European Commission

Project: **SEAWave**

Exposure by the latest FR2-enabled enduser devices

Work Package: WP 4

Deliverable: D4.3

Deliverable No.: D14

Abstract

Deliverable 4.3, with the objective of enabling experimental evaluation of FR2-enabled devices with the developed and validated absorbed power density (APD) measurement system, is the third and final deliverable of work package 4 (WP4) of Project SEAWave.
This report, which documents the successful completion of Deliverable 4.3, entails the experimental assessment of FR2-enabled devices using the validated APD measurement system developed in this project. Due to the current unavailability of commercially marketed FR2 devices in Europe, a specialized development device containing integrated and controllable FR2 modules was procured directly from the manufacturer. The report summarizes tests conducted on three distinct FR2 modules embedded in the development device. The assessments were performed with the measurement equipment and protocols specifically developed under this work package. The focus of the measurements was on the determination of both the APD and incident power density (IPD) at a distance of 2 mm from the device surface, at an operating frequency of 27.5 GHz, with the antenna beam oriented in the boresight direction. For these specific modules, the ratio of the IPD to APD is nearly a factor of two. It should be noted that the ratio can vary by $\pm$6 dB, depending on the near-field characteristics of the transmitter [1]. However, depending on the design of the FR2 module, and as shown for the tested modules, testing with APD limits with a skin-simulating phantom may mitigate the compliance burden for device manufacturers. The use of APD criteria also demonstrably decreases the uncertainty in the testing and enhances the reliability of evaluations of wireless device safety. Such an approach presents clear benefits for industry stakeholders, regulatory bodies, and end-users.
The results of this work contributed to the IEC TC106 WG11 regarding the APD product test standard IEC/IEEE pt63195-3 ”Evaluation of Absorbed Power Density Related to Human Exposure to Radio Frequency Fields from Wireless Communication Devices Operating between 6 GHz and 300 GHz”. The successful assessment of real-world FR2-enabled wireless underscores the fitness of the developed APD assessment system for compliance testing of end-user products.

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Deliverable Details

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Keywords	FR2 Uplink Exposure

Contents

1 Introduction

To safeguard human health against potential adverse effects of exposure to electromagnetic fields (EMFs), several international organizations have established safety guidelines. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the IEEE International Committee on Electromagnetic Safety (IEEE ICES) provide guidelines that include basic restrictions (dosimetric limits) and reference levels (incident field limits) [2, 3].

The specific absorption rate (SAR), defined as the power absorbed per unit mass of tissue, has served as the dosimetric quantity used to define basic restrictions to regulate exposure to EMF. This standard applies to frequencies of up to 6 GHz [2] or 10 GHz [3], with the aim to limit tissue heating to a maximum of 1°C. Established in the early 1970s [4], SAR has remained a cornerstone of safety guidelines. To support compliance, product standards have been developed to facilitate the assessment of peak spatial SAR values, particularly for transmitters operating within 2 mm of tissue simulating media [5].

The existing compliance framework for electromagnetic (EM) exposure proved adequate until the allocation of new frequency bands for fifth-generation (5G) cellular network technologies that operate at frequencies above 10 GHz. These higher frequency bands were introduced to address the growing demand for faster data transfer rates, more secure communication, and lower latency. However, adoption of these bands has introduced novel human exposure scenarios, particularly for near-field exposures in the millimeter-wave (mmW) range.

Initially, incident power density (IPD) [6] was employed as a pseudo-dosimetric limit and is currently used for wireless product compliance testing at frequencies above 10 GHz [7]. However, IPD does not account for near-field coupling or backscattering effects involving the human body, making it an inadequate metric for accurate exposure assessment [1]. To address these limitations, the concept of absorbed power density (APD) [2] or epithelial power density (EPD) [3] has been introduced as a metric for basic restrictions in the most recently formulated safety guidelines. These metrics are averaged over a square area of 4 cm^2 for frequencies between 6 – 30 GHz and over 1 cm^2 for frequencies above 30 GHz, ensuring a more accurate limitation of maximum tissue heating.

1.1 State-of-the-Art

At the start of the SEAWave project, the frequency range of commercial APD test systems was limited to 10 GHz to support testing in accordance with [8]. At frequencies above 10 GHz, only IPD test systems were available to support product compliance testing in accordance with [7]. Until now, due to the lack of APD compliance test systems as well as delayed adoption of APD limits above 10 GHz, commercial wireless devices have been tested on the basis of the IPD metric.

1.2 Objective

In WP4 of the SEAWave project, we have developed 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 multiple-input multiple-output (MIMO) transmitters; and (iii) demonstrating that the instrumentation operates as intended in any device configuration.

In particular, the objective of D4.3 was to apply the developed and validated APD test system (D4.2) to assess commercial FR2-enabled 5G devices and document the results. As FR2-enabled end-user devices are not yet available in Europe, an FR2-enabled development device was sourced, and the APD and IPD of three FR2 communication modules in these devices were assessed.

