latter also includes the reactive energy of the field source. Eqn. (2) may be applicable to conservatively assess the exposure to inclinated angeles of incidence where increased absorption can occur, e.g., at the Brewster angle [5, 6], or at close distances where the near-field of the field source contributes to the absorption [7]. In the far field, Eqns. (1) – (3) converge to the same result if the surface normal is perpendicular to the direction of propagation.

For compliance with safety limits, the overall maximum of Eqn. (4), the peak spatial average incident power density (psPD), is evaluated on the entire evaluation surface.

$$\text{psPD} = \max_{\text{r}_0} \left(\text{sPD}(\text{r}_0)\right) \tag{5}$$

The safety standards (ICNIRP [2] and IEEE [1]) and most regulatory guidelines (Canada [8, 9]) and EU [10, 11]) do not specify which formulation to use, but ICNIRP (and Canada) states that the IPD limits do not apply to the reactive near-field zone. Nevertheless, the difference can be more than 6 dB for distances $< \lambda/2$ between antenna and exposed body [7]. In USA, where there are no APD limits, the psPD must be used to provide a conservative IPD estimate.

2.2 Definition of Absorbed Power Density (APD)

The absorbed power density (APD) or epithelial power density is a measure of the power density that passes through the surface of an exposed body or phantom and is converted into thermal energy due to the dielectric losses of the biological tissue or the tissue simulant. As for the IPD (Section 2.1), averaged quantities can be defined in terms of the spatial average absorbed power density (sAPD) and peak spatial average power density (psAPD). It is temporally averaged over the averaging time t_avg (see Table 1 for the specifications of A_avg and t_avg).

The quantity that is averaged is the Poynting vector of the transmitted electromagnetic field $\mathbf{S_t}(\mathbf{r}) = \frac{1}{2}\,\mathbf{E_t}(\mathbf{r}) \times \mathbf{H_t}^*(\mathbf{r})$, where $\mathbf{E_t}$ and $\mathbf{H_t}$ are the transmitted electric and magnetic time harmonic field vectors at the location $\mathbf{r}$ on the evaluation surface, respectively, and the asterisk indicates the complex conjugate. $\mathbf{E_t}$ and $\mathbf{H_t}$ consider the transmission coefficient.

For the calculation of the APD on a planar evaluation surface, only the perpendicular component of the transmitted Poynting vector $\mathbf{S_t}$ is considered because its tangential components are not attenuated and do therefore not contribute to the dissipated power. The APD can therefore be calculated as

$$\text{APD}(\mathbf{r}) = \frac{1}{2}\Re\left\{\mathbf{E_t}(\mathbf{r}) \times \mathbf{H_t}^*(\mathbf{r})\right\} \cdot \mathbf{u}_\text{n}(\mathbf{r}). \tag{6}$$

The sAPD and the psAPD are defined analogously to the sPD and the psPD:

$$\text{sAPD}(\mathbf{r_0}) = \frac{1}{A_\text{avg}} \iint_{A_\text{avg}(\mathbf{r_0})} \text{APD}(\mathbf{r})\, dA. \tag{7}$$

and

$$\text{psAPD} = \max_{\text{r}_0}\left(\text{sAPD}(\text{r}_0)\right) \tag{8}$$

r_0 is a location on the evaluation surface.

The APD on the evaluation surface is difficult to measure directly due to physical limitations of the probe, but it can be evaluated by integrating the specific absorption rate (SAR) inside the phantom, as one can make use of the fact that all of the power on the surface is absorbed inside the phantom. Details can be found in [12, 13].

2.3 International Standards

Both ICNIRP and IEEE (by the International Committee on Electromagnetic Safety, ICES) recently published revised standards that include new limits at millimeter wave frequencies [2, 1]. At millimeter wave frequencies, both standards define basic restrictions for APD (referred to by IEEE as epithelial power density), and reference levels for IPD.

The basic restrictions specified in [2, 1] refer to the limits of the fields that are induced in the body. Above a frequency of 100 kHz, thes limits are determined with the objective to avoid adverse health effects in terms of the temperature increase in the tissue. [1] contains an extensive review of the related scientific literature and how it is applied to arrive at the basic restrictions. Above 10 GHz, absorbed power density closely approximates maximum increase in skin temperature [2]. It should be noted that the IEEE standard [1] refers to the basic restrictions as “dosimetric reference limits”. We will use the term “basic restrictions” throughout this report, as the ICNIRP limits are more broadly accepted, especially in Europe. The basic restrictions on APD are summarized in Table 1.

Since the assessment of the exposure in terms of basic restrictions generally requires experimental or numerical dosimetric evaluations, the guidelines derive reference levels for the incident fields at which the dosimetric basic restrictions are intrinsically met. The exposure in terms of reference levels can be evaluated using free space measurements. The correlation of reference levels and basic restrictions is based on conservative dosimetric models. This means that if the exposure is compliant with the reference levels, an additional dosimetric evaluation in terms of the basic restrictions is not required. Otherwise, the demonstration with the basic restrictions is necessary to demonstrate compliance. The IEEE standard refers to the reference levels as “exposure reference levels”. We will use the term “reference levels” in this report. At lower frequencies, [2] and [1] specify

Standard or Region	Occup. psAPD limit (W/m^2)	Gen. Public psAPD limit (W/m^2)	Occup. & Gen. Public A_{avg} (cm^2)	f_G (GHz)	t_{avg} (min.)
ICNIRP, IEEE, Canada	100	20	4	6 – 300	6
ICNIRP, IEEE*, Canada	200	40	1	30 – 300	6
USA	–	–	–	–	–
EU	–	–	–	–	–

Notes to table:

- f_G, A_{avg}, and t_{avg} are the frequency in GHz, the averaging area in cm^2 and the averaging time in minutes, respectively.
- The averaging area A_{avg} is in the shape of a square.
- * For IEEE [1], the 1 cm^2 psAPD limit applies only if the 3 dB contours around the peak are less than 1 cm^2 in size.
- For ICNIRP [2], IEEE, and Canada [8], both the 4 cm^2 and 1 cm^2 psAPD limits apply above 30 GHz.
- for IEEE and ICNIRP, the whole body SAR limit of 0.08 W/kg (gen. public) or 0.4 W/kg (occup.) must be met at frequencies from 6 GHz to 300 GHz.
- For Canada, both the psAPD limits and psSAR limits (e.g., 1.6 W/kg for 1-gram average, for general public exposure at the head or torso) must be met if the frequency range of the communication system crosses 6 GHz (i.e., it has both a minimum frequency below 6 GHz and a maximum frequency above 6 GHz).
- EU does not presently have psAPD limits but is expected to adopt ICNIRP limits in the near future.
- USA does not presently have psAPD limits. However, it extends SAR measurements to frequencies up to 8.5 GHz including an IPD measurement at the configuration with the highest psSAR [14].

Table 1: Basic restrictions on APD above 6 GHz for occupational and general public exposure, listed by international standard or region.

Standard or Region	Occup. psPD limit (W/m^2)	Gen. Public psPD limit (W/m^2)	Occup. & Gen. Public A_{avg} (cm^2)	f_G (GHz)	t_{avg} (min.)
ICNIRP, IEEE	50	10	whole body	2 – 300	30
Canada	50	10	whole body	6 – 15	6
Canada	50	10	whole body	15 – 150	$616000/f_M^{1.2}$
Canada	$3.33 \times 10^{-4} f_M$	$6.67 \times 10^{-5} f_M$	whole body	150 – 300	$616000/f_M^{1.2}$
ICNIRP*, Canada*, IEEE	$275/f_G^{0.177}$	$55/f_G^{0.177}$	4	6 – 300	6
ICNIRP*, Canada*, IEEE†	$550/f_G^{0.177}$	$110/f_G^{0.177}$	1	30 – 300	6
EU (2013/35/EU)	50	–	20	6 – 300	$\lfloor 6; 68/f_G^{1.05} \rfloor$‡
EU (2013/35/EU)	1000	–	1	6 – 300	$\lfloor 6; 68/f_G^{1.05} \rfloor$‡
EU (2013/35/EU)	50000	–	20	6 – 300	τ
EU (1999/519/EC)‖	–	10	♮	10 – 300	$68/f_G^{1.05}$
USA	50	10	4	1.5 – 100	T

Notes to table:

- f_G, f_M, A_{avg}, and t_{avg} are the frequency in GHz and MHz, the averaging area in cm^2 and the averaging time in minutes, respectively.
- The averaging area A_{avg} is in the shape of a square, except that in USA [15] it is in the shape of a circle.
- τ is the pulse width for the EU general public limit of 50000 W/m^2.
- T is 6 minutes for occupational exposure and 30 minutes for the general public. [16]
- * For ICNIRP [2] and Canada [8], the psPD limits do not apply to the reactive near-field zone.
- For ICNIRP, Canada, and IEEE [1], both the 4 cm^2 and 1 cm^2 psPD limits apply above 30 GHz.
- The ICNIRP, Canada, and IEEE general public limits over the frequency range [6, 300] GHz vary over the IPD range [40, 20] W/m^2 for A_{avg} = 4 cm^2 and [80, 40] W/m^2 for A_{avg} = 1 cm^2, while occupational limits vary over the IPD range [200, 100] W/m^2 for A_{avg} = 4 cm^2 and [400, 200] W/m^2 for A_{avg} = 1 cm^2.
- According to the EU occupational limits [11], all three psPD limits of 50, 1000, and 50000 (short pulses only) apply for all frequencies.
- † For IEEE, the IPD limits apply only if the 3 dB contours below the peak give an area less than 1 cm^2.
- ‡ t_{avg} is 6 minutes for $f_G < 10$ GHz and $68/f_G^{1.05}$ for $f_G \geq 10$ GHz.
- ‖ EU (1999/519/EC) specifies an incident power density of 10 W/m^2 also as basic restriction.
- ♮ Averaging area is not specified in the document.

Table 2: Reference levels on IPD for occupational and general public exposure, listed by international standard or region.

Standard or Region	Occup. Energy dens. (kJ/m^2)	Gen. Public Energy dens. (kJ/m^2)	Occup. & Gen. Public A_{avg} (cm^2)	f_G (GHz)	t_{exp} (min.)
ICNIRP*, Canada*	$S \cdot 0.36 \cdot (0.05 + 0.95\sqrt{t_{exp}/6})$		4	6 – 300	< 6
ICNIRP*, Canada*	$S \cdot 0.36 \cdot (0.025 + 0.975\sqrt{t_{exp}/6})$		1	30 – 300	< 6
IEEE †	$\tau^{1/2}$	$0.2\tau^{1/2}$	1	30 – 300	–
IEEE ‡	$\sum_{i=1}^{n}(S_{i\text{peak}} \times \tau_i) \leq \frac{1}{5}S \times 6$ min		1 or 4	1×10^{-4} – 300	–
USA	–	–	–	–	–
EU	–	–	–	–	–

Notes to table:

- f_G, A_{avg}, and t_{exp} are the frequency in GHz, the averaging area in cm^2 and the exposure duration in minutes, respectively.
- The averaging area A_{avg} is in the shape of a square.
- τ is the pulse width in seconds.
- * For ICNIRP [2] and Canada [8], S is the psAPD limit (see Table 1) or psPD limit (see Table 2), as applicable. The same formula applies to occupational and general public exposure limits, but using different limits S.
- For ICNIRP and Canada, both the 4 cm^2 and 1 cm^2 energy density limits apply above 30 GHz.
- † IEEE [1] limits the energy density per pulse, applicable to reference levels. There are no corresponding basic restrictions.
- ‡ $S_{i\text{peak}}$ is the average temporal power density of the pulse i, τ_i is the width of the i^{th} pulse, and S is the psPD limit (see Table 2). Refer to [1] for details.
- USA and EU do no presently have energy density limits for frequencies above 6 GHz.

