

Assessment of ICNIRP 2020 Limit Relevance for Small-Area and Short-Term Millimeter-Wave Exposure from Fixed Transmitting Installations

conducted by

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A report on behalf of the Swiss Federal Office for the Environment (FOEN).

Zurich, 2 September 2026
(Revision 2)

The names of IT^{IS} and any of the researchers involved may be mentioned only in connection with statements or results from this report.

Imprint

Client:	Swiss Federal Office for the Environment (FOEN) Noise and NIR Division, CH-3003 Bern The FOEN is an office of the Federal Department of the Environment, Transport, Energy and Communications (DETEC)
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Note:	This study was commissioned by the Swiss Federal Office for the Environment (FOEN). The contractor is solely responsible for the content.
Date:	2 September 2026
Version:	V 1.2

Executive Summary

In its 2020 radiofrequency guidelines, ICNIRP revised the exposure limits for the mmWave range, adding local incident power density reference levels (spatially averaged over 4 cm^2 at 2 GHz and above and additionally 1 cm^2 at and above 30 GHz, time-averaged over 6 minutes), also referred to as peak spatial average incident power density (psIPD). Additionally, new brief exposure restrictions on the cumulative incident energy density over intervals shorter than 6 minutes [1] were introduced. The Swiss Federal Office for the Environment (FOEN) plans to incorporate these limits, or a subset of these limits, extending the Ordinance on Protection against Non-Ionising Radiation (ONIR) above 6 GHz, with a revision planned for 2027. This study assesses, for realistic future fixed millimeter-wave transmitting installations within the scope of the ONIR (general public, fixed communication system), under which conditions the ICNIRP limits become relevant and which of the limiting quantities are decisive. If FOEN plans to introduce precautionary limits, i.e., by reducing ICNIRP limits by a factor x , the results of this report can be applied by considering the factor x .

To address these questions, first, a review of the ICNIRP 2020 guidelines and the relevant compliance-testing standards were conducted. The technological state of the art and prospective future deployment scenarios were addressed by reviewing the scientific literature, standardization documents, and currently deployed and emerging fixed mmWave systems in Switzerland and abroad. Representative signal transmission levels, antenna, and exposure scenario characteristics were derived from the review. Based on these characteristics, a multi-dimensional (exposure distance, gain, beam-steering, antenna radiated power) exposure evaluation of whole-body and local (4 cm^2 , 1 cm^2) incident power density limits was performed using a semi-analytical patch-array model validated against FDTD simulations. A linear time-invariant thermal model as well as peer-reviewed literature data were used to assess under which duty cycles the short-term exposure limits based on cumulative energy density may become limiting compared to the 6-minute averaged local power density limits.

The scope of the evaluation focuses on public, fixed mmWave communication installations; other mmWave applications such as general mobile or private links are outside the scope of this report. The main identified relevant installations are cellular and fixed wireless access (FWA) in FR2 (24.25–71 GHz) and, prospectively, FR3 (7–24 GHz). Sub-terahertz ($>100\text{ GHz}$) operation is not expected to emerge before the early 2030s (WRC-31) and, considering the low worldwide commercial FR2 adoption, is unlikely to be implemented in public communication networks. Neither sufficiently defined technical parameters nor a credible path to commercial adoption of sub-terahertz communication systems is currently available. The study therefore considers phased-array installations in the frequency range from 7 GHz to 40 GHz with realistic maximum Effective Isotropic Radiated Power (EIRP) from approximately 40 dBm (pico cells) to 85 dBm (macro cells), serving users at base-station distances of from 2 m to 20 m (pico cells) and approximately 35 m to several hundred meters for macro cell installations. Internationally, actual deployments are confined to high-capacity hotspots and to fixed wireless access (FWA) in areas lacking wired broadband. In Switzerland, no such deployments currently exist. From the international deployment history and Switzerland's existing infrastructure, it is unlikely that FR2 cellular will be deployed beyond high-capacity hotspots or FWA outside underserved remote areas. Broader adoption is expected for FR3 at the earliest by ~ 2029 –2030 together with the introduction of 6G.

The exposure relative to the limits is governed mainly by the distance from the antenna, its mounting height, its directivity, and power radiated.

For the whole-body limit, which is frequency-independent above 2 GHz, the maximum permissible radiated power can be expressed through these parameters. The whole-body limit becomes the decisive quantity for person-to-antenna distances beyond approximately 7 m, at an EIRP of approximately 65 to 75 dBm depending on array type. Whereas the local psIPD limit becomes restrictive only at much shorter distances, below approx-

imately 5 m reaching as low as 55 dBm EIRP at 1 m distance. At the minimum base-station-to-person distances of the scenarios (35 m for the macro, 2 m for the pico TS 38.104 base-station class), the whole-body limit permits a maximum EIRP of approximately 80 dBm and 65 dBm, respectively. The effect of the whole-body averaging area may be as much as 5 dB comparing adult- and child-equivalents. Therefore, future assessment guidelines should consider averaging areas representing the surface area of children.

At the relevant distances, the whole-body limit is generally the more restrictive (by approximately 5 dB compared to the local psIPD limit both for adults and children); compliance with the local small-area limit therefore does not guarantee compliance with the whole-body limit. Conversely, whole-body compliance also ensures local compliance beyond approximately 7 m, with the crossover distance increasing with array size. In general, the local psIPD limit can only become the decisive quantity within approximately 5 m from the antenna and at an EIRP above ≈ 55 dBm at 1 m and rapidly increasing to ≈ 65 dBm at 5 m. For fixed mmWave installations, the whole-body incident-power-density limit is typically the decisive quantity, while the local psIPD only becomes relevant at close person-to-base-station distances. Ground reflections and horizontal beam steering each further reduce the permissible power, by up to approximately 3.5 dB for larger arrays and up to 6 dB for smaller arrays.

Regarding brief exposure limits, the six-minute average is generally more restrictive for realistic communication waveforms. The brief exposure energy-density limits become binding only for exposures with a high peak-to-average ratio and a low duty cycle. Such properties are unrealistic for fixed mmWave communication installations, so the short-term limits do not constrain them beyond the whole-body and psIPD limits. Future fixed installations may, however, integrate sensing functionality (integrated sensing and communication, ISAC). As long as sensing reuses the communication signal and amplifier chain, the brief-exposure limits do not become relevant. However, if a separate, radar-like transmit chain is integrated that can generate substantially higher peak powers, brief exposure limits may require consideration.

For fixed mmWave installations within the scope of the ONIR, a subset of the ICNIRP 2020 limits is sufficient for the safety assessment: the whole-body incident-power-density limit is decisive in configurations above distances of approximately 7 m, complemented by the local psIPD limit at short separations. The short-term energy-density limits do not require separate assessment for realistic communication signals, unless radar-like or ISAC functionality with a separate high-peak-power transmit chain is integrated into fixed installations.

Note: The results presented in this report are evaluated against the ICNIRP exposure limits [1] applicable to frequencies above 6 GHz and do not include any precautionary limits. Since the results scale with the applicable exposure limits, they can be readily adapted to more restrictive limits by applying the appropriate scaling factor.

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1 List of Abbreviations and Acronyms

Nomenclature

3GPP	3rd Generation Partnership Project
AAU	Active Antenna Unit
ACLR	Adjacent Channel Leakage Ratio
AMC	Adaptive Modulation and Coding
BS	Base Station
CAGR	Compound Annual Growth Rate
CEPT	European Conference of Postal and Telecommunications Administrations
CFR	Crest-Factor Reduction
CPE	Customer-Premises Equipment
ECC	Electronic Communications Committee (of CEPT)
EIRP	Equivalent Isotropic Radiated Power
EMF	Electromagnetic Field
ERP	Effective Radiated Power
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FDTD	Finite-Difference Time-Domain
FOEN	Federal Office for the Environment
FR2	Frequency Range 2
FR3	Frequency Range 3
FTTH	Fiber to the Home
FWA	Fixed Wireless Access
HAPS	High-Altitude Platform System
IAB	Integrated Access and Backhaul
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications

IPD	Incident Power Density
ISAC	Integrated Sensing and Communication
ISD	Inter-Site Distance
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication Sector
METAS	Swiss Federal Institute of Metrology
MFCN	Mobile/Fixed Communications Networks
MIMO	Multiple-Input Multiple-Output
mmWave	millimeter-wave
NFAP	National Frequency Allocation Plan
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
ONIR	Ordinance on Protection against Non-Ionizing Radiation (Verordnung über den Schutz vor nichtionisierender Strahlung, NISV)
PAPR	Peak-to-Average Power Ratio
PD	Power Density
psAPD	peak spatial-average absorbed power density
psIPD	peak spatial-average incident power density
QAM	Quadrature Amplitude Modulation
RF	Radiofrequency
RIR	Technical Interface Regulations
RIS	Reconfigurable Intelligent Surface
RMS	Root Mean Square
RSPG	Radio Spectrum Policy Group
SAR	Specific Absorption Rate
SDMA	Spatial Division Multiple Access
SNR	Signal-to-Noise Ratio
STAR-RIS	Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface
TDD	Time-Division Duplex
TRP	Total Radiated Power
UAV	Unmanned Aerial Vehicle

UBR	Unlicensed Band Radio
UE	User Equipment
UHF	Ultra-High Frequency
WiGig	Wireless Gigabit (IEEE 802.11ad/ay)
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WRC	World Radiocommunication Conference

2 Introduction

In its 2020 radiofrequency guidelines [1], the International Commission on Non-Ionizing Radiation Protection (ICNIRP) revised the exposure limits for the millimeter-wave (mmWave) range, introducing local incident-power-density reference levels spatially averaged over 4 cm^2 (at and above 2 GHz) and 1 cm^2 (at and above 30 GHz), and time-averaged over 6 minutes. Additionally, new short-term restrictions were also added limiting the cumulative incident *energy density* U_{inc} over any interval shorter than 6 minutes, to prevent excessive local skin heating from brief, pulsed exposures that could occur despite compliance with the time-averaged incident power density limits.

On 22 November 2023, the Swiss Federal Council released a report stating that the use of mmWave for mobile communications will only be permitted after regulatory requirements are in place and industry has shown commercial interest [2].

The Swiss Federal Office for the Environment (FOEN) plans to incorporate new restrictions on incident exposure for fixed installations above 6 GHz into the revision of the Ordinance on Protection against Non-Ionizing Radiation (ONIR) planned for 2027.

In January 2026, the FOEN mandated the Foundation for Research on Information Technologies in Society (IT'IS) to conduct a research study on fixed mmWave installations in Switzerland. The study prospectively assesses expected future applications, along with their transmission, installation, and usage characteristics, and evaluates the applicability of the ICNIRP 2020 [1] limits, in particular whether only a subset of these limits is required to assess the safety of such installations. The study is limited to fixed transmitting installations that fall within the scope of the ONIR and operate in the frequency range from 6 to 300 GHz, and it addresses the exposure of the general public.

Section 3 of this report outlines the specific objectives of this study. In the following, the report is structured as follows: a review of the ICNIRP 2020 [1] guidelines in Section 4, followed by a review of technologies and trends in fixed mmWave communication systems, including an outlook on prospective deployment scenarios in Switzerland in Section 5. Section 6 derives the key transmission characteristics and exposure scenarios for future fixed mmWave installations, serving as the basic input for the safety evaluation with respect to the ICNIRP 2020 limits performed in Section 7. The report summarizes limitations and findings in Section 8.

3 Objectives

The study addresses the following three objectives:

1. Determine which technical applications and scenarios of fixed mmWave installations (within the scope of the ONIR) exist or are expected in Switzerland, and compare the situation against deployments abroad.
2. Determine which source properties (radiated power, radiation/beam characteristics, distance to exposed persons) future fixed mmWave installations must have for the power-density and cumulative-energy-density limits to become relevant, and present the exposure scenarios in which the immissions approach these reference levels.
3. Assess whether compliance with the short-term, small-area (local) limits automatically ensures compliance with the whole-body limits and vice versa, and which of the limiting quantities are particularly relevant for fixed mmWave installations and which can be considered less significant.

4 Review of the ICNIRP 2020 Guidelines

4.1 Overview

4.1.1 General

The objective of the electromagnetic field (EMF) exposure guidelines, such as those issued by the ICNIRP [1] or by the Technical Committee 95 of the Institute of Electrical and Electronics Engineers (IEEE) [3], is to specify limits below which harmful effects on exposed persons can be ruled out. To quantify exposure levels, ICNIRP requires substantiated scientific evidence, meaning that potentially harmful effects must have been independently and consistently verified by the scientific community. The effects considered by the ICNIRP include, e.g., nerve stimulation in the low-frequency range below 10 MHz and, at higher frequencies, temperature increases caused by the dissipation of electromagnetic energy in biological tissue.