2 Assessment of FR2-Enabled Enduser Devices

The following sections document the test setup and results used to assess the IPD and APD of three commercial FR2 modules in a development kit wireless device.

2.1 Equipment Under Test

The equipment under test (EUT) is a development kit resembling the form factor of a typical mobile wireless device. The EUT integrated three distinct 5G FR2 communication modules on its top, left, and right sides. The locations of these modules is shown in Figure 1. Each of the three modules can be controlled independently with software provided by the EUT manufacturer. To maintain confidentiality related to the tested device, this document primarily uses schematic drawings and blurred photographs of the EUT.

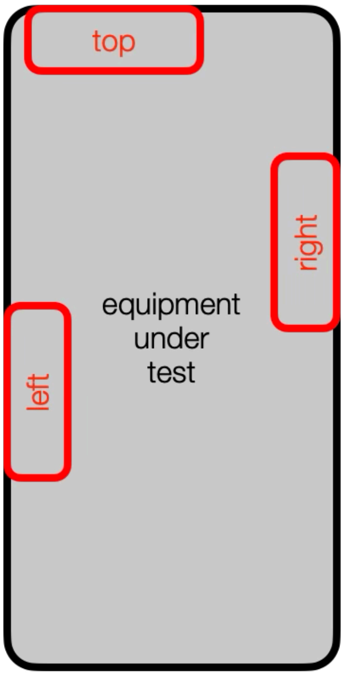


Figure 1: Schematic (front view) diagram of the EUT, indicating the locations of the top, left, and right FR2 communication modules.

2.2 Measurement Systems

2.2.1 APD Measurement System

Figure 2 shows the functional principle and a photograph of the APD measurement system developed in WP4 of the SEAWave project.

The specific DASY8 system used in the measurements of the APD is detailed in Table 1. All components critical for the measurement results were calibrated within <12 months before the test, and the dielectric parameters of the skin-simulating liquid were measured before and after the tests. The system was checked with a verification source before the EUT measurements. Verification results were within the combined standard uncertainty of the APD measurement system, i.e., <0.80 dB.

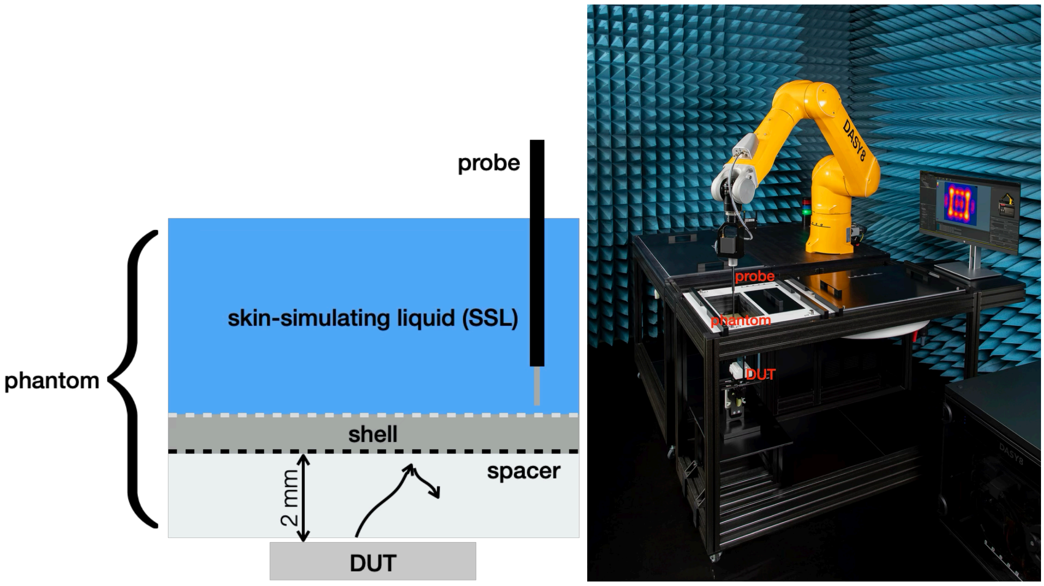


Figure 2: DASY8 Module APD. Left: Schematic diagram of the APD measurement system based on the dosimetric probe principle. The skin-emulating phantom and skin-simulating liquid, the EUAPDVx pseudo-vector probe, and the EUT under the phantom are shown. Right: Commercial implementation of the APD measurement system in DASY8 Module APD.

System	Type:	DASY8 Module APD
	Software Version:	1.2.2
	Manufacturer:	Schmid & Partner Engineering AG, Switzerland
Positioner	Robot:	TX2-60L
	Serial No:	F/23/0048739/A/005
	Controller:	CS9
	Serial No:	F/23/0048739/C/005
	Manufacturer:	Stäubli, France
Data Acquisition System	Type:	DAE8APD
	Serial No:	1753
	Calibrated On:	Feb. 28, 2025
	Manufacturer:	Schmid & Partner Engineering AG, Switzerland
Probe	Type:	EUAPDV2
	Serial Number:	1024
	Calibrated On:	Feb. 20, 2025
	Manufacturer:	Schmid & Partner Engineering AG, Switzerland
Phantom	Type:	PHA-30GV2
	Serial Number:	1003
	Manufacturer:	Schmid & Partner Engineering AG, Switzerland
SSL	Type:	SSL-30GV2
	Permittivity (ϵ_r):	5.4± 3.2%
	Conductivity (σ):	3.12± 5.2% S/m
	Manufacturer:	Schmid & Partner Engineering AG, Switzerland

Table 1: Measurement system used for the near-field assessment of the APD.