Table 3: Energy density limits for occupational and general public exposure, and for basic restrictions and reference levels (see Table notes), listed by international standard or region.

different reference levels for the incident electric and magnetic fields. In the millimeter wave frequency range, the reference levels are defined in terms of the IPD, which correlates E- and H-fields by the free space wave impedance. The ICNIRP Guidelines [2] note that this correlation is not applicable in the near-field and that, in such cases, exposure need be evaluated in terms of the basic restrictions. The reference levels on IPD are summarized in Table 2.

Two tiers of EM exposure limits are adopted in these standards, as seen in Table 1 and Table 2. General public tier applies to people of all ages and differing health statuses, including vulnerable individuals, who may not be aware that they are being exposed and have not been trained on how to mitigate their exposure [2]. The IEEE standard refers to the general public as 'persons in unrestricted environments'. The occupational tier permits higher limits, typically by a factor of 5, compared to the general public tier, and applies to occupationally-exposed individuals (called 'persons in restricted environments' in IEEE [1]) which ICNIRP [2] defines as:

> Occupationally-exposed individuals are defined as adults who are exposed under controlled conditions associated with their occupational duties, trained to be aware of potential radiofrequency EMF risks and to employ appropriate harm-mitigation measures, and who have the sensory and behavioral capacity for such awareness and harm mitigation response. An occupationally-exposed worker must also be subject to an appropriate health and safety program that provides the above information and protection.

The APD or IPD limits are temporally averaged over an averaging time of t_{avg} = 6 minutes, as shown in Table 1 and Table 2. For brief exposure of less than 6 minutes duration, such as short pulses, additional constraints are imposed to limit the temporal increase in absorbed power density, thus limiting the temperature rise in tissue. These energy density limits are shown in Table 3, and for ICNIRP, they are scaled by the applicable psAPD or psPD limit. For wireless communication devices that are used for voice call or continuous data transmission (i.e., using 3G, 4G, 5G or WiFi), the 6-minute averaging time applies, so the psAPD or psPD limits should be used, and wireless device manufacturers are allowed to use exposure control techniques (see Section 6) to maintain the exposure below the limit over the 6-minute duration.

The power density is spatially averaged over a square surface area of the body (skin surface), denoted A_{avg} in the tables. The evaluation of the psPD according to [3, 4] requires that the square area be rotated about its center point to identify the orientation with the maximum result. In some cases, multiple limits apply simultaneously. For example, ICNIRP and IEEE have psAPD limits for the general public of 20 W/m^2 averaged over 4 cm^2 (6 – 300 GHz) and additionally 40 W/m^2 averaged over 1 cm^2 (30 – 300 GHz). This means that both limits apply above 30 GHz. The additional 1 cm^2 limit is intended to limit spatially focused exposure at high frequencies.

Energy density limits for pulsed signals are based on the same rationales and are given in Table 3.

2.4 Regulatory Limits in European Union and EFTA countries

In the European Union and European Free Trade Association (EFTA) countries, the exposure limits to electromagnetic fields are generally set by Council Recommendation 1999/519/EC for the general public [10] and Directive 2013/35/EU for occupational exposure [11]. These documents have not yet been updated to reflect ICNIRP 2020 guidelines, but they are expected to do so.

The European Commission created an independent committee to provide scientific advice to the European Commission called SCHEER (Scientific Committee on Health, Environmental and Emerging Risks). The SCHEER released a preliminary opinion in August 2022 [17] in favor of revising Council Recommendation 1999/519/EC and Directive 2013/35/EU to incorporate the new guidance of ICNIRP 2020. It states that the new dosimetric quantities in ICNIRP 2020 "can protect humans more effectively from emerging technological applications of RF EMF" and that there is a need for more research on the health effects with regard to millimeter wave exposure. This preliminary opinion is expected to be finalized in 2023 after the comments from the public consultation have been examined. Then the process to revise 1999/519/EC and 2013/35/EU is expected to begin.

Until then, the current exposure limits in the EU and EFTA countries are based on IPD only as shown in Table 2. At present, there are no APD or energy density limits. For occupational exposure, Directive 2013/35/EU limits the IPD to 50 W/m^2 averaged over any 20 cm^2 of exposed area. In addition, the IPD averaged over 1 cm^2 should not exceed 1000 W/m^2 to limit spatially sharp exposures, and there is a limit of 50000 W/m^2 averaged over the pulse width and a 20 cm^2 averaging area to limit short pulses.

2.5 Regulatory Limits in Canada

In Canada, the regulatory limits for electromagnetic exposure are established by Health Canada and published in Safety Code 6 published in 2015 6 [9]. An additional Notice [8] was published in 2021 in response to the publication of the ICNIRP 2020 Guidelines [2].

Health Canada agrees with the conclusions of ICNIRP 2020 and has established the same osPD and psAPD limits (for exposure in the far field, see Table 2), psAPD limits (for exposure in the far-field and in the reactive near field, see Table 1) and energy density limits (see Table 3) for the frequency range 6 GHz to 300 GHz.

2.6 Regulatory Limits in the USA

The regulatory limits in the USA for exposure to electromagnetic fields are established by the Food and Drug Administration and documented in the US Code of Federal Regulations, Title 47, Section 1.1310 [16].

Additionally, updated information on the exposure limits and evaluation procedures are provided by the Federal Communications Commission (FCC) in Knowledge Database (KDB) documents and in presentations at semi-annual TCB Council workshops (see Section 3).

For frequencies above 6 GHz, no psAPD limits are defined. The US government has not yet provided updated limits in response to the recent ICNIRP and ICES publications in [2, 1].

For frequencies from 6 GHz to 8.5 GHz, where the SAR limits at 6 GHz have been extended [14]. The test lab must measure SAR for all test configurations in the 6 – 8.5 GHz range, and additionally the IPD for the test configuration with the highest SAR. This procedure warrants consistency for communication signals whose operating frequency band extends both below and above 6 GHz (e.g., U-NII, which is from 5.15 GHz to 7.125 GHz). This frequency range is not relevant to 5G NR FR2.

The October 2018 presentation of the FCC [15] gives interim guidance on the assessment of IPD limits above 6 GHz. The averaging area for the compliance testing of portable devices will be increased to 4 cm^2, but the limit of 10 W/m^2 will be retained for both local and whole body exposure. This guidance may be withdrawn in the future. If time averaging is applied the averaging time for IPD evaluation decreases with increasing frequency above 6 GHz in a manner similar to the occupational EU limits [11]. The averaging time vs. frequency is shown in Table 4.

limit	f_G (GHz)	t_{avg} (s)
SAR	< 3	100
	3 – 6	60
IPD	6 – 10	30
	10 – 16	14
	16 – 24	8
	24 – 42	4
	42 – 95	2

Table 4: FCC-defined averaging time t_{avg} as a function of frequency f_G for its IPD limits.

The averaging time is inversely proportional to frequency, starting at 100 s at 3 GHz and decreasing to 2 s at 95 GHz. This is justified by maintaining a fixed limit for the temperature rise in the skin ΔT and recognizing that the SAR at the skin surface increases with frequency due to the shorter penetration depth and increasing conductivity. SAR is proportional to temperature rise as described in Equation 9, where c is the specific heat capacity of skin [2].

$$SAR = c \cdot \frac{\Delta T}{t_{avg}} \tag{9}$$

3 List of Standards for Exposure Evaluation

The following standards and national regulatory procedures are applicable to the evaluation of human exposure to radiated fields from wireless devices utilizing 5G NR FR2 transmission. IEC/IEEE standards for evaluation of incident power density are very new, having been published earlier this year. National regulatory agencies have been involved in the development of these standards and are starting to provide regulatory guidance in this area.

– IEC/IEEE 63195-1, "Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (frequency range of 6 GHz to 300 GHz) - Part 1: Measurement procedure", May 2022.

  This standard provides requirements for the measurement of incident power density (IPD) from a wireless device that transmits within the 6 GHz to 300 GHz frequency range. The test procedure and equipment specifications are given for repeatable and reproducible measurements that give a conservative estimate of the exposure incident on the head or body of the user. The measurement uncertainty, validation and verification of the measurement system are specified in detail.

– IEC/IEEE 63195-2, "Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (frequency range of 6 GHz to 300 GHz) - Part 2: Computational procedure", May 2022.

  This is a companion standard to IEC/IEEE 63195-2, where computational methods rather than measurements are applied to evaluate the IPD from a wireless device. The applicable frequency range is also 6 GHz to 300 GHz.

– ISED Canada SPR-003, "Supplementary Procedure for Assessing Radio Frequency Exposure Compliance of Portable Devices Operating in the 60 GHz Frequency Band (57-71 GHz)", March 2021.

  This document, for compliance evaluation of devices sold in Canada, gives procedures for both measurement and computational analysis of IPD in the 60 GHz band. The procedures were prepared after consultation with draft versions of IEC/IEEE 63195-1 and IEC/IEEE 63195-2.

– FCC KDB 447498 D01, "General RF Exposure Guidance", draft version August 2022.

  This Knowledge Database (KDB) document, for compliance evaluation of devices sold in USA, does not contain procedures for IPD evaluation but references interim guidance found in FCC presentations at semi-annual workshops of the Telecommunication Certification Body Council (TCBC). Until detailed procedures are documented, test reports are submitted directly to the FCC making use of KDB inquiries. However, IEC/IEEE 63195-1 procedures are generally acceptable.

To date, there are no standards or national regulatory procedures for evaluation of APD at millimeter wave frequencies, although there is considerable interest in this area of research. However, the IEC recently released a Publicly Available Specification (PAS) and ISED has released a supplementary procedure:

– IEC PAS 63446, "Conversion method of specific absorption rate to absorbed power density for the assessment of human exposure to radio frequency electromagnetic fields from wireless devices in close proximity to the head and body - Frequency range of 6 GHz to 10 GHz", October 2022.

  This is the first IEC specification specifying procedures for APD assessment. It is restricted in frequency to 6 GHz to 10 GHz (it uses SAR measurements and a conversion factor to APD), so it is only applicable to 5G NR FR1 and therefore not directly relevant to this project. However, it has generated interest in APD evaluation for regulatory compliance.

– ISED Canada SPR-APD, "Supplementary Procedure for Assessing Specific Absorption Rate (SAR) and Absorbed Power Density (APD) Compliance of Portable Devices in the 6 GHz Band (5925-7125 MHz)", June 2022.

  This Canadian procedure is the first national regulatory procedure for APD evaluation. It allows APD evaluation in accordance with IEC PAS 63446, as ISED Canada is an active member of the IEC committee that developed it.

4 Review of Communication Signals Used in Biological Studies

The millimeter wave band (30 – 300 GHz) is relatively new for consumer telecommunication equipment, although it has been used for decades in other fields such as radio astronomy [18] and remote sensing [19].