The exposure limits are set in two tiers by correlating the threshold at which adverse health effects are reported in the scientific literature with the incident or induced fields. The first tier applies to occupational exposure, i.e., to the exposure of adults who are assumed to be healthy, aware of the exposure at their workplace, and ready to take mitigation measures in case of any adverse symptom. To take into account uncertainties in the considered literature, reduction factors are specified, such as a factor of ten for the whole-body exposure limits to keep the maximum temperature increase below 1.0°C. For the second tier, the general public, which also includes more sensitive population groups, such as sick or elderly people or children, an additional reduction factor of five is introduced.

The exposure limits are specified in terms of reference levels and basic restrictions. Basic restrictions refer to the fields induced in the body of the exposed person that can be directly correlated with an adverse health effect, such as an increase in temperature. Assessing induced fields requires experimental or numerical dosimetric methods and is generally more complex than measuring incident fields. Hence, the reference levels are specified based on a conservative correlation between the induced and incident fields. Compliance with exposure limits can therefore be assessed relative to the incident field reference levels using relatively simple measurements or validated computational models. The assessment of the induced fields against the basic restrictions is only required if the incident fields are not compliant with the exposure reference levels. Details are discussed in Section 4.2.

4.1.2 Considerations for Millimeter Wave Exposure

For plane-wave exposure in the millimeter wave frequency range, the electromagnetic energy that penetrates into the tissue of an exposed person is absorbed almost entirely in the layers of the skin. The penetration depth, at which the power density of the incident field drops to $1/e^2$, i.e., by 8.7 dB, with respect to its value at the surface, is approximately 1 mm at 27.5 GHz. The power transmission coefficient for plane waves in the millimeter wave frequency range increases from 0.5 at 10 GHz to 0.7 at 100 GHz, assuming a homogeneous skin model, but may increase to values above 0.9 in case of constructive interference caused by the stratum corneum [4, 5]. The temperature increase in the skin can range from approximately 0.2°C to 0.4°C under worst-case considerations under plane wave conditions for 10 W/m² [4]. In case of a strongly focused incident field, this temperature increase can be even higher when averaging the power density over an area that is larger than the exposed surface [6–8].

Plane-wave exposure can only be assumed at larger distances from the antenna. The far-field distances quantified for the antenna arrays considered in this study are summarized in Table 10. In the reactive near-field region, the electric and magnetic fields generated by the radiating elements of the antenna are not necessarily correlated. The Poynting vector is complex, meaning that the flux of electromagnetic energy changes direction as a function of time. Electric and magnetic fields can contribute to exposure through capacitive or inductive coupling with the tissue [9, 10]. With increasing distance from the antenna, the imaginary part of the complex Poynting vector vanishes, and electric and magnetic fields converge to the orthogonal field components of the plane wave. The ICNIRP Guidelines [1] consider this by distinguishing between the incident power density S_{inc} and plane-wave equivalent incident power density S_{eq} . Details can be found in Section 4.2.2.

4.2 Exposure Limits

4.2.1 Updated ICNIRP Guidelines

As mentioned in Section 2, the ICNIRP issued updated guidelines for the exposure to electromagnetic fields in 2020 [1] because of the beginning deployment of wireless services of the fifth generation (5G) operating in the millimeter wave frequency range. With respect to the previous ICNIRP Guidelines issued in 1998 [11], these updates concern, in particular, the exposure in the millimeter wave frequency range as summarized here [12]:

- The whole body reference levels on the incident electric (E-) and magnetic (H-)field above 2 GHz were suspended.
- A new category of reference levels was introduced concerning local exposure to electromagnetic fields between 100 kHz and 300 GHz.
- The different coupling characteristics of the incident fields in the near- and the far-field zones, in particular of handheld wireless devices, are recognized and appropriately limit the applicability of the reference levels.
- A clear distinction is made between absorbed and incident power density, where the former refers to a basic restriction and the latter to a reference level.
- Local specific absorption rate (SAR) limits apply to up to 6 GHz instead of 10 GHz. Above 6 GHz, power density limits apply.
- The dimensions of the averaging area for the absorbed power density were reduced to 4 cm² and 1 cm², which entails updated exposure limits, a constant 6-minute averaging time, as well as particular restrictions for exposure to short pulses.
- The frequency range for the limit of whole body SAR was increased to 300 GHz.

The reference levels and basic restrictions of the ICNIRP 2020 Guidelines [1] are discussed in detail in Sections 4.2.2 and 4.2.3, as far as they concern exposure above 6 GHz.

4.2.2 Reference Levels

Reference levels for the incident power density S_{inc} are specified for whole-body exposure and for local exposure on a square evaluation surface of 4 cm² over a frequency range from 2 GHz to 300 GHz, and on a square evaluation surface of 1 cm² over a frequency range from 30 GHz to 300 GHz. Averaging times are 30 minutes for whole-body exposure and six minutes for local exposure. Section 4.3 discusses the details of the evaluation of the square surface with respect to compliance testing. Figure 1 shows the reference levels as a function of

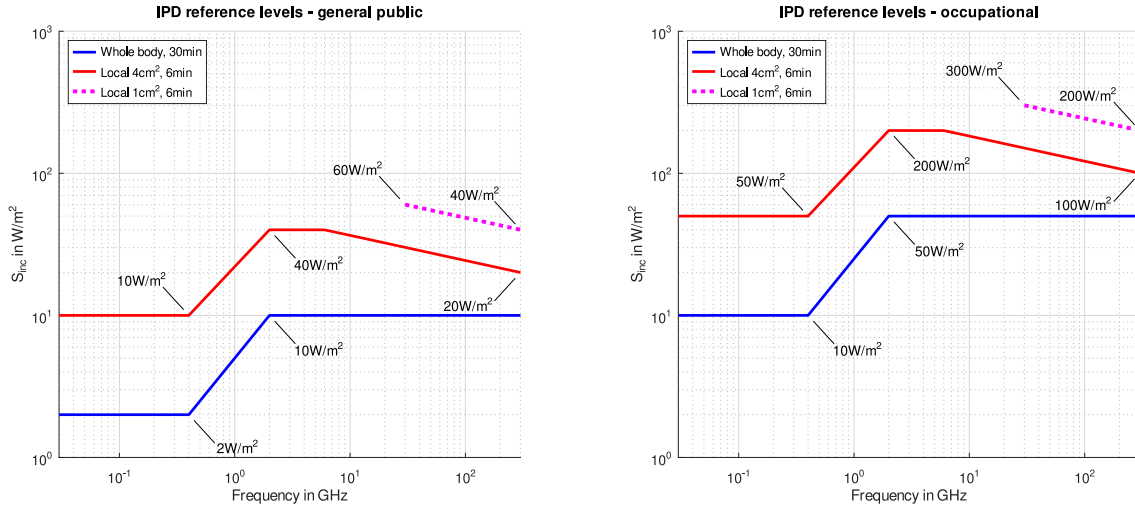


Figure 1: Local and whole body reference levels of the incident power density in the millimeter wave frequency range according to [1] for the general public (left) and occupational exposure (right).

the frequency. The ICNIRP Guidelines [1] specify S_{inc} as

$$S_{inc} = ||\mathbf{E} \times \mathbf{H}^*|| \quad (1)$$

with $\mathbf{E}$ and $\mathbf{H}$ as the complex root-mean-square (RMS) phasors of the electric and magnetic field. The asterisk denotes the complex conjugate. Written for RMS quantities, Eqn. 1 contains no factor $1/2$; it is equivalent to $\frac{1}{2} ||\mathbf{E} \times \mathbf{H}^*||$ evaluated with peak amplitudes.

In the far-field of an antenna, plane wave propagation can be assumed, i.e., the Poynting vector has a radial component S_r only, and its imaginary part is zero. The incident electric and magnetic fields E_u and H_v are orthogonal to one another and correlated by the free-space wave impedance Z_0 .

$$S_{eq} = \frac{1}{Z_0} E_u^2 = Z_0 H_v^2. \quad (2)$$

E_u and H_v indicate the RMS values of the incident electric (E) and magnetic (H) field components.¹

4.2.3 Basic Restrictions

The basic restrictions on local exposure to electromagnetic fields in the frequency range from 6 GHz to 300 GHz as specified in [1] are based on the induced temperature increase due to absorption. According to [1], adverse health effects are avoided if the maximum absorbed power density averaged over a square-shaped area of 4 cm^2 is limited to 200 W/m^2 averaged over a period of 6 minutes. To arrive at the basic restrictions, additional reduction factors of 2 and 10 are introduced for occupational exposure and the general population, respectively. This metric is referred to as the peak spatial-average absorbed power density (psAPD) in the remainder of this report. Above 30 GHz, additional limits on the psAPD are introduced that are averaged over a reduced area of

¹Unless indicated otherwise, all field components are RMS values throughout this report.

1 cm² to limit local temperature increases for highly focused exposures. These limits are relaxed by a factor of two. For whole-body exposure in the frequency range between 6 GHz and 300 GHz, [1] applies the whole-body SAR limit specified for frequencies above 100 kHz. Because of the lower penetration depth of electromagnetic fields at higher frequencies, the limit is regarded as conservative with respect to the increase of the body core temperature. The basic restrictions on whole-body SAR and the psAPD are given in Table 1.

Table 1: Basic restrictions on EMF exposure in the millimeter wave frequency range according to [1] for the general public and occupational exposure.

Quantity	Freq. range	Averaging time	Occupational	General public
Whole body SAR	6 – 300 GHz	30 min.	0.4 W/kg	0.08 W/kg
4 cm ² psAPD	6 – 300 GHz	6 min.	100 W/m ²	20 W/m ²
1 cm ² psAPD	30 – 300 GHz	6 min.	200 W/m ²	40 W/m ²

4.2.4 Brief Exposures

The six-minute averaging of the local exposure limits (Sections 4.2.2 and 4.2.3) permits higher peak power densities if the exposure lasts less than the averaging time. If the energy is delivered within a substantially shorter interval, heat diffusion is too slow to limit the local temperature rise. The ICNIRP Guidelines [1] therefore specify a separate set of limits for *brief exposures*, i.e., for integration intervals between >0 and <6 minutes, expressed in terms of the energy density rather than the power density. These constraints apply to local exposure only; no brief-exposure limit is specified for whole-body exposure, and none is specified below 400 MHz, where the penetration depth is large enough that the six-minute average is sufficient [1].

Above 6 GHz, the relevant quantities are the absorbed energy density U_{ab} as a basic restriction and the incident energy density U_{inc} as a reference level. Both are defined as the temporal integrals of the corresponding power densities over the exposure interval from t_1 to t_2 [1]:

$$U_{ab} = \int_{t_1}^{t_2} S_{ab}(t) dt, \quad U_{inc} = \int_{t_1}^{t_2} S_{inc}(t) dt. \quad (3)$$

The limits take the general form

$$U(t) = U_{6min} \left[c + (1 - c) \sqrt{\frac{t}{360s}} \right], \quad (4)$$

where t is the exposure interval in seconds, U_{6min} is the energy density obtained by multiplying the corresponding six-minute power density limit by 360 s, and $c = 0.05$ for the 4 cm² and $c = 0.025$ for the 1 cm² averaging area. The limits are therefore not proportional to $\sqrt{t}$: the additive term c retains a finite fraction of the six-minute energy density as $t \rightarrow 0$, which becomes the binding constraint for very short pulses. The restrictions must be satisfied for all values of t between >0 and <360 s, regardless of the temporal characteristics of the exposure itself, and the exposure delivered in t seconds by any pulse, group of pulses, or subgroup of pulses in a train, as well as by the summation of exposures including non-pulsed fields, must be taken into account [1]. The resulting limits above 6 GHz are given in Table 2.

Table 2: Brief-exposure limits above 6 GHz for integrating intervals of >0 to <6 minutes according to [1] (Tables 3 and 7 therein), where t is the exposure duration in seconds and f_G the frequency in GHz. The factor 0.36 in the reference levels is the 360 s averaging period expressed in kJ/m^2 , i.e., $275 f_G^{-0.177} \text{ W/m}^2 \times 360 \text{ s} = 275 f_G^{-0.177} \cdot 0.36 \text{ kJ/m}^2$; in the basic restrictions the same conversion is already contained in the numerical values.

Quantity	Freq. range	Occupational	General public
<i>Basic restrictions: absorbed energy density U_{ab} in kJ/m^2</i>			
$4 \text{ cm}^2 U_{ab}$	6–300 GHz	$36 [0.05 + 0.95 \sqrt{t/360}]$	$7.2 [0.05 + 0.95 \sqrt{t/360}]$
$1 \text{ cm}^2 U_{ab}$	30–300 GHz	$72 [0.025 + 0.975 \sqrt{t/360}]$	$14.4 [0.025 + 0.975 \sqrt{t/360}]$
<i>Reference levels: incident energy density U_{inc} in kJ/m^2</i>			
$4 \text{ cm}^2 U_{inc}$	6–300 GHz	$275 f_G^{-0.177} \cdot 0.36 [0.05 + 0.95 \sqrt{t/360}]$	$55 f_G^{-0.177} \cdot 0.36 [0.05 + 0.95 \sqrt{t/360}]$
$1 \text{ cm}^2 U_{inc}$	30–300 GHz	$275 f_G^{-0.177} \cdot 0.72 [0.025 + 0.975 \sqrt{t/360}]$	$55 f_G^{-0.177} \cdot 0.72 [0.025 + 0.975 \sqrt{t/360}]$

The incident energy density limits correspond to the S_{inc} reference levels of Figure 1, whose local values above 6 GHz are $275/f_G^{0.177} \text{ W/m}^2$ for occupational and $55/f_G^{0.177} \text{ W/m}^2$ for general public exposure, multiplied by 360 s. At 300 GHz, [1] specifies the endpoint values of 100 W/m^2 and 20 W/m^2 . As for the six-minute reference levels, the brief-exposure reference levels cannot be applied in the reactive near-field zone, where compliance must be demonstrated against the basic restrictions [1].