2.2.2 IPD Measurement System

Figure 3 shows a photograph of the DASY8 Module mmWave measurement system used for IPD measurements in the SEAWave project. DASY8 Module mmWave is fully compliant with the product test standard [7] for compliance testing of millimeter-wave communication devices with IPD limits.

The specific DASY8 system used in the measurements of the IPD is detailed in Table 2. All components critical for the measurement results were calibrated within $<$12 months before the test, and the system was checked with a verification source before the EUT measurements. Verification results were within the combined standard uncertainty of the IPD measurement system, i.e., $<$0.75 dB.

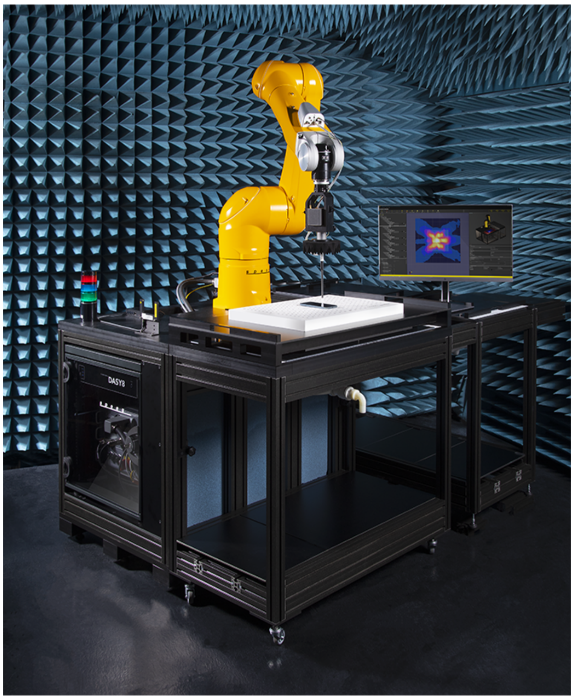


Figure 3: DASY8 Module mmWave measurement system for IPD assessments in compliance with IEC/IEEE 63195-1 [7].

System	Type: Software Version: Manufacturer:	DASY8 Module mmWave 3.2.2 Schmid & Partner Engineering AG, Switzerland
Positioner	Robot: Serial No: Controller: Serial No: Manufacturer:	TX2-90XL F/20/0020175/A/001 CS9 F/20/0020175/C/001 Stäubli, France
Data Acquisition System	Type: Serial No: Calibrated On: Manufacturer:	DAE4ip 1339 Oct. 15, 2024 Schmid & Partner Engineering AG, Switzerland
Probe	Type: Serial Number: Calibrated On: Manufacturer:	EUmmWV4 9477 Jun. 06, 2024 Schmid & Partner Engineering AG, Switzerland

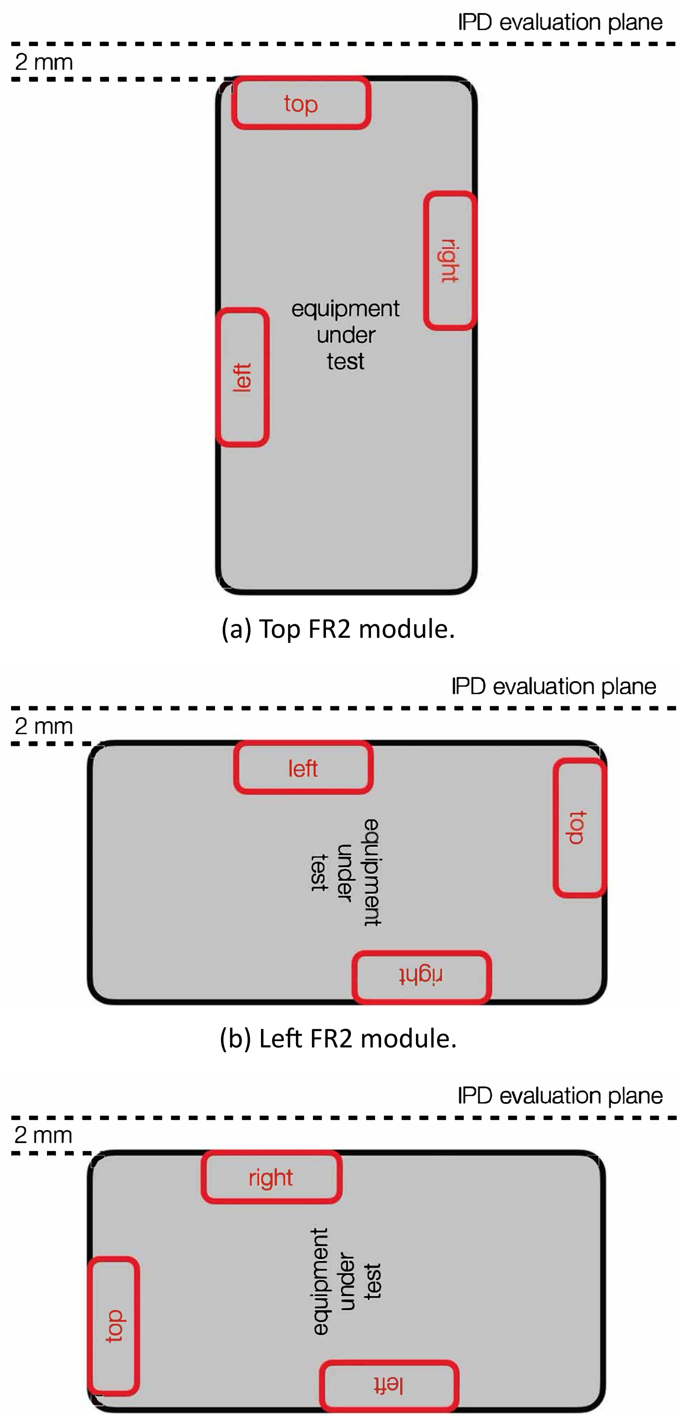
Table 2: Measurement system used for the near-field assessment of the IPD.