Prior to the introduction of 5G, communication applications in the millimeter wave band included point-to-point microwave data links [20] and satellite communication [21] where high bandwidths are essential. These are applications with a low prevalence of human exposure, so 5G presents a new type of exposure.

In addition, the advent of beamforming (which is not present in earlier generations of communication systems) and dynamic power control and antenna selection diversity (which are very recent innovations) changes the type of exposure of the user. The expected proliferation of 5G devices, both fixed and portable, also changes the scenarios in which the user is exposed.

While there is a large number (over 7000) of scientific papers on biological effects of EMF at frequencies below 6 GHz, including several review papers (e.g., [22]), the new FR2 frequency range is relatively unexplored. In addition to the higher carrier frequencies, 5G NR FR2 differs in important ways from previously introduced transmit signals such as 2G, 3G, 4G and WiFi, as explained earlier.

A 2021 review by Karipidis *et al.* [23] examined the available literature on bioeffects above 6 GHz. It was able to include 107 experimental studies and 31 epidemiological studies in its analysis. The studies examined genotoxicity, cell proliferation, gene expression, cell signalling, and membrane effects. Although the paper found no conclusive evidence that low-level RF is hazardous to human health, it said that a systematic review is not possible due to the low quality methods of the majority of the experimental studies, and it recommends further study with improvements to the experimental design (in particular, temperature control and dosimetry), and continued epidemiological studies to monitor long-term health effects.

A companion 2021 paper to [23] by Wood *et al.* [24] attempted to correlate exposure (IPD or SAR) with effect size. It was able to study 88 papers. The paper recommended further research in the 5G bands due to the lack of studies there, particularly in the 26 – 28 GHz range.

The literature review published in IEEE C95.1 [1] found only 17 papers relevant to thermoregulation, 14 publications relevant to gene or protein expression, 19 papers on cell proliferation and apoptosis, and a limited number of studies relevant to effects on the immune system and hematology.

5 5G FR2 Bands and Modulations

5.1 FR2 Frequency Ranges

5G NR (New Radio) is a radio access technology defined and maintained by the 3GPP (3rd Generation Partnership Project), a consortium of national and regional standards organizations. 3GPP has defined two frequency ranges for 5G. Frequency Range 1 (FR1) currently covers the frequency range from 410 MHz to 7125 MHz.

Designation	Frequency Range
FR1	410 MHz – 7125 MHz
FR2-1	24.25 GHz – 52.60 GHz
FR2-2 (unlicensed)	52.60 GHz – 71.00 GHz

Table 5: Definition of 5G frequency ranges [25].

Frequency Range 2 (FR2), the frequency range of interest to this project, now covers the frequency range from 24.25 GHz to 71.0 GHz. Since June 2022, the upper end of the FR2 range was extended from 52.6 GHz to 71.0 GHz by adding a second sub-band denoted FR2-2 as shown in Table 5.

FR2-2 is an unlicensed band, which means that devices can use the frequency range non-exclusively (i.e., without a network operator having to pay a license fee for exclusive usage), although the devices must still demonstrate that they meet RF safety guidelines and other transmitter rules. Devices using unlicensed spectrum tend to transmit over shorter duration and over shorter distances than devices using licensed spectrum, due to the higher potential interference in an unlicensed spectrum. In addition, the FR2-2 frequency range has been intentionally chosen to correspond to a band where there is high atmospheric attenuation due to absorption by oxygen molecules (see Figure 1). For these reasons, FR2-2 is less interesting for this project.

Sub Band	NR FR2 Band	Frequency Range (GHz)	Bandwidth (GHz)
FR2-1	n257	26.50 – 29.50	3.00
	n258	24.25 – 27.50	3.25
	n259	39.50 – 43.50	4.00
	n260	37.00 – 40.00	3.00
	n261	27.50 – 28.35	0.85
	n262	47.20 – 48.20	1.00
FR2-2	n263	57.00 – 71.00	14.00

Table 6: NR FR2 frequency bands [25].

There is considerable interest in extending the FR1 and FR2 bands for 5G and 6G. This is a topic of active research by wireless device manufacturers and others, and it is being seriously discussed within 3GPP. As an example, Samsung recently released a white paper

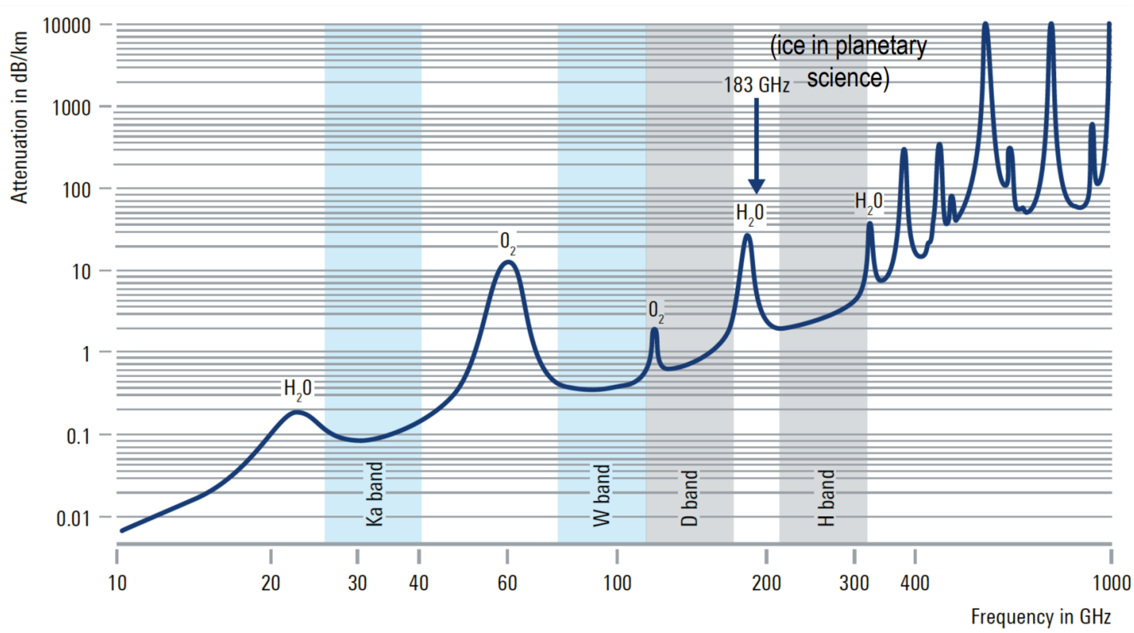


Figure 1: Atmospheric attenuation is high near 60 GHz, where 5G NR FR2-2 band is located, due to oxygen absorption. This frequency range is ideal for unlicensed bands where devices transmit over short distances, leaving the rest of the spectrum for longer-range communication [26].

proposing several candidate bands for 6G [27]. These include proposals for the mid band (below 24 GHz), mmWave band (24 – 92 GHz band) and sub-THz band (92 – 300 GHz).

The NR FR2 bands in Table 6 are sub-divided into channels, and a signal transmits on one of these channels, or multiple channels if carrier aggregation is used (see Section 5.2). The possible channel bandwidths are shown in Table 7 as a function of the subcarrier spacing, SCS, which is explained in Section 5.3. The network assigns one of the shown channel bandwidths to the signal depending on the channel needs and network availability.

Sub Band	NR FR2 Band	SCS (kHz)	UE channel bandwidth (MHz)						
			50	100	200	400	800	1600	2000
FR2-1	n257	60	50	100	200				
	–	120	50	100	200	400			
	n262	240		100	200	400			
		120		100		400			
FR2-2	n263	480				400	800	1600	
		960				400	800	1600	2000

Table 7: Channel bandwidths for each NR FR2 band [25]. For channels n257 to n262, the 400 MHz channel bandwidth is optional as of release 17.7.0 [25].

5.2 Bandwidth Enhancement in 5G

5G employs two main techniques in order to access large bandwidths so that high data rates can be achieved: carrier aggregation (CA) and dual connectivity (DC).

CA is the transmission of a signal among multiple channels simultaneously. These channels may be within the same band or in different bands. CA can be used for uplink or downlink communication (i.e., transmission from the user equipment, such as a mobile phone, to the base station, or vice versa, respectively). It is more commonly used for downlink communication.

DC is a technique allowing the data transmission to be split between more than one access technology. The concept was initially introduced in LTE which allows the UE to connect simultaneously to two base stations. The two base stations are involved in a connection whose signals do not need to be time-synchronized and therefore are not required to be physically collocated. In 5G dual connectivity can involve two NR base stations (NR-DC) or one NR and one LTE (Multi-Radio-DC, often called NSA - non-standalone). Only LTE is considered for possible multi-radio connectivity with NR. Other technologies as GSM and WCDMA cannot be combined in DC with NR.

There are also techniques to improve the data rate to overcome interference on the network. Supplemental uplink (SUL) switches the transmission to another channel (typically at a lower frequency) when the primary channel is out of range. Uplink MIMO (multi-input, multi-output) overcomes multipath interference on a network by transmitting the signal using multiple antennas. Some handsets on the market switch between two antennas (e.g., one near the bottom of the handset and one near the top) depending on which has better communication. This helps, for example, when the user's hand is covering the bottom antenna.

5.3 5G FR2 Modulations

This section is a brief overview of the important aspects of signal modulation in 5G FR2 and it will be useful when deriving the 5G signal characteristics for the exposure studies in Section 8.

Before 5G signals are transmitted, they are encoded using Orthogonal Frequency-Division Multiplexing (OFDM), an efficient method of transmitting a signal using multiple subcarrier frequencies. The working principle of OFDM is that the data bits are grouped into symbols and each symbol is transmitted simultaneously on a separate carrier. The carrier signals are orthogonal in the frequency domain, meaning that at the center frequency of one carrier, the signal amplitude is at a maximum where all other signals have zero amplitude (see Figure 2). This feature allows the carriers to be tightly packed, leading to a high spectral efficiency. The use of multiple carriers results in high data rates, even if each individual carrier has a low data rate using lower order modulations such as $\pi/2$ BPSK or QPSK (see below). The advantage of lower order modulations is that they reduce errors due to the harsh conditions of wireless transmission in a dense urban environment. OFDM is inherently a frequency diversity method due to the use of multiple carriers, which makes it robust against channel fading. For these reasons, OFDM is a popular multiplexing scheme

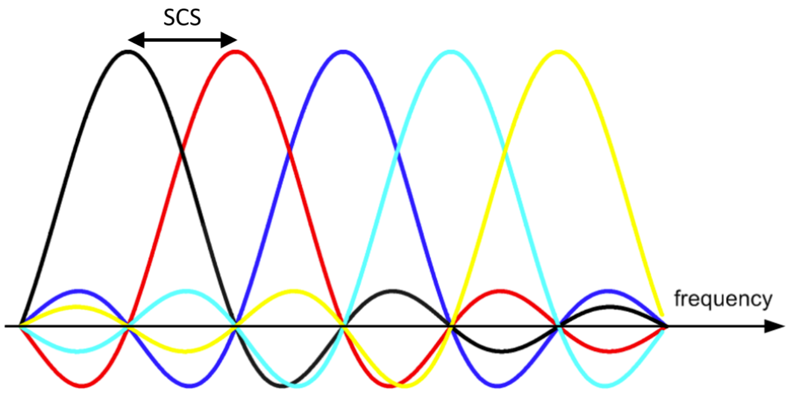


Figure 2: Concept of OFDM showing the tightly packed subcarriers with subcarrier spacing SCS. Each symbol is modulated onto a different subcarrier. The carrier signals are orthogonal as the peak amplitude of one signal corresponds to zero amplitude of the other signals [28].

that is commonly used in WiFi, 4G, and 5G.