4.3 Compliance Testing Standards

4.3.1 IEC 62232 – Exposure to Base Stations

The International Electrotechnical Commission (IEC) standard IEC 62232 [13] specifies experimental and computational methods and protocols to determine the exposure from base stations in terms of SAR and, for frequencies between 6 GHz and 300 GHz, of the incident power density (IPD). For the assessment of the peak spatial-average IPD (psIPD) with respect to the exposure limits, the methods specified in IEC/IEEE 63195-1 and -2 [14, 15] are used. While exposure in the reactive near-field of base station antennas is considered and the methods specified in [14, 15] (Section 4.3.2) provide particular expressions which yield a more conservative result of the psIPD in the presence of reactive field components, a detailed methodology is not specified.²

For the quantification of the exposure from 5G base station antennas, [13] permits the actual transmitted power to be used as reference instead of the equivalent isotropic radiated power (EIRP). The actual transmitted power considers power control options specified in the 5G transmission protocols and implemented in the software of the base station antennas. For the measurements of the incident fields, code-selective methods can be applied, as well as frequency-selective methods.³

²It should be noted that [1] does not specify independent reference levels for the incident E- or H-field above 2 GHz, which could be applied in the reactive near-field.

³The report on measurements of 5G base stations operating at frequencies up to 6 GHz issued by the Swiss Federal Institute of Metrology (METAS) explicitly recommends code-selective methods [16].

4.3.2 IEC/IEEE 63195 Series - Exposure to Wireless Devices Operating at Close Distances From the Body

The IEC/IEEE 63195 Series of standards [14, 15] describes experimental and computational techniques for the assessment of the psIPD in the frequency range from 6 GHz to 300 GHz for wireless devices operating at distances up to 200 mm from the human body. These standards specify requirements for the measurement equipment and computational software, evaluation protocols, and algorithms to calculate the psIPD based on an assessment of the local, nonuniform field distribution, considering exposure in both the near- and far-field.

Three different expressions are specified for the calculation of the IPD⁴:

$$IPD_{n+}(\mathbf{r}) = \frac{1}{2} \Re \{ \mathbf{E}(\mathbf{r}) \times \mathbf{H}^*(\mathbf{r}) \} \cdot \mathbf{u}_n(\mathbf{r}) \quad (5)$$

$$IPD_{tot+}(\mathbf{r}) = \frac{1}{2} \| \Re \{ \mathbf{E}(\mathbf{r}) \times \mathbf{H}^*(\mathbf{r}) \} \| \quad (6)$$

$$IPD_{mod+}(\mathbf{r}) = \frac{1}{2} \| \mathbf{E}(\mathbf{r}) \times \mathbf{H}^*(\mathbf{r}) \| \quad (7)$$

Eqns. 5 to 7 are presented in the peak-amplitude form used in [14, 15] and therefore carry the factor 1/2; expressed in the RMS quantities used elsewhere in this report, the factor is omitted, as in Eqn. 1.

These expressions consider only the real part of the component of the Poynting vector that is perpendicular to the evaluation surface given by its normal vector $\mathbf{u}_n$ (IPD_{n+}), all of its propagating vector components (IPD_{tot+}) and both its real and imaginary components (IPD_{mod+}). These three specifications yield an increasingly conservative assessment of the IPD for calculating the psIPD. This is relevant for devices in the scope of [14, 15], i.e., for devices that operate in the close environment of the human body where exposure to the reactive fields is relevant and where losses may be induced by reactive components in the incident field [9, 17]. In the far-field, the IPD_{tot+} and the IPD_{mod+} approach the IPD_{n+} , and, as mentioned above, only the real part of the radial component has to be regarded for the assessment of the psIPD. It should be noted that the averaging of the psIPD on a square area according to [1] requires that this square area be rotated around its center point [14, 15].⁵ It should be noted that experimental and numerical standards for the assessment of the peak spatial-average absorbed power density are currently under development as an extension of the IEC/IEEE 63195 Series.

⁴ [14, 15] refer to the IPD merely as power density (PD).

⁵ [14, 15] specify a rotating square as an averaging area only for planar evaluation surfaces. For non-planar evaluation surfaces, the psIPD is averaged over an intersection of the surface with a sphere because maximizing the intersection of the psIPD by intersecting a rotating square would lead to a disproportional increase in computational requirements.

5 Fixed mmWave Systems: Current Deployments, Key Parameters, and Future Outlook

Microwave and millimeter-wave communication systems, encompassing the upper mid-band spectrum (7 to 24 GHz) and the high-band spectrum (24 to 300 GHz), are intended to provide high-capacity wireless connectivity for a wide variety of applications, including cellular networks, fixed wireless access, indoor local networking, vehicular connectivity, and emerging integrated space–air–ground–sea communication. In this review, the term “mmWave” refers to communication systems operating across both the upper mid-band and the high-band spectrum unless otherwise specified. The term frequency range 2 (FR2) follows the 3rd Generation Partnership Project (3GPP) frequency-range definitions, whereas frequency range 3 (FR3) is commonly used for the upper mid-band. The specific frequency ranges considered in this review, along with their deployment and standardization status, are summarized in Table 3. This section first defines the regulatory scope under the ONIR [18], then reviews the cellular and fixed wireless access systems within this scope, along with their key transmission parameters, surveys the enabling technologies most relevant to exposure, and concludes with the current international deployment situation and deployment outlook for Switzerland.

Table 3: Frequency ranges for fixed mmWave transmitting systems in the 3GPP-standardized FR2 and the upper mid-band (FR3), with currently deployed and prospective bands.

Designation	Frequency range	Status and bands considered
FR3 (upper mid-band)	7 to 24 GHz	Not yet a formal 3GPP frequency range; no commercial deployment. Candidate bands under study include 6.425 to 7.125, 7.125 to 8.4, 10.0 to 10.5, and 14.8 to 15.35 GHz [19–21].
FR2-1	24.25 to 52.6 GHz	3GPP-standardized [22]; commercially deployed in the 24.25 to 29.5 and 37 to 43.5 GHz bands [23, 24].
FR2-2	52.6 to 71 GHz	3GPP-standardized (Release 17), including unlicensed operation around 60 GHz; no commercial cellular deployment [22].

5.1 Regulatory Scope of the Ordinance on Protection against Non-Ionizing Radiation

This section assesses the scope of Number 6 of Annex 1 to the ONIR [18] and its relevance to the variety of fixed mmWave installations. As the diversity of mmWave communication is broad and expanding, a clear determination is required regarding which types of fixed mmWave transmitting installations fall within ONIR, considering currently deployed technologies and those expected in the near future. Number 6 of Annex 1 to the ONIR applies to terrestrial transmitting installations that form part of public mmWave communication networks providing user access services. An installation is in scope when its primary function is to provide cellular radio access to user equipment (UE) or fixed wireless connectivity to subscriber premises. This review, therefore, focuses on outdoor installations with moderate to high radiated power that operate continuously and serve residential, business, and mobile users.

5.1.1 mmWave Installations Outside the Scope of ONIR or Precautionary Limits

Here, a distinction is drawn between two levels: whether an installation falls within the scope of ONIR at all, and, if so, whether it is additionally subject to the precautionary installation limit values. Installations within

the scope of ONIR must comply with the immission limits, which protect against confirmed health effects, irrespective of whether the precautionary installation limit values apply. The systems considered below are grouped into systems within the scope of ONIR but not subject to the precautionary installation limit values, and those that fall outside the scope of ONIR for the assessment of fixed terrestrial installations.

Within the scope of ONIR but not subject to the precautionary installation limit values:

- Installations with an effective radiated power (ERP) not exceeding 6 W are exempt from the precautionary installation limit values, provided they are either at least 5 m from other transmitting antennas or, if closer, jointly do not exceed 6 W [18]. The ERP is referred to the half-wave dipole and is therefore 2.15 dB below the EIRP.
- Transmitting antennas mounted inside a building, serving that building exclusively, and not exceeding an ERP of 6 W are likewise exempt [18]. It is this power threshold together with the exclusive-coverage condition, rather than the indoor location as such, that removes small indoor cells from the precautionary limits; an indoor installation above 6 W, or one whose coverage extends beyond its own building, remains subject to them.
- Transmitting installations with fewer than 800 hours of operation per year are exempt from the precautionary installation limit values [18], including temporary event networks, short-term trials, and research testbeds.
- In the assessment of this study, highly directional point-to-point links used to interconnect network nodes and provide building-to-building connectivity also fall into this category. In practice, compliance with exposure limits is ensured because the transmitted energy is confined to narrow, highly directive beams, with installations typically mounted at elevated positions with restricted access to the beam and minimal sidelobe radiation.
- Fixed user uplink terminals for satellite communications may be considered in scope, as they constitute fixed transmitting installations directed skywards; however, they are not currently subject to precautionary installation limits.

Outside the scope of ONIR for fixed terrestrial installation assessment:

- Indoor local networking systems represent a major excluded category, e.g., wireless local area networks (WLAN) and wireless personal area networks (WPAN), including multi-gigabit Wireless Gigabit (WiGig) WLAN systems following IEEE 802.11ad/ay in the 57 to 71 GHz band. These installations are typically located inside buildings, operate at relatively low radiated power levels, and serve only the local premises. Future indoor mmWave applications, including industrial automation links and wireless data center interconnections, fall under the same exclusion framework.
- Systems associated with non-terrestrial platforms are outside the scope. On one hand, terrestrial gateway stations for satellite communications are excluded due to controlled access (e.g., fenced perimeters that prevent public access). On the other hand, high-altitude platform systems (HAPS) and unmanned aerial vehicle (UAV) air-to-ground links are not within the scope. The same applies to emerging direct-to-device satellite services, in which user equipment connects directly to space-based transmitters [25].
- Mobile radar-based mmWave systems are also outside the scope of ONIR. This includes automotive radar systems operating in the 24 GHz and 76 to 81 GHz bands, as well as other general mobile, portable, or indoor mmWave sensing devices. These systems are characterized by mobile or intermittent operation, localized coverage, and application-specific transmission behavior, rather than continuous operation of a fixed-site public network.

5.2 mmWave Cellular Access

5.2.1 Infrastructure and Application Scenarios

The mmWave cellular access infrastructure comprises transmitting installations that utilize high-frequency radio waves in the mmWave frequency band to provide wireless connectivity between mobile devices and the cellular network [26].

Current deployments of mmWave cellular infrastructure are based on 5G New Radio (NR) operating in FR2, primarily in the 24.25 to 29.5 GHz and 37 to 43.5 GHz bands (3GPP bands n257, n258, n261, n260, and n259) [22]. 3GPP Release 17 extended FR2 to 71 GHz (FR2-2, 52.6 to 71 GHz), including operation in the unlicensed spectrum around 60 GHz, although no commercial cellular deployments exist in this range. Systems in the upper mid-band (FR3) are under development and are expected to complement FR2. FR2 enables high-capacity, short-range transmission, whereas FR3 provides improved coverage with moderate capacity enhancement [21, 26]. These devices employ massive Multiple-Input Multiple-Output (MIMO) antenna arrays and advanced hybrid beamforming architectures to generate directional beams with dynamic beam tracking, enabling spatial multiplexing and adaptive link control [27, 28]. Unlike fixed-point-to-point systems, these installations operate continuously and serve multiple users within a geographic service area via point-to-multipoint configurations. The network incorporates access-integrated infrastructure, such as integrated access and backhaul (IAB) nodes, which simultaneously provide user access and wireless backhaul to the core network, thereby enabling flexible, cost-efficient densification of urban deployments [29]. In addition, 3GPP Release 18 studied and introduced network-controlled repeaters, which amplify and forward access signals using network-controlled beamforming, on-off control, and power adjustment, complementing conventional radiofrequency (RF) repeaters for low-cost coverage extension [30]. Both node types constitute fixed transmitting installations in their own right.

FR2 systems are deployed for high-capacity, short-range scenarios, such as stadiums and dense urban microcells with inter-site distances of tens to a few hundred meters. The operation relies on highly directional beamforming and dense site deployment to mitigate high path loss and blockages, with support from advanced beam management and IABs. A conceptual overview of the deployment scenario is illustrated in Figure 2. The FR3 systems currently under study are intended to provide intermediate coverage and capacity between sub-6 GHz and FR2. They support larger cell sizes and more robust propagation, enabling deployment in urban and suburban environments with reduced site density compared to FR2 [21, 31].