2.3 Test Conditions

This section details the test conditions of the EUT with the integrated millimeter-wave modules. The locations of the three FR2-modules are shown in Figure 1.

For the APD and IPD measurements, the EUT was configured with a manufacturer-level control software. The EUT was set up to have each of the three modules radiating in boresight direction at 27.5 GHz and operating with maximum output power. It is important to note that, in an end-user device, the output power would typically be tuned to a lower level than what was tested here to meet the EM exposure safety design targets. Typically, the power is tuned to achieve a power density in the range of two-thirds of the actual safety limit.

The APD and IPD of the EUT were then measured with the evaluation surface in both cases at 2 mm away from the outside casing of the EUT. These test configurations for the three modules are visualized in Figure 4 for the IPD and in Figure 5 for the APD. Photographs of the test setups for the APD and IPD of the top FR2 module are shown in Figure 6.

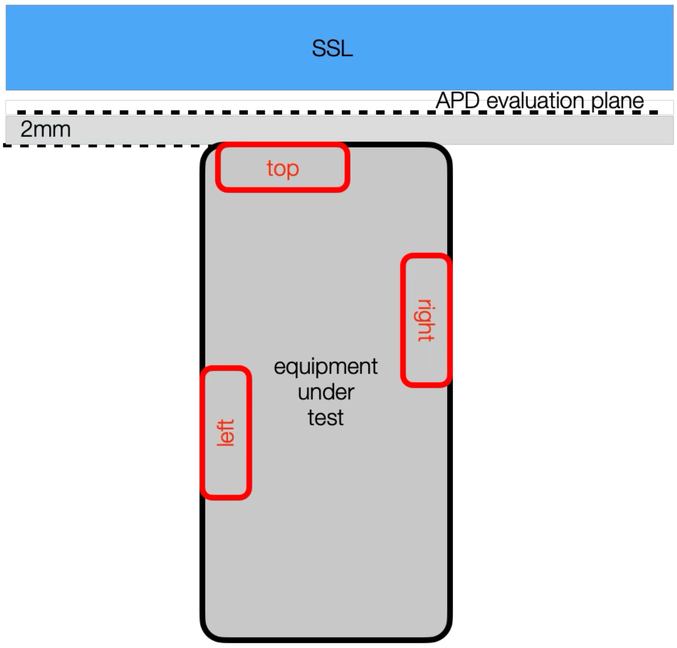


(a) Top FR2 module.

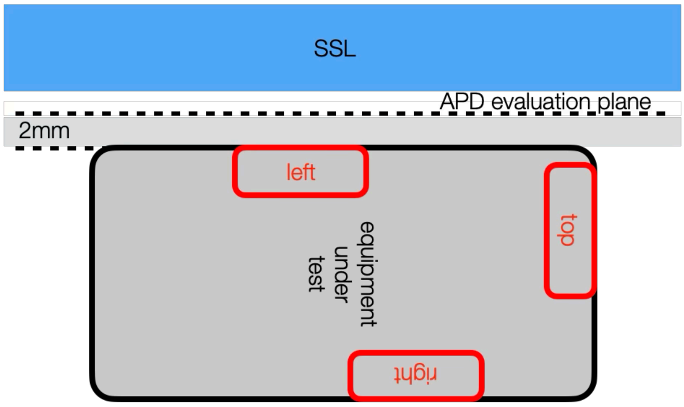
(b) Left FR2 module.

(c) Right FR2 module.