Two types of OFDM are used in 5G NR FR2, Cyclical Prefix OFDM (CP-OFDM) and Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM). CP-OFDM can be used for MIMO transmission, where DFT-s-OFDM can only be used for single signal transmission.

Each OFDM symbol is modulated onto a separate carrier frequency (colored line of Figure 2) with each symbol represented by a phase and/or amplitude. The four modulation schemes used in 5G are π/2 BPSK (binary phase shift keying), QPSK (quadrature phase shift keying), 16QAM (16 quadrature amplitude modulation) and 64QAM, which encode 1, 2, 4 and 6 bits per symbol, respectively. This means that, for example, 16QAM transmits six times as much data as π/2 BPSK. However, the trade-off is higher intersymbol interference which increases the error rate, so lower order modulations are preferred in harsh signal environments. π/2 BPSK is only used by DFT-s-OFDM, while the other three modulation schemes are used by both DFT-s-OFDM and CP-OFDM.

In the time domain, 12 or 14 symbols are combined into a slot, then N slots are combined into a subframe of 1 ms duration, and 10 subframes are combined into a frame of 10 ms duration (see Figure 3) [29]. The number of slots in a subframe, N, depends on the subcarrier spacing, SCS (see Figure 2), with N = SCS / 15 kHz. In 5G NR sub-band FR2-1, subcarrier spacings of 60 kHz, 120 kHz, and 240 kHz are allowed (see Table 7), giving N = 4, 8, or 16 slots per subframe. Wider subcarrier spacings are needed at higher frequencies to overcome errors due to doppler shift when the wireless device is moving (e.g., in a vehicle).

So far, the discussion in this section has covered the details for transmission of a one-way signal. However, two-way or duplex signalling is needed to transmit (uplink from the mobile device) and receive (downlink) at the same time. Duplex signalling in 5G NR FR2 is done exclusively in the time domain. Time-division duplexing (TDD) is achieved by reserving some slots for the downlink signal. The base station dynamically configures the radio channel to adjust the number of uplink and downlink slots as needed.

Frequency-division duplexing (FDD) is the other duplexing scheme, where two separate

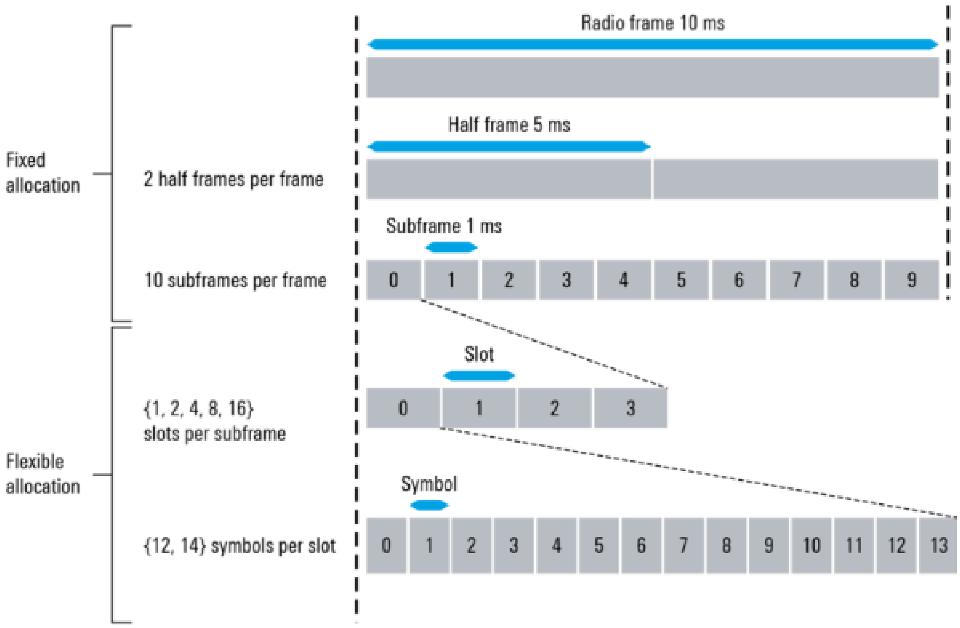


Figure 3: Frame structure in OFDM [29]. For 5G NR sub-band FR2-1, only 4, 8, or 16 slots per subframe are allowed. The four slots depicted in this figure apply to a 60 kHz subcarrier spacing.

channels are used for the uplink and downlink signals. Both FDD and TDD are utilized in 5G NR FR1, 4G and earlier communication systems, but 5G NR FR2 does not use FDD for several important reasons [29]. At millimeter-wave frequencies, the radio channel characteristics (e.g., channel attenuation, channel fading, doppler shifts) are very sensitive to frequency, so if FDD is used, the base station would not be able to optimize the downlink transmission for error correction based on information in the uplink signal. Beam forming (Section 6.2) is not practical if the uplink and downlink transmission are on different frequencies. FDD uses spectrum inefficiently for many applications of wireless communication (e.g, watching videos, playing games, texting) with asymmetric communication (e.g., when watching videos, much higher data rates are needed for downlink communication than uplink communication).

6 Exposure Control Techniques

Wireless devices use several techniques to maintain the EM exposure below the regulatory limits at all times, so that simply lowering the maximum output power can be avoided, which would result in poor communication and pressure on wireless network providers to add more base stations to the network.

This section describes these techniques. The development and implementation of these techniques has increased considerably in the last 5 years, as the result of several factors:

- regulatory agencies are increasingly enforcing testing protocols in accordance with reasonably foreseeable use conditions. For example CENELEC will soon enforce SAR testing at 0 mm distance to the body in its standard [30] for wireless devices sold in Europe (larger test distances are common today, such as 5 mm, depending on the use case). The closer distance to the body generally results in higher SAR for a given power level, although this is not always the case due to antenna detuning and other issues, as will be explored in detail in Section 7.
- the number of wireless communication protocols (e.g., 4G, 5G, WiFi, WiGig) has been increasing rapidly, as have the number of frequency bands and the number of antennas on the device. In addition, simultaneous transmission of multiple communication protocols has become common. Such a high number of transmission signals motivates the implementation of control techniques to ensure that the exposure levels are not exceeded.
- the use cases of portable wireless devices (e.g., voice call, texting, gaming, taking photos, watching videos) have increased, and wireless devices have implemented means to determine the use case, making use of sensors in the device such as gyroscopes, accelerometers, and infrared sensors. These sensors can provide input to the exposure control techniques.
- international testing standards and regulatory guidelines for evaluating exposure control techniques are being published. For example, the first IEC technical report on validation of dynamic power control will be published in early 2023 [13]. These standards and guidelines provide confidence to manufacturers on the implementation and testing of the exposure control techniques.

The exposure control techniques described below are implemented in mobile phones and other wireless devices using proprietary algorithms whose outputs are specific to the wireless communication protocol (e.g., modulation, frequency band) and use case (e.g., voice call, texting, gaming). Some techniques are used in conjunction with others.

6.1 Proximity Sensors and Motion Sensors

Proximity sensors or motion sensors detect the presence or motion of the user so that the signal level can be lowered to ensure that the exposure is below the safety limits.

Motion sensing is simply proximity sensing where the change in proximity is tracked over time, so the same equipment can be used for both proximity sensing and motion sensing.

As the wireless handset gets closer to the user's body, the exposure typically increases (see Section 7), so a proximity sensor can trigger at an appropriate distance to lower the exposure. A proximity sensor may have one or multiple trigger distances.

Motion sensing can be used to differentiate between static use cases, such as laying on a table (where the user's body is likely not to be nearby), and use cases of movement, such as being picked up or held in the hands.

A 1982 patent by Calvin [31] describes a microwave proximity sensor that uses a transmit antenna and a receive antenna that detects a portion of the transmitted signal. The proximity of the the human body or other object is detected by the change in amplitude and phase of the signal, and the motion of the object is detected by tracking those changes over time.

Capacitive proximity sensors are described in a 1982 patent and subsequent patents [32, 33, 34]. The capacitance of the sensing element is monitored, and the change in capacitance indicates the presence of the user. The sensor can be a capacitor [33, 34] or an antenna [32]. Capacitive sensing is also the predominant technology used in touch screens of wireless devices [35].

For exposure control, two types of proximity sensors are typically used in modern wireless devices, which will be referred to in Section 7 as grip sensors and antenna sensors.

Grip sensors, as described in a 2010 paper by Myllymaki *et al.* [36], use capacitive elements along the sides of the device to detect that the user's fingers are gripping the device.

Antenna sensors may use a sensor integrated into the antenna (e.g., using a parasitically coupled element), as described by Schlub *et. al* [37], Harper [38], and Heikura *et al.* [39]. Antenna sensors may also use the capacitance of the antenna itself, as described by Javitt *et al.* [40].

Khawand *et al.* [41] and Rouaissia *et al.* [42] describe methods to maximize the likelihood of detecting a human body instead of a table or other physical object, and Van Ausdall *et al.* [43] describe the use of multiple proximity sensors to enhance the detection of the human body.

Other techniques of proximity sensing, such as infrared sensors [44] and optical sensors [45], may be used to detect when the user's face is against the front screen to turn off the screen or lower the ringer volume [46].

When the proximity sensor or motion sensor is triggered, the wireless device reduces the user's exposure. This may be performed by steering the beam away from the user (Section 6.2), turning on dynamic power control (Section 6.3), selecting a different antenna (Section 6.4), or simply lowering the output power.

6.2 Beamforming

Beamforming techniques make use of antenna arrays to focus the main lobe of the radiation pattern in a direction that maximizes the signal strength at the receiver. Beamforming is designed to overcome the higher signal attenuation at the higher frequencies utilized by 5G NR FR2, as illustrated in Figure 1.

Wang *et al.* [47] and Zhang *et al.* [48] published optimization techniques using beamforming to reduce the exposure of the user. The phases and amplitudes of the antenna elements in the array are adjusted to minimize user exposure. Minimizing exposure benefits the communication link because the energy that is aborbed by the body is useless for communication.

Beamforming becomes physically realizable on wireless handsets at frequencies in the FR2 range. The physical size of each antenna element (on the order of a quarter of a wavelength) reduces with increasing frequency. At frequencies below 6 GHz, it is difficult to find space for an antenna array on a handset which typically has a size of 80 mm x 160 mm or smaller. But above 24 GHz, each antenna element is approximately 3 mm or smaller.

6.3 Dynamic Power Control

Dynamic power control is a general technique of adjusting the transmission of the wireless device over time to ensure that the time-averaged exposure is within regulatory limits. The averaging time, t_{avg}, is described in Table 2, and is 6 minutes for the general public in Europe. This section focuses on dynamic power control methods while using the same antenna. Switching between antennas is covered in Section 6.4.

Dynamic power control algorithms allow the user to have a higher exposure over a short duration as long as the time-averaged exposure is within the limit at all times. As the exposure (SAR, IPD, or APD) is directly proportional to the output power, lowering the output power lowers the exposure by the same proportion.

Lee [49] and Khawand *et al.* [41] each patented methods of lowering the output power of a signal when a proximity sensor detects human tissue but not non-human objects in close proximity.