5.2.2 Current and Future Deployments

Commercial deployments of mmWave cellular access have been most prominent in countries that have assigned FR2 spectrum and actively promoted high-capacity 5G services:

- In the United States, operators such as Verizon, AT&T, and T-Mobile US have deployed mmWave (FR2) services primarily in the 27.5 to 28.35 GHz and 37 to 40 GHz bands, with installations concentrated in dense urban areas, stadiums, airports, and selected fixed wireless access locations [23, 24]. After the initial rollout phase, FR2 expansion slowed considerably, and operators shifted capacity investment to mid-band spectrum; FR2 remains in service primarily in high-traffic hotspots and venues [24].
- In Europe, the 24.25 to 27.5 GHz band has been authorized in more than ten countries, including Italy, Finland, Germany, and the United Kingdom. However, deployment has generally remained limited to pilot installations, industrial campuses, or localized high-capacity hotspots [23, 24]. In October 2025,

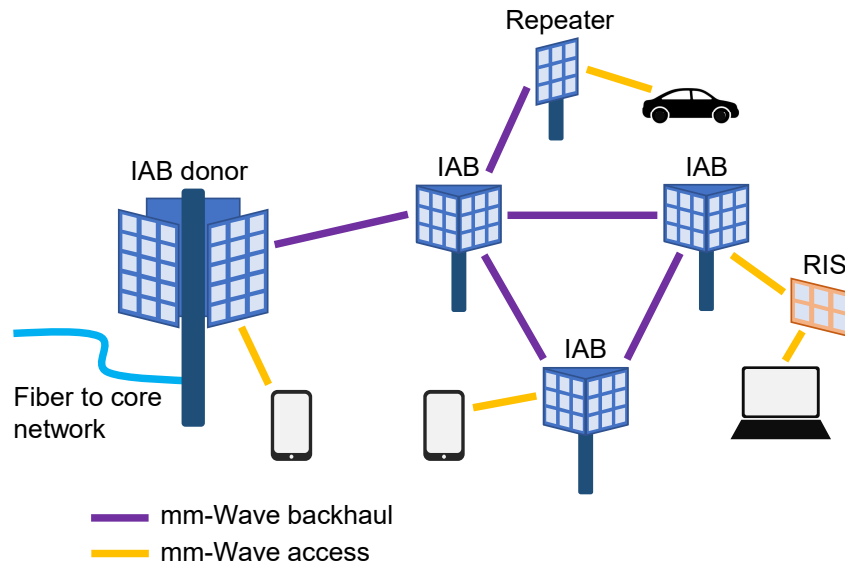


Figure 2: Conceptual illustration of a mmWave cellular network architecture, including an integrated access and backhaul (IAB) donor and IAB nodes for wireless relaying, repeaters for coverage extension, and reconfigurable intelligent surfaces (RIS) for propagation control. The network operates through directional links forming a hierarchical structure that enables coverage expansion.

the British regulator Ofcom auctioned citywide licenses in the 26 GHz and 40 GHz bands for designated high-density areas, the first large-scale mmWave award in Europe explicitly targeting commercial deployment [32].

- In East Asia, Japan has assigned the 27.0 to 28.2 GHz and 29.1 to 29.5 GHz bands, with deployments by NTT Docomo and other national operators focused on metropolitan Tokyo. The Republic of Korea initially licensed the 26.5 to 28.9 GHz range to all three national operators in 2018, but revoked the licences of KT and LG U+ in 2022 and of SK Telecom in 2023 after deployment obligations were not met [23, 24]; the spectrum was re-auctioned in 2024 to the new entrant Stage X, whose licence was cancelled within months over unmet capital requirements [33]. Other regions, such as China, Australia, and India, have allocated mmWave spectrum in the 24.25-27.5 GHz range (e.g., n258), but deployments remain in pilot or early stages [23, 24].

In the near future, mmWave access networks are expected to be deployed in high-traffic urban zones, enterprise campuses, industrial facilities, transport hubs, and major event venues. FR2 deployments will remain focused on high-capacity hotspots and targeted use cases [24]. In parallel, a gradual introduction of the upper mid-band (FR3) is expected to support broader network evolution, enhancing capacity in urban and suburban environments [21].

Looking beyond 5G, the International Telecommunication Union Radiocommunication Sector (ITU-R) framework for International Mobile Telecommunications-2030 (IMT-2030) defines the use cases for 6G, including immersive communication, integrated sensing and communication (ISAC), and integrated artificial intelligence and communication [34]. The 3GPP studies on 5G-advanced and 6G radio access technologies started in 2026 with Release 20 [35], building on the established NR frequency ranges FR1 (up to 7.125 GHz) and FR2 (24.25 to 71 GHz, comprising FR2-1 and FR2-2) defined in TS 38.104 [22], while introducing the upper mid-band (FR3, approximately 7 to 24 GHz) as a key new focus [21], with candidate bands under study including 6.425 to 7.125, 7.125 to 8.4, 10.0 to 10.5, and 14.8 to 15.35 GHz [19, 20]. Normative specifications will follow in Release 21, with technology submission to ITU-R targeted for early 2029 and commercial deployment expected

around 2030 [35]. The upper mid-band is regarded as the key candidate for balancing coverage and capacity in these networks, while sub-terahertz frequencies (> 90 GHz) remain a research topic without a near-term deployment perspective [21, 31, 36]. ISAC is particularly relevant for fixed installations, as sensing transmissions may occur independently of user traffic, thereby altering the installation's temporal activity pattern [34, 37].

5.3 mmWave Fixed Wireless Access

5.3.1 Infrastructure and Application Scenarios

Fixed wireless access infrastructure refers to mmWave transmission installations that provide broadband connectivity to specific fixed subscriber premises, typically via point-to-multipoint architectures [38, 39]. These systems can operate across FR2 (24.25 to 29.5 GHz and 37 to 43.5 GHz) and will increasingly operate across FR3 (7 to 24 GHz) in the future, enabling both high capacity and extended coverage [38, 40].

Fixed wireless access (FWA) deployments establish quasi-permanent radio links between network infrastructure (base stations) and outdoor customer-premises equipment (CPE), typically installed on building exteriors or rooftops [38, 39]. The service provides dedicated or semi-dedicated broadband access, functionally comparable to fiber or cable connections. Because subscriber locations are fixed, beam directions are generally static or slowly varying, and mobility management or handover procedures are not required. A conceptual overview of these deployment scenarios and elements is illustrated in Figure 3.

In contrast to cellular systems, FWA network planning is based on known, fixed terminal locations, allowing optimized link configuration and stable connectivity. Application scenarios include the wireless replacement or extension of fiber or cable access, particularly in remote or underserved areas, as well as high-demand residential, enterprise, and industrial environments where rapid deployment or additional capacity is required [41].

For clarity, FWA does not include tethering mobile phones to connect Wi-Fi devices via standard mobile services, portable battery-based Wi-Fi routers, or dongle-based access [39].

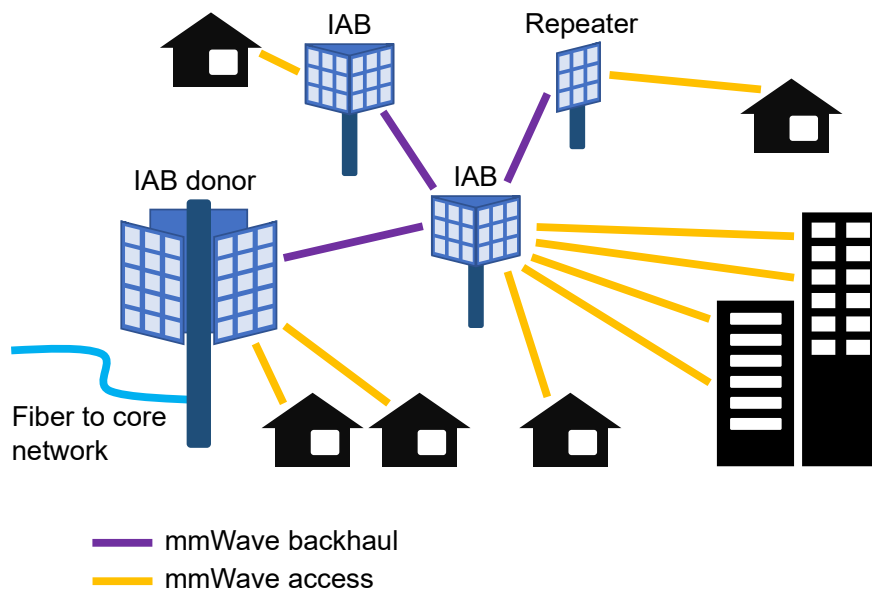


Figure 3: Conceptual illustration of the mmWave FWA network, including an integrated access and backhaul (IAB) donor and IAB nodes for wireless relaying, and repeaters for coverage extension.

5.3.2 Current and Future Deployments

Internationally, the adoption of mmWave FWA has progressed alongside 5G network deployments.

In the United States, operators including Verizon and US Cellular launched mmWave-based FWA to compete with fixed-line broadband [24]. Verizon deployed its Ultra Wideband service in the mmWave spectrum (28 and 39 GHz) and had installed approximately 33,000 mmWave small cells by the end of 2021, while US Cellular launched mmWave FWA across ten cities [24]. After acquiring mid-band C-band (3.7 GHz) spectrum in 2021, however, Verizon shifted the bulk of its FWA growth to mid-band, and mmWave FWA has since remained only within densely populated areas [24, 42] in the United States.

In India, 5G FWA has grown rapidly in the mid-band (sub-6 GHz) spectrum and unlicensed band radio (UBR, e.g., 2.4/5 GHz bands) [43, 44]. By September 2025, the combined 5G FWA user base of the two largest operators reached about 12 million connections, and the total Indian FWA subscriber base (5G and UBR) exceeded 13 million, against roughly 46 million wireline subscribers [43]. These numbers reflect the low fixed-access penetration of a predominantly mobile market, the world's second-largest, with about 735 million smartphones as of mid-2025 [43]. mmWave spectrum (the n258 band, 24.25 to 27.5 GHz) has been allocated, but mmWave deployments, including FWA, are only at a pilot or trial stage [23, 24].

In Europe, the FWA market is large and growing, projected to expand from about USD 14.4 billion in 2025 to roughly USD 29 billion by 2031, a compound annual growth rate (CAGR) of about 12%, supported by the EU Gigabit Society target and the use of FWA as a lower-cost alternative to fiber in rural and difficult-to-wire areas [45]. This growth is led by sub-6 GHz and C-band spectrum, which held the majority of the market in 2025, with the largest deployments in Germany (Deutsche Telekom) and France (Orange) [45]. mmWave FWA, by contrast, remains localized, representing the smallest band segment of the European FWA market [45]. Several countries, including Italy, Germany, Finland, Spain, and the United Kingdom, have assigned spectrum in the 26 GHz band, with FWA as a main use case, and are in the early stages of commercialization targeting urban hotspots and underserved areas [23, 24]. Notably, Italy hosts Europe's first 5G standalone mmWave network, deployed by Nokia and EOLO to connect underserved communities [46].

Due to the extensive fiber penetration in Japan, FWA is positioned in a niche rather than a mass-market broadband alternative [47, 48]. Similarly, in China, the mmWave spectrum (n258, 24.25 to 27.5 GHz) has been allocated, but commercial deployments remain in pilot or early stages, with national mobile investment concentrated on sub-6 GHz networks [23, 24].

The role of mmWave FWA in a given market depends strongly on the availability of fixed broadband infrastructure. Where fixed-line penetration is low, as in India, FWA serves as a substitute for wired access, whereas in markets with extensive fiber coverage, such as Japan, it is positioned as a niche to cover remote areas [43, 47, 48]. Switzerland falls into the latter category: high-speed fixed broadband is widely available via cable, and the expanding fiber-to-the-home (FTTH) network reached about 50% of homes in 2024 and is targeted at 75 to 80% by 2030, in the Swisscom network [49]. mmWave FWA in Switzerland is therefore likely to be relevant mainly as a high-capacity alternative in areas not served by fiber or cable.

5.4 Enabling Technologies and Their Exposure Relevance

Fixed mmWave systems counter the unfavorable propagation at these frequencies (high free-space path loss, limited diffraction, and blockage by obstacles) with three classes of techniques, each of which changes the character of the resulting exposure [28]: i) beamforming concentrates the radiated power into narrow, steerable beams and thereby defines the spatial distribution of the exposure; ii) reconfigurable surfaces redirect the radiated energy along additional propagation paths and thereby change where exposure occurs; and iii) adaptive waveforms and scheduling determine the temporal structure of the transmission and thereby the relation between the peak and the time-averaged exposure.

5.4.1 Beamforming Techniques for Directed mmWave Transmission

Fixed mmWave systems use phased antenna arrays to form high-gain, electronically steerable beams that compensate for the high free-space path loss [27, 28]. From an exposure point of view, the effect of beamforming is twofold: the incident power density in the momentary beam is high, but the radiated energy is confined to a narrow sector that is steered toward the served users. Bystanders are illuminated only intermittently, and their time-averaged exposure typically remains below the beam peak.