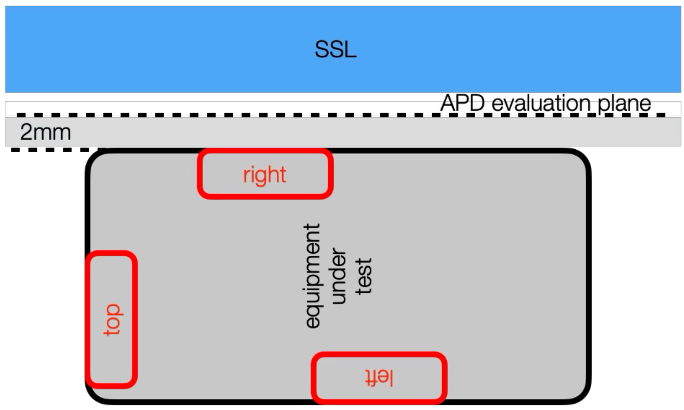
Figure 4: Test configurations for the IPD test setup with the evaluation plane set at 2 mm from the outer casing of the EUT.



(a) Top FR2 module.



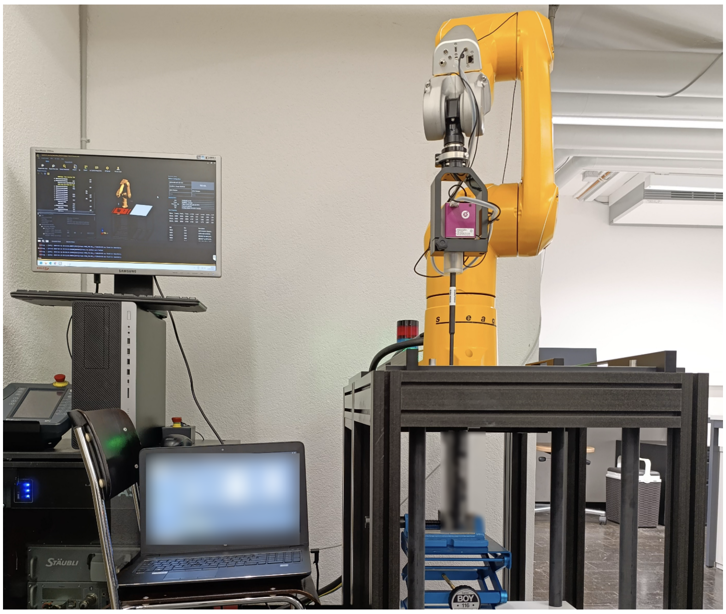
(b) Left FR2 module.



(c) Right FR2 module.

Figure 5: Test configurations for the APD test setup with the evaluation plane set at 2 mm from the outer casing of the EUT.

(a) IPD: top FR2 module.



(b) APD: top FR2 module.

Figure 6: Photographs showing the top FR2 module test setup for IPD and APD testing.

2.4 Measurement Uncertainty

The complete uncertainty budgets for APD and IPD measurements with DASY8 Modules APD and mmWave are summarized in Sections 2.4.1—2.4.2. The expanded measurement uncertainty for APD was found to be 1.64 dB for the averaging area of 1 cm^2 and 1.60 dB for the averaging area of 4 cm^2. Likewise, the expanded measurement uncertainty for IPD was found to be 1.51 dB for both the 1 cm^2 and 4 cm^2 averaging areas.

2.4.1 APD Measurement Uncertainty

The uncertainty budget for measurements performed with the DASY8 Module APD system is summarized in Table 3.