This concept was extended by Khawand *et al.* [50] and Jhadav *et al.* [51] to multiple signals. The techniques adjust the levels of simultaneous transmitters (e.g., 5G NR, LTE, WLAN and Bluetooth) in such a way to both optimize communication and maintain the exposure below the regulatory limit. Priority can be given to certain signals over others, for example.

Ngai *et al.* [52] describe a proximty sensor based power control algorithm that can, among other things, dynamically switch from one transmitter to another (e.g., from 5G NR to LTE) to control the exposure. An example of this is shown in Figure 5.

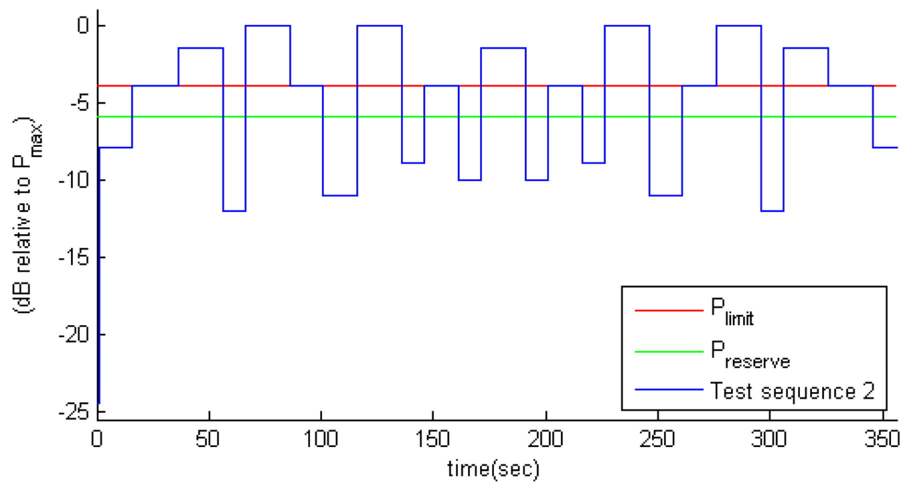


Figure 4: Example of dynamic power control of a single transmitter. The instantaneous power (blue) is varied between different levels to maintain the time-average exposure at or below the limit, P_{limit}.

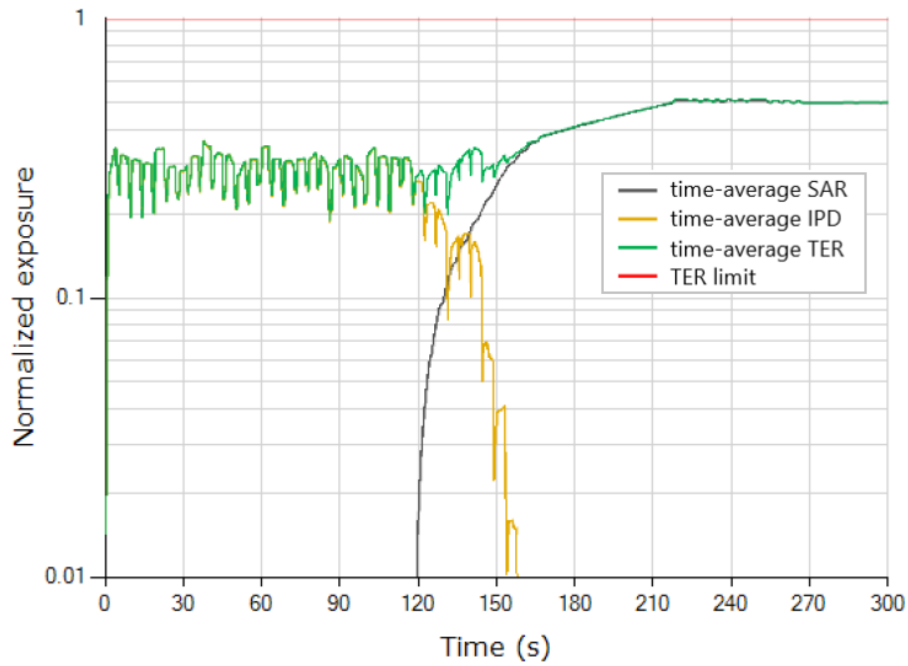


Figure 5: Example of dynamic power control when the transmission is handed over between a 5G NR FR2 signal (yellow) and a 4G LTE signal (black). The total normalized exposure (green) is calculated as per Equation 10. In this case, t_{avg} = 4 s for the 5G NR FR2 signal, and t_{avg} = 100 s for the 4G LTE signal (see Table 4).

6.4 Antenna Selection Diversity

Antenna selection diversity switches from one antenna to another antenna to improve the communication link. For example, some wireless handsets have two antennas, one located on the top of the handset and one on the bottom so that if the user's hand is covering the bottom antenna, the device can switch to the top antenna. The communication signal strength is monitored to determine which antenna to use. By switching to the antenna that is not in close proximity to the user, the exposure is reduced.

Khawand *et al.* [50] describe a method to control the power level between multiple antennas on a wireless device to maintain the exposure below the regulatory limits.

7 Preliminary Exposure Evaluation of Handheld Devices

7.1 Introduction

An initial study has been conducted using 4G-enabled wireless devices to understand the relationship between SAR in a human phantom and the distance of the device to the phantom. As explained in Section 6, there has been considerable interest recently to understand how the exposure of the user is influenced by distance at close proximity to the user's body. Regulatory agencies are increasingly enforcing testing protocols in accordance with reasonably foreseeable use conditions, and CENELEC recently proposed SAR testing at 0 mm distance to the body in [30].

Based on the two main interaction mechanisms of the coupling of the incident fields with tissue simulating media [53, 54], a monotonic increase of the induced fields with reduced distance is expected. However, there are interactions between the wireless device and the user, such as antenna detuning, that result in a higher SAR at distances greater than 0 mm to the body.

This topic deserves a thorough and comprehensive study so that a standardized testing procedure can be proposed. Understanding this behaviour at frequencies below 6 GHz will also help inform the understanding at the higher frequencies of 5G NR FR2. This information is of direct interest for the measurement of APD that is part of Work Package 4.

7.2 Selection of Devices

A review of commercially available mobile phones on the US market was conducted. The US market was chosen because RF exposure test reports are publicly available on an FCC website [55] containing detailed information about the transmit technologies used. For the study, twelve devices were selected from a diverse range of wireless device manufacturers.

Table 8 shows the twelve devices under test (DUTs). This is a blind study, so the manufacturers and model names of the devices will not be revealed. These are instead referred to as DUT1, DUT2, etc. The reason for making this a blind study is so that the absolute SAR values can be shown without implying that a specific device exceeds the safety limits. Indeed, the measurements are conducted at distances and using a measurement system that do not comply with current regulatory requirements, so even if SAR values are present above the safety limits, this does not go against the manufacturer's assertion that the device is compliant with RF safety requirements.

4G devices use a transmission technology known as LTE (Long-Term Evolution)[56]. The number of measured LTE frequency bands are shown in Table 8. The exposure control techniques, described in Section 6, are also indicated for each DUT. Beam forming is not used in 4G devices. Dynamic power control is the most common exposure control technique among these devices, utilized in 7 of the 12 DUTs. Proximity sensors and antenna selection diversity are also common.

DUT	No. of LTE Bands	Exposure Control Techniques				No. of tests
		Antenna Selection Diversity	Dynamic Power Control	Proximity Sensor (Antenna)	Proximity Sensor (Grip)	
DUT1	9					2 745
DUT2	12					3 538
DUT3	22		Y			7 259
DUT4	18		Y	Y	Y	5 429
DUT5	22					7 137
DUT6	10					3 294
DUT7	24	Y	Y	Y		5 368
DUT8	17		Y	Y		5 307
DUT9	25	Y	Y	Y	Y	6 161
DUT10	9					3 294
DUT11	8	Y	Y	Y	Y	2 379
DUT12	8	Y	Y	Y	Y	2 379
					TOTAL	54 290

Table 8: Characteristics of the DUTs for this study.

7.3 Evaluation Method

SAR measurements were performed using a DASY8^{3D} system (Schmid & Partner Engineering AG, Switzerland), as shown in Figure 6. The system uses a robot to pick up and position the DUT at any orientation and distance next to a cSAR3D flat phantom. cSAR3D is a vector-measurement based system that uses an array of E-field sensors to measure the peak spatial-average SAR in less than a second [57].

The study was conducted so that the exposure control techniques are turned off during the tests, so that the SAR vs distance characteristic can be observed purely as a function of antenna distance to the body.

For each DUT and for each LTE band, all six faces of the DUT were positioned facing the flat phantom at several distances. The chosen distances are 0 mm to 5 mm in 0.1 mm steps and 5 mm to 10 mm in 0.5 mm steps. The six faces are the front and back sides, and the left, right, top, and bottom edges, as shown in Figure 7.

This is a large study with over 54000 measurements performed (Table 8), when considering all of the DUTs, LTE bands, DUT faces, and distances. For some results, the top edge is not shown because the measured SAR is too low to measure ($\ll$ 0.1 W/kg). This happens when the antenna is located on or near the bottom edge, far away from the top edge that is positioned on the phantom. The size of the study allows the determination of the prevalence of the non-monotonic behaviour.

7.4 Results

Non-monotonic behavior of the SAR vs distance curve was observed in less than 10 % of all cases (combination of LTE band and DUT face), meaning that the SAR is most often

Figure 6: Measurement setup for the study using DASY8^{3D} [58], using a wooden block to represent the device under test.

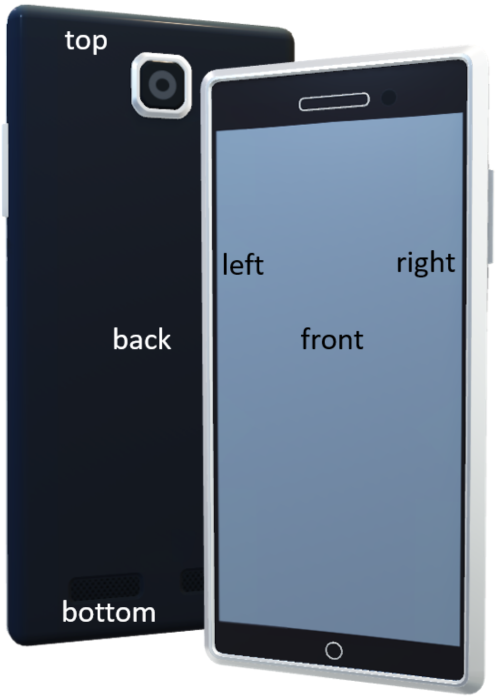


Figure 7: Measured sides and edges of the mobile phones.