Practically, beamforming is implemented in the active antenna unit (AAU), which integrates the antenna array with the RF front-ends, data converters, and beam-management modules. The AAU controls the phase and amplitude of the individual elements and hence the beam direction and shape [28]. The beamforming architecture (analog, digital, or hybrid, Figure 4) determines how many beams can be formed simultaneously [28, 50]: analog beamforming forms one beam at a time, full-digital beamforming serves multiple users with simultaneous beams, and hybrid beamforming, the common choice for mmWave massive MIMO, supports a small number of parallel beams. In regard to human exposure, this means that the total radiated power of an installation is shared among simultaneously active beams: the more parallel beams, the lower the power, and hence the maximum exposure, in any single beam direction.

Technologies such as metamaterial-based antennas are used to suppress sidelobe radiation and improve the spatial selectivity of the array, thereby reducing exposure in directions that are not being served [51].

5.4.2 Adaptive Propagation and Integrated Sensing

Reconfigurable Intelligent Surfaces (RIS, Figure 5), currently in research and early pilot studies, are passive or semi-passive surfaces that redirect, reflect, or selectively absorb incident signals under network control [52]. Because an RIS re-radiates energy received from the serving base station rather than generating its own, it does not increase the total radiated power of the network. It does, however, change where this power is delivered. Coverage, and with it exposure, is extended into non-line-of-sight areas, and the exposure maximum may occur along the redirected path rather than in a line-of-sight direction from the base station. RIS may also contribute to multi-path propagation and constructive superposition, resulting in higher exposure at a given location.

Also in the uplink, RIS-assisted links can reduce the transmit power required from the UE and thereby the exposure of the user [53].

Simultaneously Transmitting and Reflecting RIS (STAR-RIS; Figure 5) are able to split incident signals into

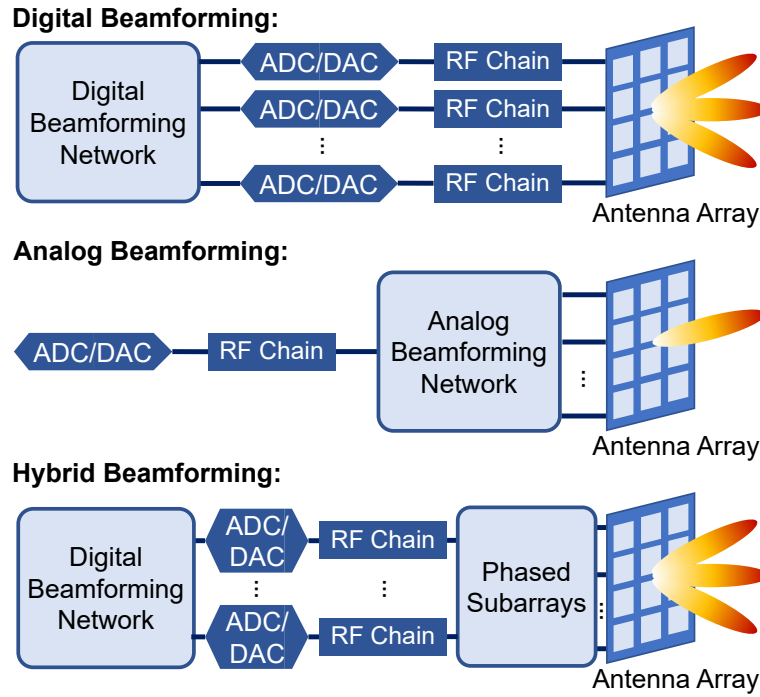


Figure 4: Beamforming system architectures for mmWave wireless systems: digital beamforming, analog beamforming, and hybrid beamforming.

a reflected and a transmitted component and can thus serve users on both sides of the surface [52]. From an exposure perspective, a STAR-RIS mounted on a building surface may introduce a deliberate outdoor-to-indoor propagation path. In contrast to the otherwise strong building-entry attenuation for mmWave signals, indoor exposure from outdoor installations cannot be assumed negligible where such surfaces are deployed, e.g., on glass fronts.

ISAC, a key ITU-R IMT-2030 usage scenario [34], reuses fixed mmWave transmitters for radar-like sensing functions such as object detection, positioning, and environment monitoring [37]. Because these sensing transmissions serve continuous or periodic monitoring tasks rather than user data traffic, they can occur independently of communication demand, decoupling the installation's temporal activity pattern from user traffic statistics [37].

Sensing-assisted and machine-learning-based beam management may in the future adapt the beam direction, power, and multiplexing in real time to the measured channel state [54]. Together with RIS, this adaptivity is expected to reduce the average exposure, since power is radiated only where and when it is needed [52], but it also makes the spatial and temporal evolution of the exposure at a given location less predictable, so that exposure assessment increasingly has to rely on statistical rather than deterministic assumptions.

5.4.3 Spectral Efficiency and Waveform Modulations

Fixed mmWave transmitting systems use spectrally efficient waveforms, i.e., orthogonal frequency division multiplexing (OFDM) with up to high-order quadrature amplitude modulation (QAM), to maximize the information transmitted per unit of bandwidth [55]. Because spectral efficiency is fundamentally limited by the signal-to-noise ratio (SNR) of the channel, adaptive modulation and coding (AMC) assigns high-order mod-

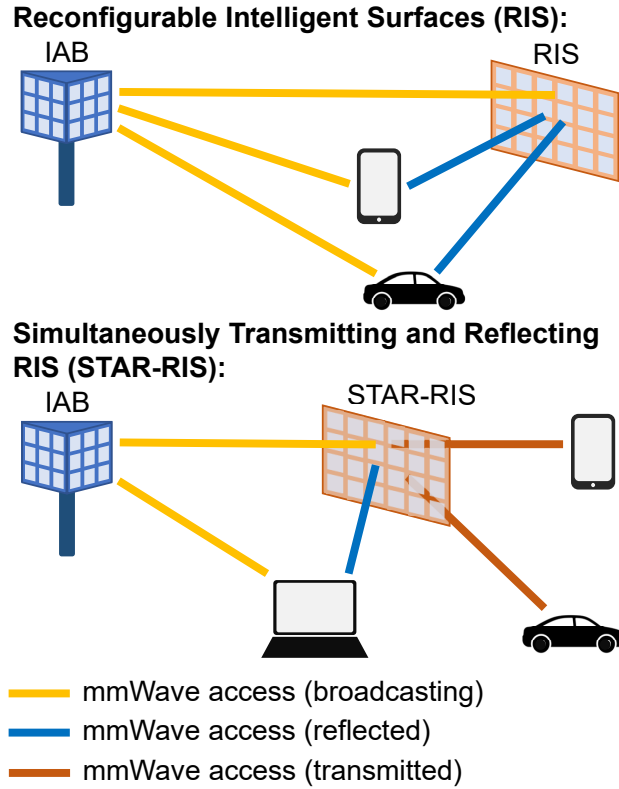


Figure 5: Conceptual illustration of an RIS-based wireless system and a STAR-RIS-based wireless system.

ulation schemes to users in favorable channel conditions rather than by raising the transmit power [27, 29]. Together with dynamic resource allocation and traffic-dependent scheduling, this makes the transmitted signal time-varying in amplitude, duty cycle, and spectral occupancy [26, 56]. The ICNIRP 2020 guidelines limit both the power density averaged over six minutes and, for shorter windows, the cumulative energy density (Section 4.2.4) [1], so both the average and the instantaneous power of the transmitted signal are relevant to exposure. This temporal structure is characterized by the peak-to-average power ratio (PAPR) and the duty cycle, which are set by the following three mechanisms.

Multi-carrier OFDM waveforms have an inherently high PAPR that grows with the number of subcarriers. In practice, the transmitted PAPR is limited to about 8 dB by the power amplifier and by crest-factor reduction (CFR), whose admissible clipping is bounded by the 3GPP transmitter requirements on error vector magnitude (EVM, e.g., 3.5% for 256-QAM) and adjacent-channel leakage (ACLR, < -45 dBc) [22, 57]. These envelope peaks occur on microsecond timescales and are therefore averaged out in the six-minute averaged fields used for compliance [58]; their relevance for the brief exposure restrictions is assessed in Section 7.3.

With beamforming and multi-user spatial multiplexing, i.e., spatial-division multiple access (SDMA), the high-gain beam illuminates a given location only a fraction of the time, as it is steered toward the served users, so that the time-averaged power in a fixed direction is a small fraction of the instantaneous beam power [59]. For a representative 5G base station, the 95th-percentile realistic maximum power is below about 15% of the theoretical maximum, reducing the far-field compliance distance by a factor of roughly 2.6 [59]. In-situ measurements of a commercial 5G massive-MIMO network in Bern, Switzerland, confirm this: even under maximized downlink traffic, the actual time-averaged exposure reached only about 0.5 to 0.6% of the reference level [60].

In time-division duplex (TDD) operation, only a fraction $F_{\text{TDD}} = (\text{DL}:\text{UL})/(\text{DL}:\text{UL} + 1)$ of the time carries downlink transmission; $F_{\text{TDD}} \approx 0.75$ is representative for 5G (a value of 0.74 was measured for the Bern network, and a typical FR2 4:1 downlink-to-uplink pattern results in a factor of about 0.8) [27, 59, 60].

These mechanisms make the realistic time-averaged downlink power much lower than the theoretical maximum: the downlink power spans a dynamic range in the order of 30 dB between the idle state (synchronization signal block only) and full traffic load [58]. Base stations can additionally control their own time-averaged transmit power against a configured threshold, so that time-averaged compliance is assessed against this threshold rather than against the maximum radiated power. A threshold of 25% of the maximum power, a value motivated by the observation that the exposure-relevant average power of a massive-MIMO base station is rarely higher, has been demonstrated for a 200 W base station at the cost of about 10% of the cell throughput; since the power density in the far field decreases with the square of the distance, it halves the compliance distance [61].

The waveform characteristics also determine the relevance of the short-term (*brief exposure*) restrictions of the ICNIRP 2020 guidelines, which cap the energy density accumulated in any window shorter than six minutes (Section 4.2.4) [1]. For exposure scenarios combining high peak-to-average ratios and low duty cycles, these limits are more restrictive than the six-minute average. However, realistic communication waveforms do not reach this regime: the microsecond OFDM peaks and millisecond TDD gating vary far faster than the thermal response of tissue and are averaged out. Exceeding the brief exposure limits while complying with the six-minute average would require the power within a symbol time to be about 57 dB above realistic values [62]. This figure refers to a symbol duration of about $36 \mu\text{s}$, corresponding to the 30 kHz subcarrier spacing typical of FR1; the 120 kHz spacing of FR2 shortens the symbol to about $9 \mu\text{s}$ [29], which increases the margin further by 3 dB, as the energy density permitted by the brief exposure limits scales with the square root of the window length. The quantitative analysis in Section 7.3 confirms that the short-term limits become binding only for radar-like, low-duty-cycle operation such as ISAC sensing.

5.5 Key Parameters of Fixed mmWave Systems

5.5.1 Power Characteristics

TS 38.104 [22] defines base station (BS) classes by the deployment scenario and the corresponding minimum BS-to-user equipment distance along the height above the ground: wide area (macro, 35 m), medium range (micro, 5 m), and local area (pico, 2 m). For FR1 (BS type 1-O), the rated carrier total radiated power (TRP) is capped for micro and pico cells, whereas for FR2 (BS type 2-O) no upper limit is defined. Although 3GPP specifies no TRP limit for FR2 base stations, representative power figures are available from the simulation assumptions of the 3GPP coexistence studies [63], which are included in Table 4 alongside the TS 38.104 classes. National regulators may also cap the radiated power directly; for example, the United States Federal Communications Commission (FCC) limits the effective isotropic radiated power (EIRP) of fixed and base stations in the licensed mmWave bands to 75 dBm per 100 MHz under 47 CFR § 30.202(a) [63, 64].

For FWA, the CPE itself constitutes a fixed transmitter. For FR2 UEs, power class 1 is defined specifically for FWA terminals, permitting a maximum TRP of 35 dBm and a peak EIRP of up to 55 dBm, substantially above the maximum EIRP of 43 dBm of handheld (power class 3) devices [38].

3GPP TR 38.921 and TR 38.922 [19, 20] are technical reports studying IMT/5G NR parameters for candidate mid-band and upper-mid-band spectrum (FR3). TR 38.921 focuses on 6.425–7.125 GHz and 10.0–10.5 GHz,

and TR 38.922 on 4400–4800 MHz, 7125–8400 MHz, and 14800–15350 MHz. Their purpose is to define and justify relevant FR3 NR base-station and user-equipment transmitter and receiver characteristics, antenna assumptions, and coexistence and sharing parameters for regulatory and ITU-R spectrum studies. The TRP for two polarizations agreed in these studies is included in Table 4; the corresponding agreed EIRP values are given in Table 5.