Uncertainty Budget **APD Measurement System** **(Frequency band: 24 –30 GHz range)**											
Sym-bol	Error Description	Unc. value	Unc. |dB	Prob. Dist.	Div.	c_i peak	c_i 1 cm^2	c_i 4 cm^2	Std. Unc. APD |dB peak	1 cm^2	4 cm^2
Measurement System											
CF	Probe Calibration	26.7	1.03	N	2	1	1	1	0.51	0.51	0.51
CF$_{drift}$	Probe Calib. Drift	1.7	0.07	R	1.73	1	1	1	0.04	0.04	0.04
LIN	Probe Linearity	4.7	0.20	R	1.73	1	1	1	0.12	0.12	0.12
BBS	Broadband Signal	2.8	0.12	R	1.73	1	1	1	0.07	0.07	0.07
ISO	Isotropy	4.7	0.20	R	1.73	1	1	1	0.12	0.12	0.12
DAE	Probe Electronics	0.8	0.03	N	1	1	1	1	0.03	0.03	0.03
AMB	RF Ambient	1.0	0.04	N	1	1	1	1	0.04	0.04	0.04
Δsys	Probe Positioning	±0.1mm	0.18	N	1	1	1	1	0.18	0.18	0.18
PPS	Skin APD Reconstr.	13.7	0.56	R	1.73	0.55	0.82	1	0.18	0.26	0.32
Phantom											
SSL(ϵ)	SSL ϵ	10.0	0.41	R	1.73	0.54	0.54	0.54	0.13	0.13	0.13
SSL(σ)	SSL σ	10.0	0.41	R	1.73	0.05	0.05	0.05	0.01	0.01	0.01
DAK(ϵ)	SSL ϵ meas.	3.2	0.14	N	2	0.54	0.54	0.54	0.04	0.04	0.04
DAK(σ)	SSL σ meas	5.2	0.22	N	2	0.05	0.05	0.05	0.01	0.01	0.01
SSL(ϵ/T)	SSL ϵ on T	1.2	0.05	R	1.73	0.54	0.54	0.54	0.02	0.02	0.02
SSL(σ/T)	SSL σ on T	5.1	0.22	R	1.73	0.05	0.05	0.05	0.01	0.01	0.01
SHP	Shell Permittivity	5.0	0.21	R	1.73	1.05	1.05	1.05	0.13	0.13	0.13
SHT	Shell Thickness	5.0	0.21	R	1.73	0.42	0.42	0.42	0.05	0.05	0.05
SME(A)	Skin Emulation	11.2	0.46	R	1.73	0.62	1	0.85	0.17	0.27	0.23
SME(f)	Frequency Resp.	5.6	0.24	R	1.73	1	1	1	0.14	0.14	0.14
Device											
DIS	EUT to Pha. Dist.	11.2	0.46	R	1.73	1	1	1	0.27	0.27	0.27
H	Holder Effects	0	0	N	1	1	1	1	0	0	0
MOD	EUT Modulation	9.7	0.4	R	1.73	1	1	1	0.23	0.23	0.23
TAAPD	Time-average APD	1.7	0.07	R	1.73	1	1	1	0.04	0.04	0.04
RF drift	EUT Drift	3.5	0.15	N	1	1	1	1	0.15	0.15	0.15
Corrections to the APD Results											
C (R)	APD scaling	0.0	0.00	R	1.73	1	1	1	0.00	0.00	0.00
uΔSAR	Combined Uncertainty								0.77	0.82	0.80
U	**Expanded Uncertainty**								**1.54**	**1.64**	**1.60**

Table 3: Worst-case uncertainty budget for APD measurements of user devices and validation sources. The budget is valid for the frequency range 24 GHz–30 GHz and represents a worst-case analysis.

2.4.2 IPD Measurement Uncertainty

The measurement uncertainty budget for the DASY8 Module mmWave IPD measurement system is summarized in Table 4.

Uncertainty Budget for IPD (avg ≥ 1 cm^2)							
Error Description		Unc.Value ($\pm$dB)	Prob. Distr.	Div.	(c_i)	Std. Unc. ($\pm$dB)	(v_i) v_{eff}
Uncertainty terms dependent on the measurement system							
CAL	Calibration	0.49	N	1	1	0.49	∞
COR	Probe correction	0	R	$\sqrt{3}$	1	0	∞
FRS	Frequency response (BW $\leq$ 1 GHz)	0.20	R	$\sqrt{3}$	1	0.12	∞
SCC	Sensor cross coupling	0	R	$\sqrt{3}$	1	0	∞
ISO	Isotropy	0.50	R	$\sqrt{3}$	1	0.29	∞
LIN	Linearity	0.20	R	$\sqrt{3}$	1	0.12	∞
PSC	Probe scattering	0	R	$\sqrt{3}$	1	0	∞
PPO	Probe positioning offset	0.30	R	$\sqrt{3}$	1	0.17	∞
PPR	Probe positioning repeatability	0.04	R	$\sqrt{3}$	1	0.02	∞
SMO	Sensor mechanical offset	0	R	$\sqrt{3}$	1	0	∞
PSR	Probe spatial resolution	0	R	$\sqrt{3}$	1	0	∞
FLD	Field impedance dependence	0	R	$\sqrt{3}$	1	0	∞
MED	Measurement drift	0.05	R	$\sqrt{3}$	1	0.03	∞
APN	Amplitude and phase noise	0.04	R	$\sqrt{3}$	1	0.02	∞
TR	Measurement area truncation	0	R	$\sqrt{3}$	1	0	∞
DAQ	Data acquisition	0.03	N	1	1	0.03	∞
SMP	Sampling	0	R	$\sqrt{3}$	1	0	∞
REC	Field reconstruction	0.60	R	$\sqrt{3}$	1	0.35	∞
SNR	Signal-to-Noise Ratio	0	R	$\sqrt{3}$	1	0	∞
TRA	FTE/MEO	0	R	$\sqrt{3}$	1	0 (0)	∞
SCA	Power density scaling	–	R	$\sqrt{3}$	1	–	∞
SAV	Spatial averaging	0.10	R	$\sqrt{3}$	1	0.06	∞
Uncertainty terms dependent on the EUT and environmental factors							
PC	Probe coupling with EUT	0	R	$\sqrt{3}$	1	0	∞
MOD	Modulation response	0.40	R	$\sqrt{3}$	1	0.23	∞
IT	Integration time	0	R	$\sqrt{3}$	1	0	∞
RT	Response time	0	R	$\sqrt{3}$	1	0	∞
DH	Device holder influence	0.10	R	$\sqrt{3}$	1	0.06	∞
DA	EUT alignment	0	R	$\sqrt{3}$	1	0	∞
AC	RF ambient conditions	0.04	R	$\sqrt{3}$	1	0.02	∞
TEM	Laboratory Temperature	0.05	R	$\sqrt{3}$	1	0.03	∞
REF	Laboratory Reflections	0.04	R	$\sqrt{3}$	1	0.02	∞
MSI	Immunity / secondary reception	0	R	$\sqrt{3}$	1	0	∞
DRI	Drift of the EUT	0.15	N	1	1	0.15	∞
Combined Std Uncertainty						0.75	∞
Expanded Std Uncertainty						**1.53**	