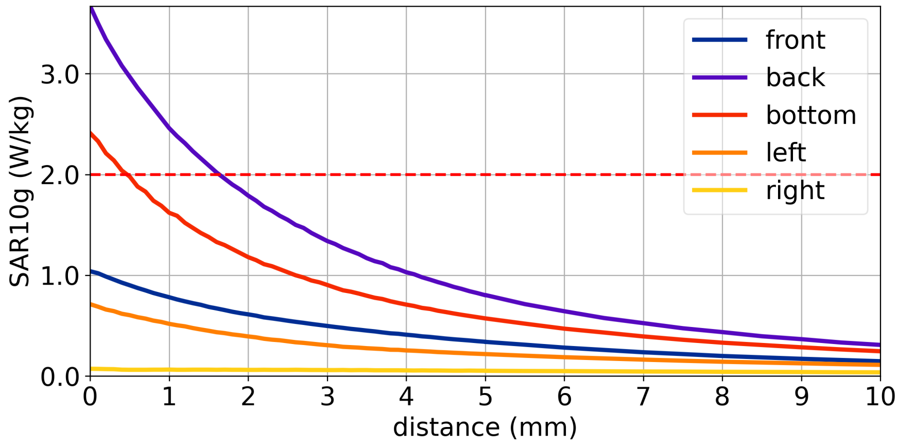


Figure 8: Typical example showing monotonic decrease of SAR with increasing distance of the DUT to the phantom. Measured peak spatial-average SAR (10-gram average) is shown for all sides and edges (except the top edge) of DUT2 for LTE Band 7 at the middle channel (2535 MHz). The SAR limit of 2 W/kg applicable to Europe is shown as a red dashed line. For the top edge, the SAR is below the noise level, so it is not shown.

highest at a d = 0 mm. A typical example is shown in Figure 8. However, non-monotonic behavior was observed in all twelve of the devices for at least one configuration of LTE band and DUT face, and in some of these cases, the highest SAR for non-monotonic behavior was significant with respect to the overall maximum SAR for that device. An example of this behaviour is shown in Figure 9.

One reason for this behavior is that the phantom presents a dielectric load to the antenna, causing a change to the impedance match between the antenna and the source, and possibly changing the frequency at which the antenna has the best match.

The prevalence of non-monotonic SAR behavior was observed in some cases to be caused by changes in the SAR pattern that indicate that capacitive coupling of the antenna to the flat phantom is dominating at smaller distances. The coupling causes a change in the SAR pattern, and the electric fields become more polarized orthogonal to the phantom surface. Such fields are evanescent and decay rapidly inside the phantom.

The use of proximity sensors significantly affects the findings. Six of the twelve DUTs make use of at least one proximity sensor. The measurements are reported with proximity sensors disabled, which was typically achieved by measuring at a lower output power so that the proximity sensor is turned off, then scaling the results to the maximum power level. However, when the proximity sensor is considered, it was observed that the triggering of the proximity sensor resulted in additional cases where the SAR at d = 0 mm is not the highest SAR.

To validate the measurements, the measured results using the array system (cSAR3D) were compared against the results using a scanning system (DASY8). The scanning system is accepted by regulators worldwide and is considered to be the benchmark for measurement accuracy. However, the array system is used for this study as the scanning is very time consuming, making it practically impossible to conduct so many measurements in a reasonable amount of time. For measurements of all DUTs at two distances (d = 0 mm

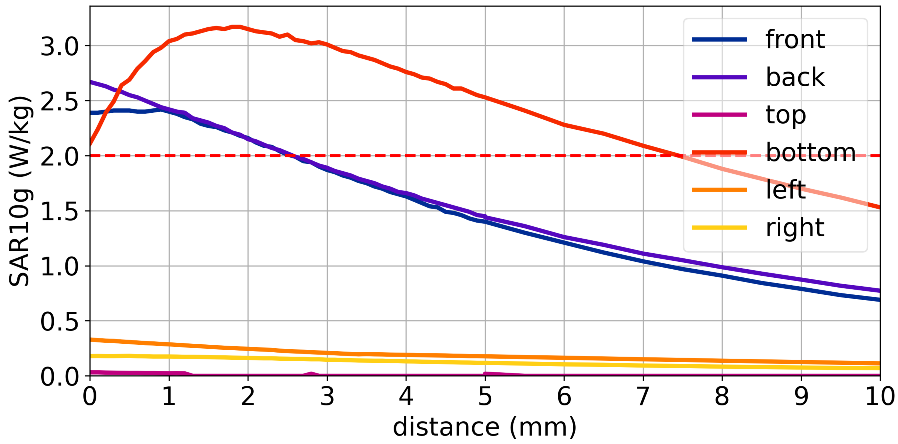


Figure 9: Example showing non-monotonic SAR vs distance characteristic. Measured peak spatial-average SAR (10-gram average) is shown for all tested sides and edges of DUT6 for LTE Band 1 at the middle channel (1950 MHz). The SAR limit of 2 W/kg applicable to Europe is shown as a red dashed line.

and 10 mm) the differences are within the combined standard uncertainty of the two systems.

As the study has not been completed, these results are preliminary. Once the full study is complete, the results will be evaluated with respect to compliance with regulatory limits. In addition, the prevalence of the non-monotonic behavior will be evaluated, and a proposal will be formulated, if appropriate, to adapt the distances to be measured for compliance testing. Such a proposal will take into consideration minimizing any additional testing burden. This proposal and the full results will be presented to IEC TC106, of which the authors are active members.

8 Signal and APD Synthesis for Risk Assessment Experiments of FR2 Exposures

8.1 Introduction

A key objective of the SEAWave project is to assess health risks from 5G NR FR2. This section defines the parameters of 5G NR FR2 signals that are planned for the exposure setups in the *in vitro* studies, *in vivo* studies, and human studies in Work Packages 6, 7, and 8, respectively.

The new exposure control techniques described in Section 6 may significantly change the exposure of the user. Dynamic power control results in higher short-term exposure of the user as long as the average exposure is below the limit over the six-minute duration given in ICNIRP 2020 guidelines [2]. 5G NR FR2 will require a denser network of base stations with beam forming antennas.

The chosen approach to select a signal for an exposure study is consistent with the approach taken in a published study by Schuermann *et al.* [59]. In that study, human cells were exposed to GSM, UMTS, WiFi, and RFID modulated signals. Signals were produced having characteristics consistent with those in their published standards.

8.2 Review of 5G NR FR2 Devices on the Market

A review of commercially available wireless devices on the US market was conducted (this is a different set of devices than what was presented in Section 7). The purpose of this review is to determine the key 5G NR FR2 characteristics and exposure parameters that are popular among currently available devices.

The US market was chosen because RF exposure test reports are publicly available on an FCC website [55] containing detailed information about the transmit technologies used. While some of the frequency bands are country specific, the other parameters such as signal bandwidth and modulation are expected to be the same in Europe as in the USA.

A review of the FCC database found 16 wireless devices containing 5G NR FR2 transmitters in the FR2-1 band where an RF exposure application was submitted to the FCC between January 2020 and August 2022. These devices are listed in Table 9 along with their key signal properties and exposure properties.

8.2.1 Signal Properties

It can be seen from Table 9 that the FR2 bands, bandwidths, and modulations are quite common among these devices. Signal bandwidths of 50 MHz, 100 MHz, and 200 MHz are all common, with all devices using 100 MHz bandwidth.

Regarding modulations, all of the devices use QPSK, 16-QAM, and 64-QAM for both CP-

OFDM and DFT-s-OFDM, and most of them also use $\pi/2$ BPSK modulation for DFT-s-OFDM.

All of the devices transmit in FR2 bands n260 and n261, making these bands of interest for the study. It should also be noted that band n258 is common in Europe. A frequency of 27.5 GHz is common to bands n258 and n261.

The subcarrier spacing is not always provided on the RF exposure test reports, so it is not listed here. The possible values of subcarrier spacing for FR2-1 are 60 kHz, 120 kHz, and 240 kHz, as shown in Table 7.

Based on this analysis, the following signal properties are selected for the test signal described in Section 8.3:

- 27.5 GHz carrier frequency
- 100 MHz modulation bandwidth
- QPSK modulation
- 60 kHz subcarrier spacing

8.2.2 Exposure Properties

Table 9 also shows the highest reported IPD and total exposure ratio (TER) of each device, as reported by the test lab. In USA, the IPD is evaluated according to Equation **??**. In other words, it is the total power incident on the averaging area (which is a circle with 4 cm^2 area) rather than the power flowing through the averaging area. The IPD is compared with the limit of 10 W/m^2 (see Table 2).

IPD measurements are only conducted on a small number of antenna configurations, due to the large number of beam configurations (i.e., amplitude and phase combinations of the antenna array), and the long IPD measurement time. Numerical simulations are performed on each antenna array for all beam configurations to determine the configurations having the highest exposure for each of the six sides and edges of the device.

The TER considers all simultaneous transmissions. The evaluated basic restrictions or reference levels that can transmit simultaneously are each normalized to their respective limits and then added together, as per Equation 10. The TER must be 1 or less. In the calculation of TER, the IPD values are scaled to their maximum values It is notable that the TER is within 5 % of the limit for 14 of the 16 devices. In fact, the TER is at the limit for two of the devices.

$$TER = \sum_{i\,=\,100\text{ kHz}}^{6\text{ GHz}} \frac{SAR_i}{SAR_{lim}} + \sum_{i\,>\,6\text{ GHz}}^{100\text{ GHz}} \frac{IPD_i}{IPD_{lim}} \leq 1 \tag{10}$$

An example calculation of the TER is shown in Table 10. Results are taken from the FCC test report of the Sony Experia 1-IV [67]. This example is for body-worn exposure where

Manufacturer, Model	Signal Properties: FR2 Bands	Signal Properties: BW (MHz)	Signal Properties: mods.	Exposure: IPD (W/m^2)	Exposure: TER (%)
Samsung Galaxy S20+ [60]	n260, n261	50, 100	Q,16,64	6.50	98.1
Apple iPhone 12 [61]	n260, n261	50, 100	B,Q,16,64	6.82	99.8
Google Pixel 6 Pro [62]	n260, n261	100, 200	Q,16,64	4.24	94.9
Samsung Galaxy S22 Ultra [63]	n258, n260, n261	50, 100	B,Q,16,64	6.09	99.0
Samsung Galaxy Tab S8 Plus [64]	n260, n261	50, 100	B,Q,16,64	6.50	99.8
Samsung Galaxy A53 [65]	n260, n261	50, 100	B,Q,16,64	5.11	98.6
Motorola Edge+ (2022) [66]	n260, n261	50, 100, 200	Q,16,64	5.18	95.7
Sony Experia 1-IV [67]	n260, n261	50, 100	B,Q,16,64	4.77	100.0
Microsoft Surface Pro 9 [68]	n260, n261	50, 100	B,Q,16,64	7.74	98.4
Samsung Galaxy S21 [69]	n260, n261	50, 100	B,Q,16,64	6.20	99.4
Samsung Galaxy Z4 Fold [70]	n258, n260, n261	50, 100	B,Q,16,64	5.99	97.7
Samsung Galaxy Z4 Flip [71]	n258, n260, n261	50, 100	B,Q,16,64	3.70	99.4
Motorola Edge [72]	n260, n261	50, 100	B,Q,16,64	3.27	82.0
Apple iPhone 14 [73]	n258, n260, n261	50, 100	B,Q,16,64	6.89	97.6
Apple iPad [74]	n258, n260, n261	50, 100	B,Q,16,64	5.31	99.9
Apple iPhone 14 Plus [75]	n258, n260, n261	100, 200	B,Q,16,64	5.67	100.0

Table 9: Sample of wireless devices with 5G NR FR2 capability that have applied for FCC certification between January 2020 and August 2022. Shown for each device are the signal properties (frequency bands, bandwidths (BW), and modulations (mods.)), and the exposure properties (IPD and total exposure ratio (TER)). The abbreviations in the modulations column are B = $\pi/2$ BPSK, Q = QPSK, 16 = 16-QAM, and 64 = 64-QAM.

the back side of the device is facing the body. The device is capable of transmitting 5G NR FR2, Bluetooth, and two WLAN 5 GHz channels simultaneously (there are many other combinations of simultaneous transmission for this device; this is one example).