Table 4: NR base station output power by base station class: rated carrier TRP limits per TS 38.104 (FR1: BS type 1-O; FR2: BS type 2-O), representative FR2 figures from the 3GPP coexistence-study assumptions, and the TRP agreed in the FR3 band studies [19, 20, 22, 63]

BS class	Min. BS–UE distance	Rated TRP, FR1 dBm	Rated TRP, FR2 dBm	Repr. TRP, FR2 dBm	TRP, 2 pol., FR3 dBm 6.425–7.125, 10.0–10.5, 7.125–8.4 GHz	TRP, 2 pol., FR3 dBm 14.8–15.35 GHz
Wide area (macro)	35 m	None	None	43	46	46
Medium range (micro) ^(a)	5 m	≤ 47	None	33	37	36
Local area (pico) ^(b)	2 m	≤ 33	None	23	24	23

The representative FR2 values are simulation assumptions from the 3GPP coexistence studies [63] for operation around 30 GHz in the urban macro, dense urban micro, and indoor scenarios, respectively; they are not standardized limits. Both FR2 and the FR3 macro sub-urban, macro urban, and micro urban scenarios of [19, 20] correspond only approximately to the TS 38.104 base station classes. The FR3 studies distinguish a macro sub-urban from a macro urban scenario; the two share the same TRP and differ only in the antenna parameters of Table 5.

“None” denotes that no upper limit is defined.

Note (a): reported as “small cell outdoor/micro urban” in the 14.8 to 15.35 GHz study.

Note (b): the FR3 studies label this scenario “small cell indoor”; it is retained here for the reason given with Table 5. No such parameter set is defined for the 7.125 to 8.4 GHz band, so the FR3 entries are those of the 6.425 to 7.125, 10.0 to 10.5, and 14.8 to 15.35 GHz studies.

5.5.2 Antenna Characteristics and Effective Isotropic Radiated Power

Typical maximum transmitter output powers and antenna characteristics were specified in [19, 20] for FR3 and in [63] for FR2. Based on the array parameters, fundamental characteristics such as EIRP can be derived. The peak EIRP can be calculated on a logarithmic scale as:

$$EIRP = P_{tx} + G_{E,max} + 20\log_{10}(MN) + 10\log_{10}(P), \quad (8)$$

where P_{tx} is the conducted power (before ohmic loss) per antenna element in dBm, and $G_{E,max}$ is the array element peak gain in dBi, (M, N) means there are M vertical and N horizontal elements, and P is the number of supported polarizations. The factor of 20 combines two contributions of $10\log_{10}(MN)$ each: the summation of the conducted power over the MN elements, and the directivity gain of the coherently excited array relative to a single element. The elements are separated by d_h horizontally and d_v vertically. They may further be grouped into sub-arrays that are fed as a single unit, in which case (M, N) counts the steerable sub-arrays rather than the individual elements, M_{sub} is the number of element rows stacked within each sub-array, d_v is the separation between sub-arrays.

Where the conducted power is specified as a total over the array rather than per element, as is the case for the representative FR2 figures of Table 4, Eq. (8) reduces to

$$EIRP = P_{tx,total} + G_{E,max} + 10\log_{10}(MN). \quad (9)$$

Here, the summation over the elements and the contribution of the two polarization directions are already contained in the total power, so that only the directivity gain $10\log_{10}(MN)$ remains.

Table 5 lists representative base station array antenna parameters for the three FR3 bands studies [19, 20] and for FR2 operation around 30 GHz as assumed in the 3GPP coexistence studies [63]. The FR2 parameter set is specified less completely than those for FR3: [63] models the array as undivided elements without a sub-array structure and gives the output power only as a total rather than per element. The resulting array is nevertheless comparable to deployed hardware, as commercial base station antennas for the 28 and 38.5 GHz bands use arrays of 24×8 ports with a peak gain of about 29 dBi taken over the envelope of all beams [62]. The FR3 studies label their small cell scenario as indoor; the corresponding parameter set is nevertheless retained here, as such installations fall within the scope of the ONIR as long as they are used for public networks, whether installed indoors or outdoors (Section 5.1.1). It is defined for the 6.425 to 7.125, 10.0 to 10.5, and 14.8 to 15.35 GHz bands, but not for the 7.125 to 8.4 GHz band [19, 20].

The last three columns of Table 5 give the total conducted power, the total array gain, and the resulting peak EIRP. Where a sub-array structure is used, the element gain is replaced by the sub-array gain $G_{E,\max} + 10\log_{10}(M_{\text{sub}})$ and P_{tx} is taken per sub-array. For the 7.125 to 8.4 and 14.8 to 15.35 GHz bands, the EIRP obtained in this way agrees with the values in [20] within 0.1 dB. No maximum base station output power per sector was agreed for the 6.425 to 7.125 and 10.0 to 10.5 GHz ranges in [19], for which the same calculation yields derived peak EIRP values of 73.6, 72.7, and 60.6 dBm for the macro sub-urban, macro urban, and micro urban scenarios, respectively. For FR2, combining the representative total powers of Table 4 with the coexistence-study array through Eq. (9) results in realistic maximum values of approximately 72, 62, and 43 dBm for the urban macro, dense urban micro, and indoor scenarios.

Table 6 lists the resulting FR2 and FR3 EIRP values against the minimum BS-to-UE distance of the corresponding TS 38.104 base station class. As for Table 4, the pairing between the coexistence-study/IMT scenario categories and the TS 38.104 BS classes is approximate.

Table 5: Base station array antenna parameters for prospective FR3 bands and for FR2 operation around 30 GHz, with the resulting total array gain and peak EIRP. Only the parameters entering the radiated power and the array geometry are listed; those common to all parameter sets are given in the notes. [19, 20, 63]

Scenario	$G_{E,max}$ dBi	(M, N)	d_v	M_{sub}	P_{tx} dBm	P_{tot} dBm	G_{tot} dBi	EIRP dBm
<i>FR3, 6.425 to 7.125 and 10.0 to 10.5 GHz [19]</i>								
Macro sub-urban	6.4	(16, 8)	0.7λ	N/A	22	46.1	27.5	73.6
Macro urban	5.5	(16, 8)	0.5λ	N/A	22	46.1	26.6	72.7
Micro urban	5.5	(8, 8)	0.5λ	N/A	16	37.1	23.6	60.6
Small cell	5.5	(4, 4)	0.5λ	N/A	9	24.1	17.5	41.6
<i>FR3, 7.125 to 8.4 GHz [20]</i>								
Macro sub-urban	6.4	(8, 16)	2.1λ	3	22 ^(a)	46.1	32.2	78.3 ^(b)
Macro urban	6.4	(8, 16)	2.1λ	3	22 ^(a)	46.1	32.2	78.3 ^(b)
Micro urban	6.4	(8, 8)	0.7λ	N/A	16 ^(a)	37.1	24.5	61.5 ^(b)
<i>FR3, 14.8 to 15.35 GHz [20]</i>								
Macro sub-urban	6.4	(16, 24)	2.8λ	4	17.2	46.1	38.3	84.3 ^(b)
Macro urban	6.4	(16, 24)	2.8λ	4	17.2	46.1	38.3	84.3 ^(b)
Micro urban	6.4	(16, 24)	2.8λ	4	7.2	36.1	38.3	74.3 ^(b)
Small cell	5	(4, 4)	0.5λ	N/A	8.0	23.1	17.0	40.0 ^(b)
<i>FR2, around 30 GHz [63]</i>								
Urban macro	8	(8, 16)	0.5λ	N/A	n.s.	43	29.1	~72
Dense urban	8	(8, 16)	0.5λ	N/A	n.s.	33	29.1	~62
Indoor	5	(4, 8)	0.5λ	N/A	n.s.	23	20.1	~43

Common to all parameter sets: $P = 2$ and $d_h = 0.5\lambda$; where a sub-array structure is used, $d_{v,sub} = 0.7\lambda$ and $\theta_{subtilt} = 3$ degree. The element pattern (A_m , SLA_v , φ_{3dB} , θ_{3dB}) and the scan and tilt ranges ($\varphi_{escan} = \pm 60$ degree in the FR3 macro and micro sets, θ_{etilt} , θ_{mech}) are specified in the cited reports but are not reproduced here.

N/A denotes a parameter that does not apply, n.s. one that is not specified in the cited report.

(a): P_{tx} for the 7.125 to 8.4 GHz band is not provided directly in [20]; it is calculated from the rated TRP (46, 46, and 37 dBm), corresponding to the conducted power per sub-array (macro) or per element (micro).

(b): the EIRP agreed in [20]; the value derived from the array parameters via Eq. (8) agrees within 0.1 dB (40.1 dBm for the 14.8 to 15.35 GHz small cell), which validates the normalization of the equation. No EIRP was agreed for the remaining bands, for which the derived value is given.

Table 6: Realistic maximum EIRP for FR2 and FR3 versus the minimum BS-to-UE distance of the corresponding (approximate) TS 38.104 base station class [19, 20, 22, 63]

BS class (approx.)	Min. BS-UE distance	Realistic max EIRP, FR2 (~30 GHz) dBm	Max EIRP, FR3 7.125–8.4 GHz dBm	Max EIRP, FR3 14.8–15.35 GHz dBm
Wide area (macro)	35 m	~72	78.3	84.3
Medium range (micro)	5 m	~62	61.5	74.3
Local area (pico)	2 m	~43	N/A	40.0

Note: FR2 values are derived from the representative power figures of Table 4 and the coexistence-study antenna assumptions [63] via Eq. (9), and are therefore approximate; FR3 values are the agreed 3GPP values of Table 5. No FR3 EIRP is defined for a local area scenario in the 7.125 to 8.4 GHz band.

5.5.3 Deployment Scenarios

The coexistence studies that supply the power and antenna parameters of Tables 4 and 5 also define network layouts assumed for those parameter sets. Four of the defined parameters determine how a person can be exposed: the inter-site distance (ISD), which sets the site density, the base station mounting height, the minimum base station to UE separation in the horizontal plane, and the share of users located indoors. Table 7 summarizes these parameters. Note that these are standardized evaluation assumptions rather than based on implemented deployments.

Table 7: Exposure-relevant attributes of the network layouts assumed in the FR3 and FR2 coexistence studies, for the same scenarios as Table 5. [19, 20, 63]

Scenario	ISD	BS antenna height	Min. BS to UE distance (2D)	Indoor UE ratio
<i>FR3, 6.425 to 7.125 and 10.0 to 10.5 GHz</i> [19]				
Macro sub-urban	900 m	25 m	35 m	20 %
Macro urban	450 m	20 m	35 m	20 %
Micro urban	No layout defined ^(a)			
Small cell	20 m	3 m	0 m	100 %
<i>FR3, 7.125 to 8.4 GHz</i> [20]				
No network layout defined for this band ^(b)				
<i>FR3, 14.8 to 15.35 GHz</i> [20]				
Macro urban	450 m	25 m	35 m	20 or 0 %
Micro urban	450 m ^(c)	10 m	3 m	80 %
Small cell	20 m	3 m	0 m	100 %
<i>FR2, around 30 GHz</i> [63]				
Urban macro	200 m	25 m	35 m	20 %
Dense urban micro	200 m ^(c)	10 m	3 m	80 %
Indoor	20 m	3 m	0 m	100 %

Above macro layouts have a hexagonal grid of 19 sites with three sectors per site.

Small cell and indoor layouts have 12 base stations in a 50 by 120 m floor plan, mounted on the ceiling.

(a): the dense urban scenario was de-prioritized in [19], as it imposes the least demanding requirements of the three scenarios simulated in [63]; micro urban antenna parameters are nevertheless defined for these bands in Table 5.

(b): [20] specifies base station, UE, and antenna parameters for the 7.125 to 8.4 GHz band, but no coexistence network layout; the deployment scenarios are likely comparable to those of the 6.425 to 7.125 and 10.0 to 10.5 GHz bands.

(c): the micro base stations are placed within three cluster circles inside a macro cell of the stated ISD, one per circle, serving UEs within 64.95 m (FR3) or 28.9 m (FR2).

The minimum separation distances in Table 7 range from 35 m for macro scenarios to 0 m for small cell scenarios. These coexistence study assumptions are more conservative than the TS 38.104 base station class distances used in Table 6: 3 m versus 5 m for the micro class, and 0 m versus 2 m for the pico class.

The indoor user share rises from 20 % in macro to 80 % in micro scenarios. mmWave signals are strongly attenuated by building materials. Therefore, the most compliance-relevant exposure scenarios are those of the outdoor pedestrians near street-level cells or below rooftop-mounted macro sites. Indoor coverage, were it deployed, would not automatically be exempt. The small cell parameter sets of Table 5 correspond to an ERP of 8.8 W for the 6.425 to 7.125 and 10.0 to 10.5 GHz bands, 6.1 W for the 14.8 to 15.35 GHz band, and 12.2 W for the FR2 indoor scenario, obtained from the peak EIRP values of Table 5 (41.6, 40.0, and ~43 dBm) by subtracting the 2.15 dB half-wave dipole reference, all at or above the 6 W threshold currently defined in the ONIR (Section 5.1.1).