Table 4: Uncertainty budget for DASY8 Module mmWave for IPD complies with IEC/IEEE 63195-1 [7]. The budget is valid for evaluation distances $\geq \lambda/25$.

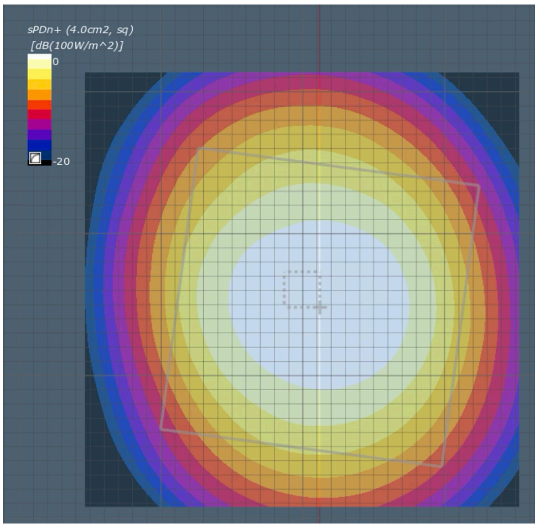
2.5 Test Results

The APD and IPD results of the three tested 5G FR2 modules are summarized in Table 5 . Figure 7 shows comparative IPD and APD distributions of the 4 cm^2 averaged results. While the shapes of the distributions are not much different between IPD and APD, the ratio of the IPD to APD is generally about 3 dB. It should be noted that, in an end-user device, the adjustment of the FR2 module output power would include a sufficient margin to comply with the safety limit. For example, the power would be adjusted to meet the targeted APD value of $\approx$14 W/m^2, i.e., approximately 4 dB lower than the value listed in Table 5.

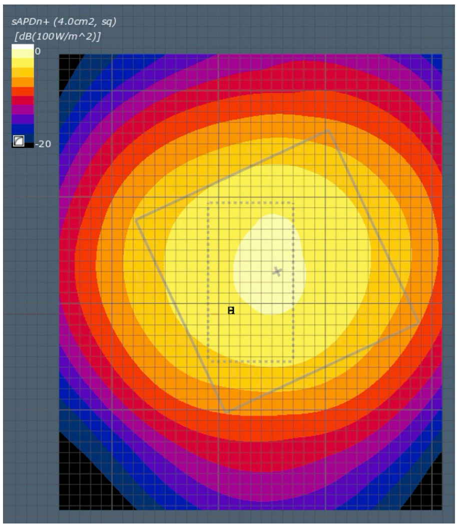
Module		**APDn+ (rotating square average)**				**IPDn+ (rotating square average)**			
	f /GHz	**E_{max}** [a] /(V/m)	**peak** [a]	**1 cm^2** [b] /(W/m^2)	**4 cm^2** [c]	**E_{max}** [d] /(V/m)	**peak** [d]	**1 cm^2** [e] /(W/m^2)	**4 cm^2** [e]
top	27.5	60.7	41.5	29.2	17.5	193	106	60.3	35.5
right	27.5	64.9	46.5	31	18.7	194	91.8	59.2	34
left	27.5	80.4	71.3	38.3	20	216	121	62.4	35.3

[a] Expanded Uncertainty: ±1.54 dB
[b] Expanded Uncertainty: ±1.64 dB
[c] Expanded Uncertainty: ±1.60 dB
[d] Expanded Uncertainty: ±1.73 dB
[e] Expanded Uncertainty: ±1.53 dB

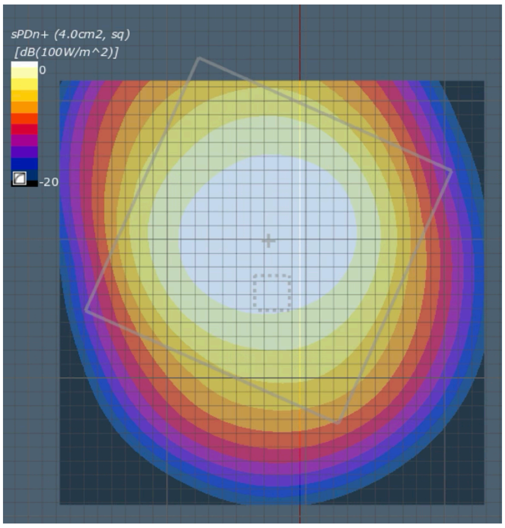
Table 5: APD and IPD measurement results for the different 5G FR2 modules in a mobile device.