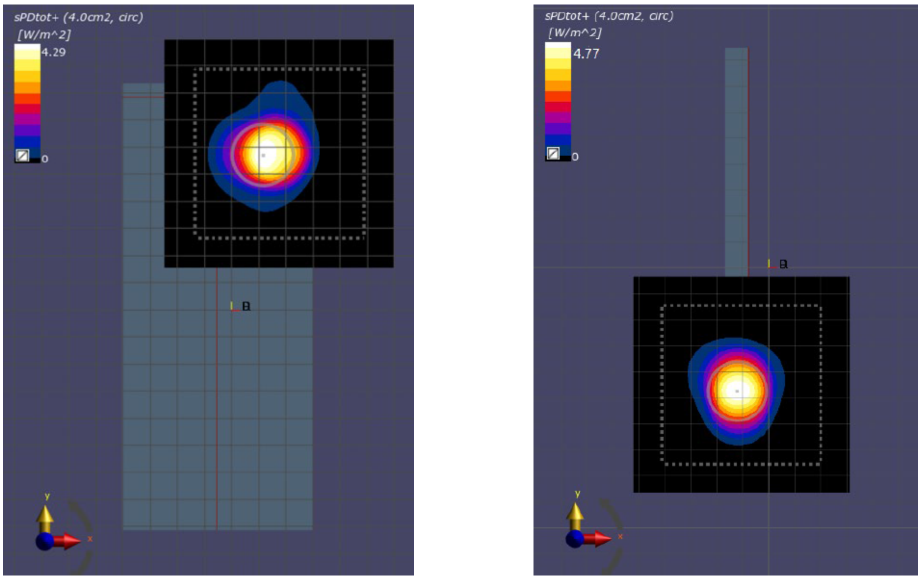
The Bluetooth and two WLAN 5 GHz signals transmit below 6 GHz, so the SAR was measured and found to have a maximum value of 4.1 %, 1.6 %, and 9.7 % of the SAR limit, respectively. The highest IPD for 5G NR FR2 is 79.4% of the limit. Adding these numbers gives a TER of 94.8 % for this case. It is observed that the 5G NR FR2 signal dominates the exposure.

Some test reports describe that a smart transmit algorithm is implemented to dynamically control the output power levels of all simultaneous transmitters to ensure that the TER is below 1 at all times. Given that there is very little margin to the limit for these devices, it is apparent that the devices are reliant on these algorithms to accurately estimate the exposure and control the transmitters accordingly.

	SAR_{meas} (W/kg)	SAR_{limit} (W/kg)	IPD_{meas} (W/m^2)	IPD_{limit} (W/m^2)	ratio (%)
5G NR FR2 (band n261)	–	–	7.94	10	79.4
Bluetooth 2.4 GHz	0.066	1.6	–	–	4.1
WLAN 5 GHz: Chain 0	0.026	1.6	–	–	1.6
WLAN 5 GHz: Chain 1	0.155	1.6	–	–	9.7
				TER	94.8

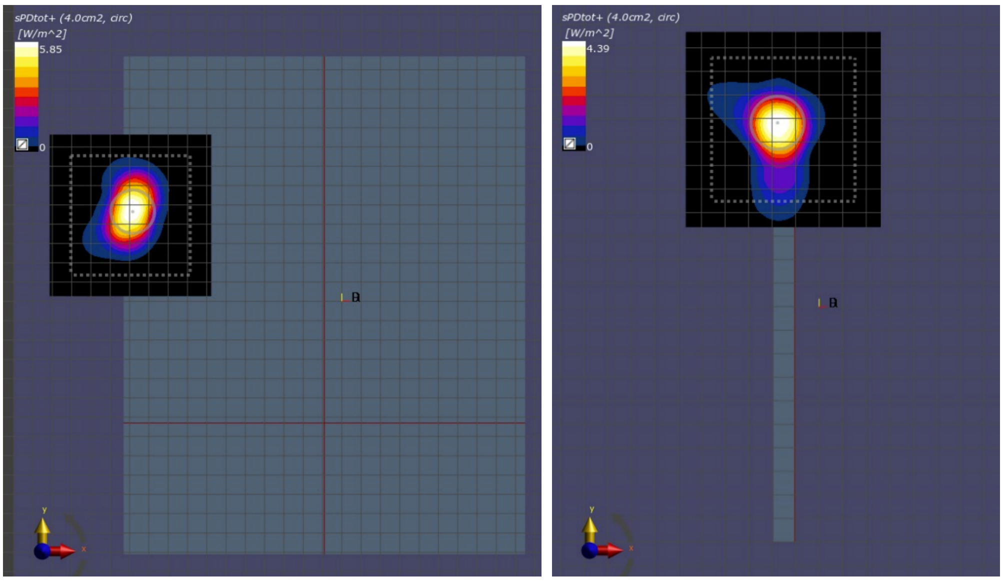
Table 10: Example TER calculation for Sony Experia 1-IV, taken from [67] for the back side of the device facing the body with four transmitters operating simultaneously: 5G NR FR2, Bluetooth, and two WLAN 5 GHz channels.

Example IPD distributions are shown for the Experia 1-IV at 5G NR Band n261 in Figure 10 and the Microsoft Surface Pro 9 at 5G NR Band n260 in Figure 11. The circle in the middle of the distribution shows the location and shape of the peak 4 cm^2 IPD. The IPD peak is focused at the antenna location and drops sharply with distance, with a radial distance from the peak to the -3 dB point ranging from 1.0 cm to 1.5 cm. For this reason, a very fine resolution is needed for good measurement accuracy (e.g., λ/4, which ranges from approximately 2 mm to 3 mm at these frequencies).



(a) (b)

Figure 10: IPD distributions at 2 mm distance from the (a) back and (b) right sides of the Sony Experia 1-IV for 5G NR FR2, band n261. The highest measured IPD values for this band are (a) 4.29 W/m^2 at 27.55 GHz and (b) 4.77 W/m^2 at 27.925 GHz. The outline of the DUT is shown by the blue box.



(a) (b)

Figure 11: IPD distributions at 2 mm distance from the (a) front and (b) right sides of the Microsoft Surface Pro 9 for 5G NR FR2, band n260. The highest measured IPD values for this band are (a) 5.85 W/m^2 at 38.50 GHz and (b) 4.39 W/m^2 at 37.05 GHz. The outline of the DUT is shown by the blue box.

8.3 Signal Selection for FR2 Exposures

From the preceding information in this report, a modulated 5G FR2 signal for exposure assessment should have the following characteristics:

- The operating frequency should be within the FR2-1 band (i.e., between 24.25 GHz and 52.6 GHz),
- The baseband signal should include frequency components at 100 Hz and 1 kHz to represent the 10 ms frame and 1 ms subframe structures, as well as a higher frequency component to represent the slot structure,
- The baseband signal should include some low frequency components to represent changing resource block allocations in time during transmission.
- The modulated signal should be either a CP-OFDM or DFT-s-OFDM signal with a bandwidth, subcarrier spacing, and modulation that are representative of 5G FR2 signals.
- It should have blank slots in the time domain to represent Time-Division Duplex (TDD) signal characteristics.

8.3.1 Selected Signal Characteristics

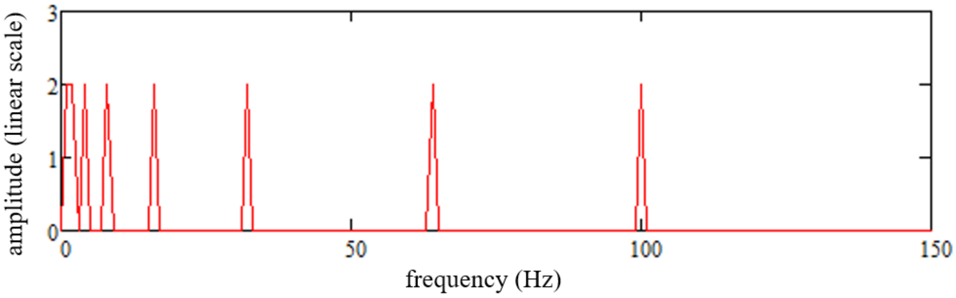
An operating frequency of 27.5 GHz has been selected for this signal. This frequency is contained within three of the FR2-1 bands: n257, n258, and n261 (see Table 6). One or more of these bands are allocated for use in both Europe and North America.

Baseband signal components have been selected at 1, 2, 4, 8, 16, 32, and 64 Hz. These low frequency components cover the different numbers of resource blocks allocated over time. Components at 100 Hz, 1 kHz, and 2 kHz have been added to represent the frame, subframe, and slot structures, respectively, as shown in Figure 12. This represents a signal with 60 kHz subcarrier spacing (see Table 7) which has four slots per subframe (see Figure 3), resulting in 4 kHz structure. However, using TDD with alternating full slots for uplink and downlink results in the 2 kHz component that has been incorporated.

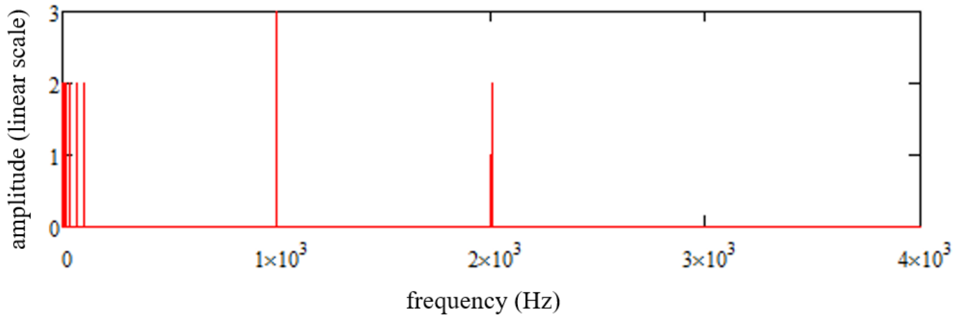
To create the TDD components, an inverse Fourier transform of the signal was performed to transfer it to a time-domain signal, and all amplitude components below a certain threshold were cut off. This is depicted in Figure 13. As shown in Figure 13b, there are now gaps in the time domain signal representing empty TDD slots.

Figure 14 shows the same signal transformed back to the frequency domain. It is observed that the frequency components of Figure 12 are present with significant amplitudes, and there are additional components due to the cutting off of low amplitude time-domain components. The peak-to-average power ratio of this signal is approximately 10 dB.

The modulated signal has been selected to have signal characteristics of published 5G NR FR2 signals. The signal characteristics are summarized in Table 11. The peak-to-average



(a)



(b)

Figure 12: Baseband signal showing the frequency components at (a) 1, 2, 4, 8, 16, 32, 64, and 100 Hz, and (b) zoomed out to show the 1 kHz and 2 kHz components.

power ratio of this modulation is 5.86 dB. The baseband components of Figure 14 is also included, which has a peak-to-average power ratio of approximately 10 dB. The final signal has been adjusted to ensure that the overall peak-to-average power ratio is within the PAR range of 5G signals.