5.6 Situation and Outlook for Switzerland

Commercial mmWave cellular access and FWA have not been deployed in Switzerland, and all nationwide 5G services are currently provided in sub-6 GHz bands. The National Frequency Allocation Plan (NFAP) is based on the ITU Radio Regulations and the relevant publications of the European Conference of Postal and Telecommunications Administrations (CEPT) and generally follows their prescriptions [65]. The 26 and 40 GHz ranges (24.25 to 27.5 and 40.5 to 43.5 GHz) are accordingly already allocated to the mobile service and identified for IMT, with Mobile/Fixed Communications Networks (MFCN) listed as the planned future main use of both ranges (“MFCN primary”), in line with the harmonized European framework of the Electronic Communications Committee (ECC), namely ECC/DEC/(18)06 and ECC/DEC/(22)06, under which the licenses in neighboring countries have been issued (Section 5.2.2). This designation has, however, not been implemented in Switzerland: the current main use of both ranges remains with incumbent services, in particular point-to-point radio relay links and satellite applications, with fixed links in the 26.5 to 27 GHz range permitted until the end of 2028. No frequencies have been assigned to mobile network operators [65, 66]. Implementation would require migrating the incumbent services out of these ranges or coordinating shared use with them; adapting the Technical Interface Regulations (RIR) [67], which specify the licensing conditions per band; updating the ONIR and associated guidelines; and finally establishing an award procedure.

Table 8 summarizes the international and national milestones that govern the possible uptake of frequencies above 6 GHz for fixed installations. Internationally, the 2023 World Radiocommunication Conference (WRC-23) identified the upper 6 GHz band (6.425 to 7.125 GHz) for IMT in Region 1, and the European Radio Spectrum Policy Group (RSPG) recommended in November 2025 that 540 MHz of it be prioritized for mobile and fixed communication networks, with the remaining 160 MHz held pending WRC-27; CEPT is developing the harmonized technical conditions expected to form the basis of a European Commission implementing decision [68, 69]. Nationally, ComCom decided in 2024 to re-tender only the mobile frequencies expiring at the end of 2028, explicitly without spectrum from the 6, 26, and 40 GHz bands [66, 70]; no award vehicle for mmWave or upper 6 GHz access spectrum therefore exists in the current allocation cycle.

The international experience reviewed above also limits which deployments would be plausible in Switzerland. FR2 cellular access has stayed concentrated in stadiums, airports, and dense urban hotspots, and has been scaled back or withdrawn where those conditions were absent, most sharply in the Republic of Korea [23, 24, 33]. Swiss urban densities and venue sizes are modest in comparison. Therefore, similar implementations are less likely in the near future. For FWA, the extensive fiber and cable penetration discussed in Section 5.3.2 also limits possible mmWave installations to areas not served by wired access. Fixed FR2 exposure in Switzerland is thus expected to be, at most, spatially confined rather than nationally distributed. FR3 is the more likely candidate for broad deployment. Its more robust propagation and larger cell sizes support urban and suburban coverage at reduced site density. This is also why the upper mid-band was prioritized in early 6G standardization [21]. Initial availability of FR2 or FR3 spectrum for mobile and fixed access services in Switzerland is not expected before approximately 2029 to 2030, in line with the commercial introduction of 6G targeted around 2030 [35, 71].

Table 8: Spectrum and regulatory timeline relevant to fixed mmWave deployment in Switzerland.

Period	Milestone
2023	WRC-23 identifies the upper 6 GHz band (6.425 to 7.125 GHz) for IMT in Region 1 [68].
2024	ComCom decides to re-tender only the existing mobile bands (800, 900, 1800, 2100, and 2600 MHz), without 6, 26, or 40 GHz spectrum [66].
Nov. 2025	European Radio Spectrum Policy Group recommends prioritizing 540 MHz of the upper 6 GHz band for mobile/fixed communication networks [69].
2026	Planned Swiss public tender for the re-tendered mobile bands [66].
2027	WRC-27 evaluates the 4.4 to 4.8, 7.125 to 8.4, and 14.8 to 15.35 GHz candidate bands [72]. Swiss auction of the re-tendered bands [66]. Expected CEPT harmonized technical conditions and European Commission implementation decision for the upper 6 GHz band [69]. Planned revision of the ONIR, intended to incorporate the ICNIRP 2020 restrictions on incident exposure above 6 GHz for fixed installations.
End of 2028	Current Swiss mobile licenses expire [66]. Fixed radio relay links in the 26.5 to 27 GHz segment no longer permitted [65].
~2029–2030	Earliest expected availability of FR2/FR3 spectrum in Switzerland and 6G commercial deployment, FR3 most likely first [35, 71].
2031	WRC-31 expected to review ultra-high frequency (UHF) band (470 to 694 MHz) use and expansion toward sub-THz frequencies [73].

6 Determination of the Transmission Characteristics of Fixed Transmitting Systems

6.1 Parameters of the Fixed Transmitting Systems for Exposure Evaluation

Table 9 summarizes the exposure-relevant parameters of the fixed mmWave transmitting systems reviewed in Section 5.5 into the representative scenarios used for the evaluation. It combines the radiated power by base station class of Table 4, the array geometry, total array gain, and resulting peak EIRP of Table 5, the minimum base station to UE distance of Table 6, and the base station antenna height assumed in the corresponding coexistence layout of Table 7.

Table 9: Representative parameters of fixed mmWave transmitting systems for the exposure evaluation, consolidated from Tables 4, 5, 6, and 7. [19, 20, 22, 63]

BS class (approx.)	Min. BS–UE dist.		Antenna height	Array (M, N)	G_{tot} dBi	TRP dBm	EIRP dBm
	TS 38.104	Coexist. layout					
<i>FR2, around 30 GHz; evaluated at 27.5 GHz [63]</i>							
Wide area (macro)	35 m	35 m	25 m	(8, 16)	29.1	43	~ 72
Medium range (micro)	5 m	3 m	10 m	(8, 16)	29.1	33	~ 62
Local area (pico)	2 m	0 m	3 m	(4, 8)	20.1	23	~ 43
<i>FR3, 6.425 to 7.125 and 10.0 to 10.5 GHz; evaluated at 7 GHz [19]</i>							
Wide area (macro)	35 m	35 m	25 m	(16, 8)	27.5	46	73.6
Medium range (micro)	5 m	n.d. ^(d)	n.d. ^(d)	(8, 8)	23.6	37	60.6
Local area (pico)	2 m	0 m	3 m	(4, 4)	17.5	24	41.6
<i>FR3, 7.125 to 8.4 GHz; evaluated at 7 GHz [20]</i>							
Wide area (macro)	35 m	n.d. ^(c)	25 m ^(c)	(8, 16) ^(a)	32.2	46	78.3
Medium range (micro)	5 m	n.d. ^(c)	10 m ^(c)	(8, 8)	24.5	37	61.5
Local area (pico)	2 m	Not defined for this band ^(b)					
<i>FR3, 14.8 to 15.35 GHz; evaluated at 14.5 GHz [20]</i>							
Wide area (macro)	35 m	35 m	25 m	(16, 24) ^(a)	38.3	46	84.3
Medium range (micro)	5 m	3 m	10 m	(16, 24) ^(a)	38.3	36	74.3
Local area (pico)	2 m	0 m	3 m	(4, 4)	17.0	23	40.0

Two minimum base station to UE separations are given: the TS 38.104 base station class distance [22] used in Table 6, and the smaller, more conservative distance assumed in the corresponding coexistence layout (Table 7). The antenna heights are also those of the coexistence layouts. (M, N) denotes M vertical and N horizontal elements or sub-arrays; G_{tot} is the total array gain and the EIRP the resulting peak value. The FR2 EIRP values are approximate because [63] specifies only a total output power (Section 5.5).

For FWA, the CPE may be considered a fixed transmitter as well, with a maximum TRP of 35 dBm and a peak EIRP of up to 55 dBm for FR2 power class 1 [38].

(a): includes a sub-array structure ($M_{\text{sub}} = 3$ for 7.125 to 8.4 GHz and $M_{\text{sub}} = 4$ for 14.8 to 15.35 GHz), so (M, N) counts steerable sub-arrays; see Table 5.

(b): [20] defines no small cell parameter set for the 7.125 to 8.4 GHz band.

(c): no coexistence network layout is defined for the 7.125 to 8.4 GHz band (“n.d.”); the antenna heights given are those of the comparable layouts of the neighboring FR3 bands (Table 7, note (b)).

(d): the micro urban scenario of the 6.425 to 7.125 and 10.0 to 10.5 GHz bands has antenna parameters but no network layout (Table 7, note (a)).

6.2 Analytical Modeling of Antenna Arrays for Fixed Transmitting Systems

The incident power density is calculated with the help of an analytical approximation of the electromagnetic field of a patch antenna array. Each element of the array is represented by a set of eight magnetic elementary dipoles in front of an infinite ground plane (Figure 6). The fields emitted by the array can be calculated as a function of the antenna topology, i.e., of the number of its horizontal times its vertical elements, the spatial offset of the array elements and their distance from the ground plane. Examples are given in Section 6.3.

The analytical formulation of the electromagnetic field emitted by the patch array is given in [74]. The formulation has been validated against numerical simulations using the finite-difference time-domain (FDTD) method (Sim4Life, Version 8.0, ZMT Zurich MedTech AG, Zurich, Switzerland). Deviations of the Poynting vector of the main beam were found to be smaller than 1 dB at distances from the antenna array as close as the dimensions of a single patch.

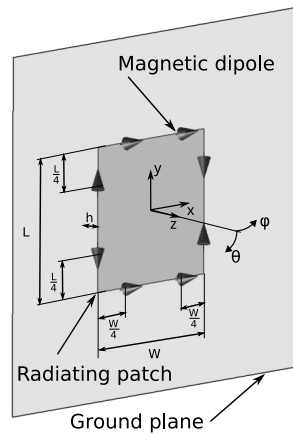


Figure 6: Analytical representation of a radiating patch of length L and width W at a distance h from an infinite ground plane by eight magnetic elementary dipoles [74].

6.3 Exposure Metrics for the Antenna Arrays

Based on the parameters identified in Section 6.1, antenna models with array sizes from 4×4 to 16×24 elements are selected for evaluation of the exposure. The antennas use square elements, i.e., permitting operation with both E- and H-polarization. Their dimensions are given in Table 10. Their far-field characteristics are described in Section 7.2.

The exposure is determined in terms of the whole body IPD and the local psIPD averaged over 4 cm^2 according to the method specified in [15]. Above 30 GHz, [1] specifies an additional local limit averaged over a reduced area of 1 cm^2 , the value of which is a factor of two above the corresponding 4 cm^2 limit (Table 1). The 1 cm^2 limit can therefore only become binding where the incident power density is concentrated strongly enough that reducing the averaging area by a factor of four more than doubles the average. This is not the case at the separations considered here: the smallest base station to user equipment distance of the deployment scenarios is 2 m (Table 9), whereas the largest far-field distance of the arrays operating above 30 GHz is 1.09 m (Table 10). The beam has therefore already formed and is no longer strongly focused. The incident power density then varies only slightly across the $2 \text{ cm} \times 2 \text{ cm}$ averaging square, and the 1 cm^2 and 4 cm^2 averages nearly coincide. The evaluation of the local exposure is therefore restricted to the 4 cm^2 psIPD, which is the more restrictive of the two limits. The exposure limits according to the ICNIRP Guidelines [1] are given in Figure 1.

Table 10: Dimensions of the patch antenna arrays. Figure 6 indicates the length L and width W of the patches and their distance h from the ground plane. The x - and y -offsets are the spacing between the patches in the array. N_x is the number of columns and N_y the number of rows of the array, i.e., x is the horizontal and y the vertical direction, and the array size A_a is given as horizontal $\times$ vertical extent, measured over the outer edges of the corner patches, i.e., $(N_x - 1)\Delta x + W$ by $(N_y - 1)\Delta y + L$. The No. of elements column lists $N_y \times N_x$, i.e., row $\times$ column, matching the (M, N) notation of Table 9, which follows the row $\times$ column convention of [19, 20]. r_D denotes the limit of the far-field zone evaluated according to [75]; it is given as complementary information and is not the Fraunhofer distance $2D^2/\lambda_0$.