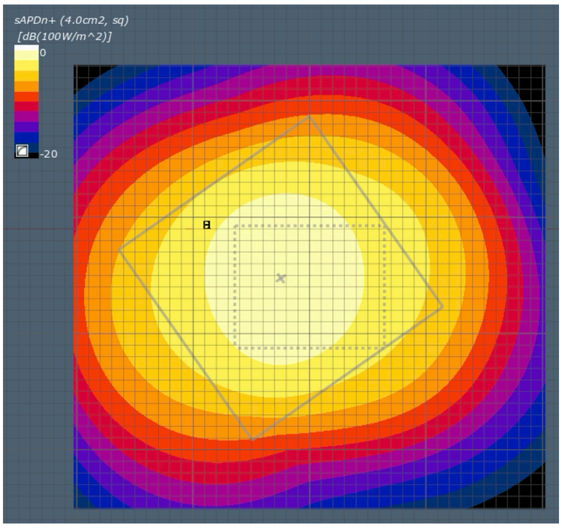
(a) IPD: top module.



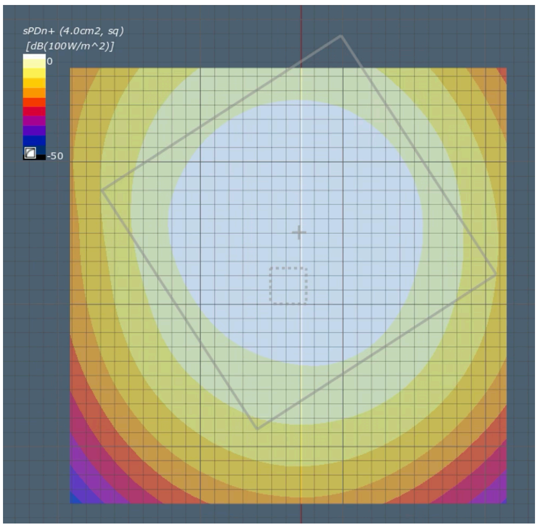
(b) APD: top module.



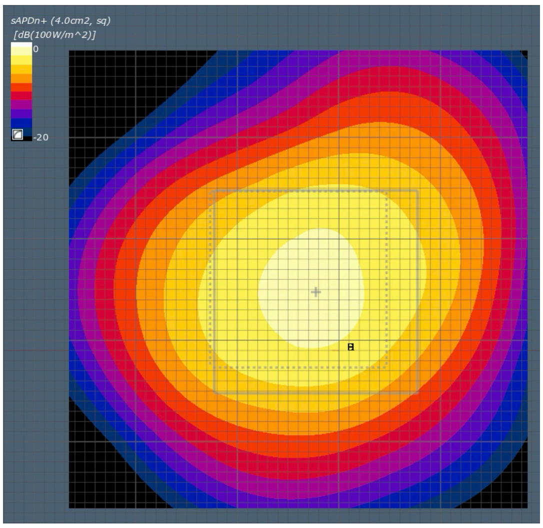
(c) IPD: left module.



(d) APD: left module.



(e) IPD: right module.



(f) APD: right module.

Figure 7: Plots of the 4 cm_2 average incident and absorbed densities of the three 5G FR2 modules integrated in a mobile device.

3 Conclusions

This report documents the successful completion of Deliverable 4.3, which entails the experimental assessment of FR2-enabled devices with the validated APD measurement system developed in this project. Due to the current unavailability of commercially marketed FR2 devices in Europe, a specialized development device containing integrated and controllable FR2 modules was procured directly from a wireless chip manufacturer.

The report summarizes tests conducted on three distinct FR2 modules embedded in the development device. The assessments were performed with the measurement equipment according to protocols specifically developed under this work package. The measurements were focused on the determination of both APD and IPD at a distance of 2 mm from the surface of the device and at an operating frequency of 27.5 GHz, with the antenna beam oriented in the direction of the boresight.

For these specific modules, the ratios of the IPD to APD are close to a factor of two. It should be noted that this ratio can vary by as much as ± 6 dB, depending on the near-field characteristics of the transmitter [1].

However, depending on the FR2 module design and, as shown for the tested modules, the use of a skin-simulating phantom for testing with APD limits may mitigate the compliance burden for device manufacturers. The use of APD criteria also demonstrably decreases the testing uncertainty and enhances the reliability of wireless device safety evaluations. Such an approach presents clear benefits for industry stakeholders, regulatory bodies, and end-users.

The results of the work contributed to the IEC TC106 WG11 working on the APD product test standard IEC/IEEE pt63195-3 ”Evaluation of Absorbed Power Density Related to Human Exposure to Radio Frequency Fields from Wireless Communication Devices Operating between 6 GHz and 300 GHz”. The successful assessment of real-world FR2-enabled wireless underscores the fitness of the APD assessment system developed here for compliance testing of end-user products.

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