The 100 MHz bandwidth is consistent with the most common value that was found in the market survey of 5G NR FR2 wireless devices in Section 8.2. QPSK was also found to be a common modulation scheme.

Parameter	Value
name	5G NR (DFT-s-OFDM, 100 MHz, QPSK, 60 kHz)
category	random amplitude modulation
PAR	5.86 dB
frequency	27.5 GHz
multiplexing scheme	DFT-s-OFDM
modulation scheme	QPSK
subcarrier spacing	60 kHz
bandwidth	100.0 MHz

Table 11: Details of the selected 5G NR FR2 modulated signal.

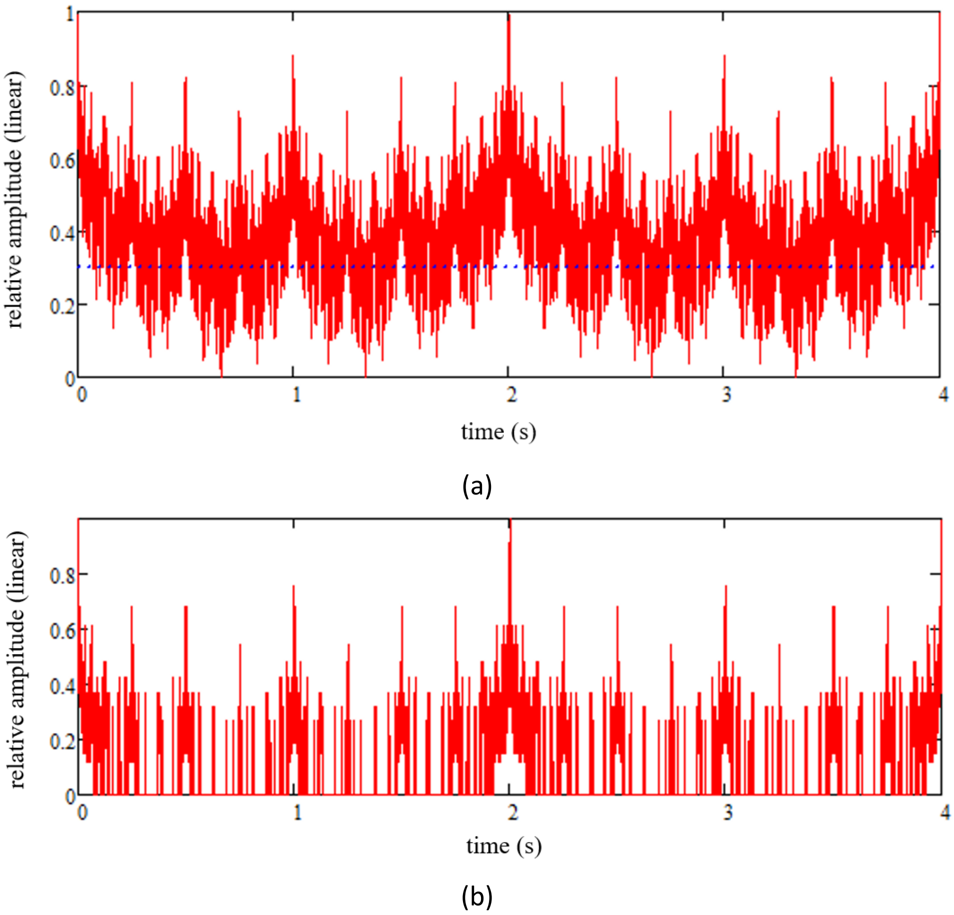
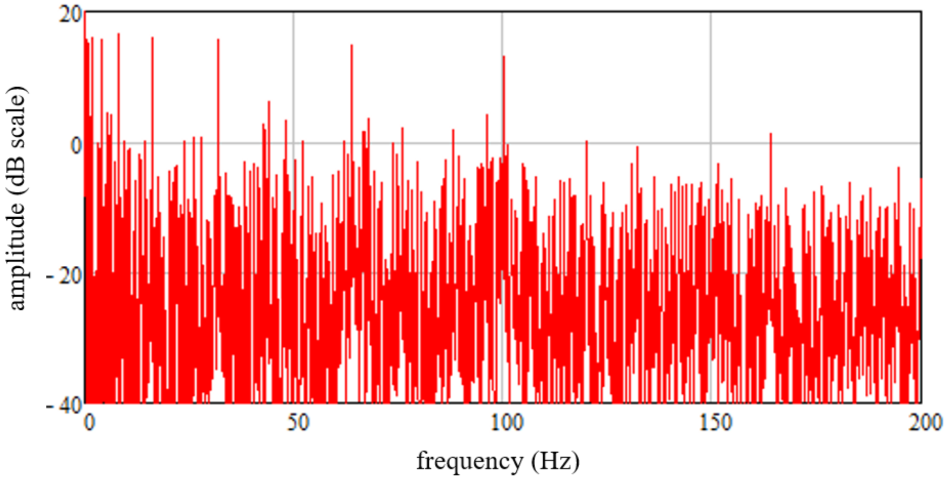
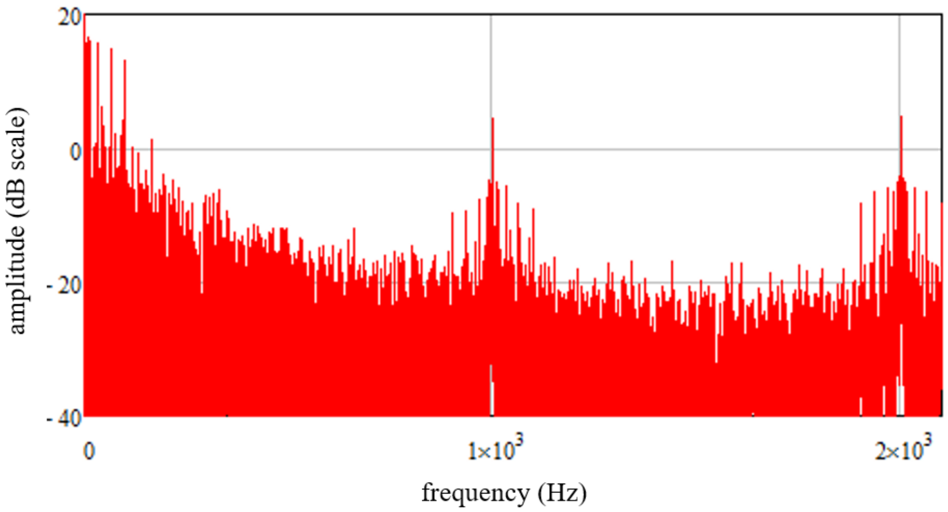


Figure 13: (a) The signal of Figure 12 depicted in the time domain, and an amplitude threshold (blue dotted line); (b) the signal of (a) with all components below the threshold cut off.



(a)



(b)

Figure 14: The signal of Figure 13b Fourier transformed to the frequency domain for frequency components up to (a) 200 Hz and (b) over 2 kHz.

8.3.2 Synthesis of the Signal

The IT'IS Foundation has developed a setup to generate the signal described in Section 8.3.1. The setup consists of a vector signal generator (commercially available from Rohde & Schwarz) and a frequency upconverter and amplifier (manufactured by Zurich Med Tech (ZMT) for this project). For the specific exposure systems for WP5–7, there is additional equipment that is described in the reports of those Work Packages.

The vector signal generator (see Figure 15) has the options described in Table 12. The output power range is –145 dBm to +16 dBm.

Option	Description
SMCV100B	Vector signal generator, base unit
SMCVB-B103	frequency range of 4 kHz to 3 GHz
SMCVB-K505	arbitrary waveform streaming
SMCVB-K512	memory extension to 1 Giga-samples
SMCVB-K521	extension to 120 MHz RF bandwidth

Table 12: Options of the Rohde & Schwarz vector signal generator SMCV100B.

A waveform file is uploaded to the signal generator. The waveform file consists of the signal as described in Table 11. This signal consists of 0.5 ms blocks, each having the in-phase and quadrature components of the modulated signal, and 8001 of these blocks is concatenated to make the 4 second sequence that is shown in Figure 13.

To achieve the low frequency baseband components (1, 2, 4, 8 16, 32, 64, 100, 1000, and 2000 Hz), each of the blocks has its own amplitude and is concantenated in a certain sequence. There are 17 unique blocks that are concatenated in this way to generate the 8001-block, 4-second sequence. The vector signal generator generates the modulated signal at an intermediate frequency of 2 GHz.

The 2 GHz waveform is fed into the integrated upconverter and amplifier shown in Figure 16. The components inside the red lines are integrated into one package and are described here. The other equipment is described in the relevant work packages (WP5-

Figure 15: Signal generator.

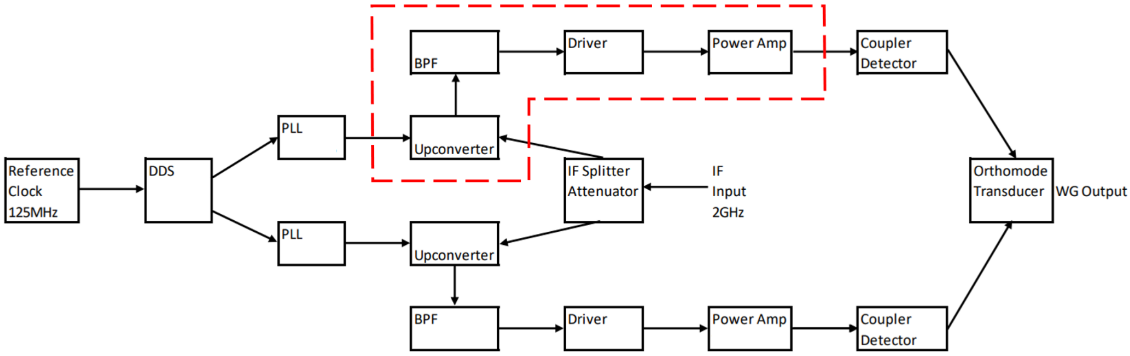


Figure 16: Exposure system hardware. The equipment inside the red lines is described here and is used for frequency up-conversion, band-pass filtering (BPF) and amplification of the signal.

7). The signal is split into two branches to provide two signals out of phase for circular polarization in the exposure setup.

The upconverter mixes the 2 GHz signal with a local oscillator at 25.5 GHz. This creates two frequency components, the desired component at 27.5 GHz and the unwanted component at 23.5 GHz.

The band pass filter (BPF in Figure 16) rejects the unwanted component from the upconverter, leaving the desired 27.5 GHz signal. The bandwidth of the pass band is approximately 2.5 GHz. The attenuation of the unwanted signal is nearly 50 dB.

The driver amplifier and the power amplifier are used together provide sufficient power at 27.5 GHz for the exposure setups. The total gain is more than 50 dB over the required 100 MHz modulation bandwidth.

9 Conclusion

This report documents the completion of Deliverable 4.1. The signal characteristics have been chosen for the exposure setups in the *in vitro* studies, *in vivo* studies, and human studies in Work Packages 6, 7, and 8, respectively. Justification for the signal characteristics has been provided based on the information in the previous sections, including a review of commercially available 5G NR FR2 devices on the market in Section 8.2. To provide the necessary background for this Work Package, the regulatory and standards framework has been laid out in Sections 2, and 3, and the fundamentals of 5G NR FR2 and techniques for exposure control have been described in Sections 5, and 6. An exposure evaluation study has been conducted in Section 7.

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