Freq. / GHz	No. of elements $N_y \times N_x$	Array size A_a / mm ^a	Patch size $W \times L$ / mm	x -offset Δx / mm	y -offset Δy / mm	Distance h h / mm	r_D / m
7.0	4 $\times$ 4	90.4 $\times$ 90.4	19.64 $\times$ 19.64	23.57	23.57	1.18	0.39
7.0	4 $\times$ 8	184.6 $\times$ 90.4	19.64 $\times$ 19.64	23.57	23.57	1.18	0.85
7.0	8 $\times$ 8	184.6 $\times$ 184.6	19.64 $\times$ 19.64	23.57	23.57	1.18	1.26
7.0	8 $\times$ 16	373.2 $\times$ 184.6	19.64 $\times$ 19.64	23.57	23.57	1.18	2.76
7.0	16 $\times$ 24	561.8 $\times$ 373.2	19.64 $\times$ 19.64	23.57	23.57	1.18	6.24
7.0	16 $\times$ 8	184.6 $\times$ 373.2	19.64 $\times$ 19.64	23.57	23.57	1.18	2.76
14.5	4 $\times$ 4	43.6 $\times$ 43.6	9.48 $\times$ 9.48	11.38	11.38	0.57	0.19
14.5	4 $\times$ 8	89.1 $\times$ 43.6	9.48 $\times$ 9.48	11.38	11.38	0.57	0.41
14.5	8 $\times$ 8	89.1 $\times$ 89.1	9.48 $\times$ 9.48	11.38	11.38	0.57	0.61
14.5	8 $\times$ 16	180.2 $\times$ 89.1	9.48 $\times$ 9.48	11.38	11.38	0.57	1.33
14.5	16 $\times$ 24	271.2 $\times$ 180.2	9.48 $\times$ 9.48	11.38	11.38	0.57	3.01
14.5	16 $\times$ 8	89.1 $\times$ 180.2	9.48 $\times$ 9.48	11.38	11.38	0.57	1.33
27.5	4 $\times$ 4	23.0 $\times$ 23.0	5.00 $\times$ 5.00	6.00	6.00	0.30	0.10
27.5	4 $\times$ 8	47.0 $\times$ 23.0	5.00 $\times$ 5.00	6.00	6.00	0.30	0.22
27.5	8 $\times$ 8	47.0 $\times$ 47.0	5.00 $\times$ 5.00	6.00	6.00	0.30	0.32
27.5	8 $\times$ 16	95.0 $\times$ 47.0	5.00 $\times$ 5.00	6.00	6.00	0.30	0.70
27.5	16 $\times$ 24	143.0 $\times$ 95.0	5.00 $\times$ 5.00	6.00	6.00	0.30	1.59
27.5	16 $\times$ 8	47.0 $\times$ 95.0	5.00 $\times$ 5.00	6.00	6.00	0.30	0.70
40.0	4 $\times$ 4	15.8 $\times$ 15.8	3.44 $\times$ 3.44	4.12	4.12	0.21	0.07
40.0	4 $\times$ 8	32.3 $\times$ 15.8	3.44 $\times$ 3.44	4.12	4.12	0.21	0.15
40.0	8 $\times$ 8	32.3 $\times$ 32.3	3.44 $\times$ 3.44	4.12	4.12	0.21	0.22
40.0	8 $\times$ 16	65.3 $\times$ 32.3	3.44 $\times$ 3.44	4.12	4.12	0.21	0.48
40.0	16 $\times$ 24	98.3 $\times$ 65.3	3.44 $\times$ 3.44	4.12	4.12	0.21	1.09
40.0	16 $\times$ 8	32.3 $\times$ 65.3	3.44 $\times$ 3.44	4.12	4.12	0.21	0.48

^a without ground plane

As explained in Section 4.3.2, IEC/IEEE 63195-2 [15] specifies three different expressions to calculate the incident power density as a function of the Poynting vector. In the far-field, no reactive fields of the antenna need be considered, and the Poynting vector is real-valued and points in the direction of propagation. For the assessment of the incident power density according to [15] in the far-field, the only relevant parameter is the orientation of the evaluation surface or the averaging area, on which the IPD is integrated, with respect to the direction of the Poynting vector.

To maximize the exposure, IEC/IEEE 63195-2 [15] requires that the square averaging area be rotated around its surface normal. Initial evaluations have shown that the rotation is not necessary to obtain a conservative exposure assessment of the psIPD at the distances from the antenna considered here. For the assessment of the local exposure in terms of the 4 cm^2 psIPD, the evaluation surface is assumed to be perpendicular to the Poynting vector, which yields a conservative result for the IPD_{n+} (Eqn. 5) for any orientation of the surface of the body of the exposed person.

For whole-body exposure, the ICNIRP Guidelines require that the incident power density be averaged over the “whole body space.” This study calculates whole-body exposure by averaging the IPD over a rectangular surface oriented perpendicular to the ground and normal to the horizontal tilting angle ϕ of the antenna array. As the surface of the body of the exposed person may not be aligned to the averaging rectangle, the whole-body IPD is calculated by averaging the real parts of all three components of the Poynting vector, i.e., the $\text{IPD}_{\text{tot}+}$ (Eqn. 6). For the assessment of the adult exposure, a rectangle with a height of 1.85 m and a width of 0.55 m is assumed. For children, the height of the rectangle is reduced to 0.96 m, and its width is reduced to 0.23 m according to the dimensions of the small box-shaped phantom suggested for children in [13]. For both adults and children, the beam of the antenna array is directed into the center of the rectangular evaluation areas.

7 Compliance Evaluation for Short-term, Local, and Whole-Body Exposure Quantities

Note: The following exposure evaluations are performed with respect to the ICNIRP exposure limits as discussed in Section 4.2. Where precautionary limits are defined as scaled versions of the ICNIRP limits, the results can be readily adapted by applying the corresponding scaling factor.

7.1 Exposure Configurations for IPD Assessment

The exposure to the antenna arrays is assessed for the following configurations:

- local psIPD averaged over 4 cm^2 ;
- whole body IPD;
- body dimensions of adults ($1.85 \text{ m} \times 0.55 \text{ m}$) and children ($0.96 \text{ m} \times 0.23 \text{ m}$);
- distances of the exposed person between 1 m and 30 m;
- mounting heights of the antenna between 0 m (e.g., at the level of an opposite balcony) and 30 m;
- 0° and 45° horizontal steering angles ϕ ;
- vertical steering angle θ directed to the center of the body of the exposed person limited to a maximum of 45° .

Details on the array configurations can be found in Table 10 in Section 6.3. The directivity of the evaluated antenna arrays is given in Table 11 for boresight radiation and for a vertical and horizontal steering angle of 45° . The far-field distance r_D of the antenna arrays is evaluated according to the method described in [75]. For the larger arrays at 7 GHz and 14.5 GHz, r_D exceeds the minimum evaluation distance of 1 m, which justifies the application of the analytical antenna array model described in Section 6.2.

Table 11: Directivities of the antenna arrays in Table 10.

No. of elements	Directivity [dBi]	
	boresight	$\phi = 45^\circ$, max. $\theta = 45^\circ$
4×4	18.4	12.8
4×8	21.3	15.6
8×8	24.1	20.5
8×16	27.0	23.4
16×24	31.7	28.4
16×8	27.1	23.7

The compliance distances are evaluated as a function of mounting height and distance of the exposed person with respect to the whole body and local (psIPD) exposure limits (Figure 1). The antenna array is assumed to be mounted at a height h from the ground and directs its beam towards the center of the exposed person's body (Section 6.3) at a height of $p/2$ above the ground. The person is assumed to stand on the ground at a distance d from the antenna mounting location. I.e., the vertical steering angle θ is given as

$$\tan \theta = \frac{h - p/2}{d}. \quad (10)$$

As horizontal steering angles ϕ , 0° and 45° are considered. The minimum mounting height is assumed to be 0 m with respect to the position of the exposed body. Such a configuration may be relevant if the antenna is mounted, e.g., on a mast at the level of an opposite balcony or window.

7.2 IPD and Compliance Distances

7.2.1 Whole Body Limit

As explained in Section 7.1, the exposure is evaluated as a function of mounting height h and distance d of the exposed person from the mounting location on the ground. Figure 7 shows the maximum permissible radiated power to reach the whole body exposure limit for an area with the cross section of an adult body at 27.5 GHz with and without reflection from the ground for horizontal steering angles of 0° and 45° . In general, the permissible power drops with increasing array size or directivity and with increasing distance and mounting height. When ground reflection interference is assumed, a further reduction can be observed depending on distance and mounting height. Most restrictive conditions can be generally found for mounting heights close to the ground and boresight radiation as this minimizes the distance to the antenna.

This worst case (boresight radiation) is shown in Figure 8 for all four frequencies and antenna arrays listed in Table 10. At the closest distance of 1 m, the maximum permissible power ranges from approximately 34 dBm to 41 dBm and increases to approximately 45 dBm to 62 dBm at the maximum evaluated distance of 30 m. As the whole-body exposure limit is constant over the investigated frequency range (Figure 1), these results do not significantly depend on the frequency. Reflection from ground assuming constructive interference reduces the maximum permissible power by approximately 3 dB, and the smaller cross section of the body of children assumed here (Section 7.1) leads to a reduction of the maximum permissible power by approximately 5 dB specifically at distances below 10 m and for antennas with high directivity, i.e., under conditions where the body is not exposed homogeneously. The observed reduction of the permissible power level corresponds approximately to the ratio of the body cross sections assumed for children and adults.

The EIRP of these configurations is given in Figure 9. Larger arrays generally have a higher EIRP limit because of their increased directivity. It should be noted that the EIRP is evaluated regarding the nominal directivity of the array and not adjusted for the reduced directivity at angles other than boresight.

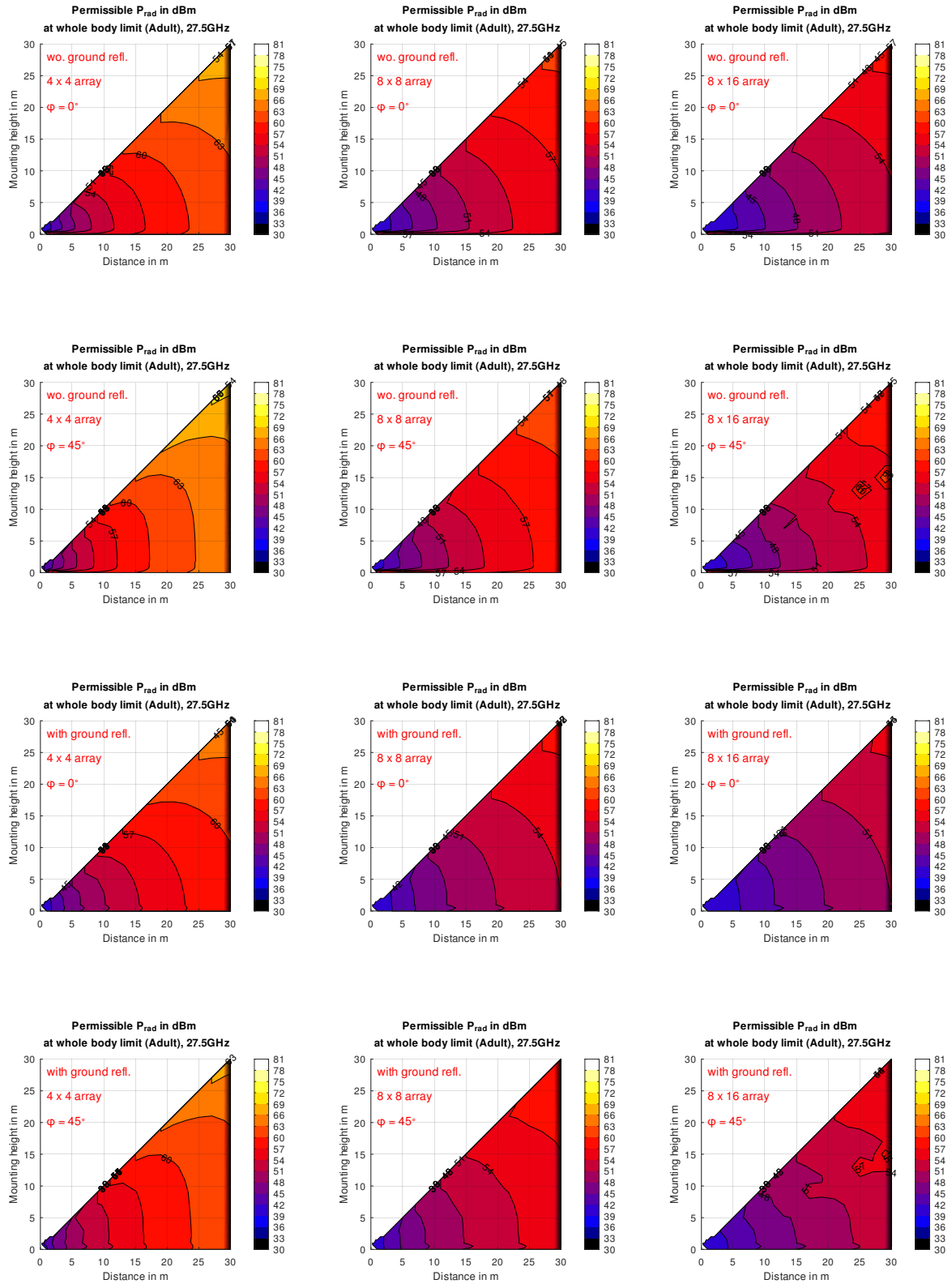


Figure 7: Maximum permissible radiated power to reach the whole body exposure limit for the 4 × 4-, the 8 × 8- and the 8 × 16-array operating at 27.5GHz as a function of the horizontal distance from the antenna mounting location and of the mounting height.

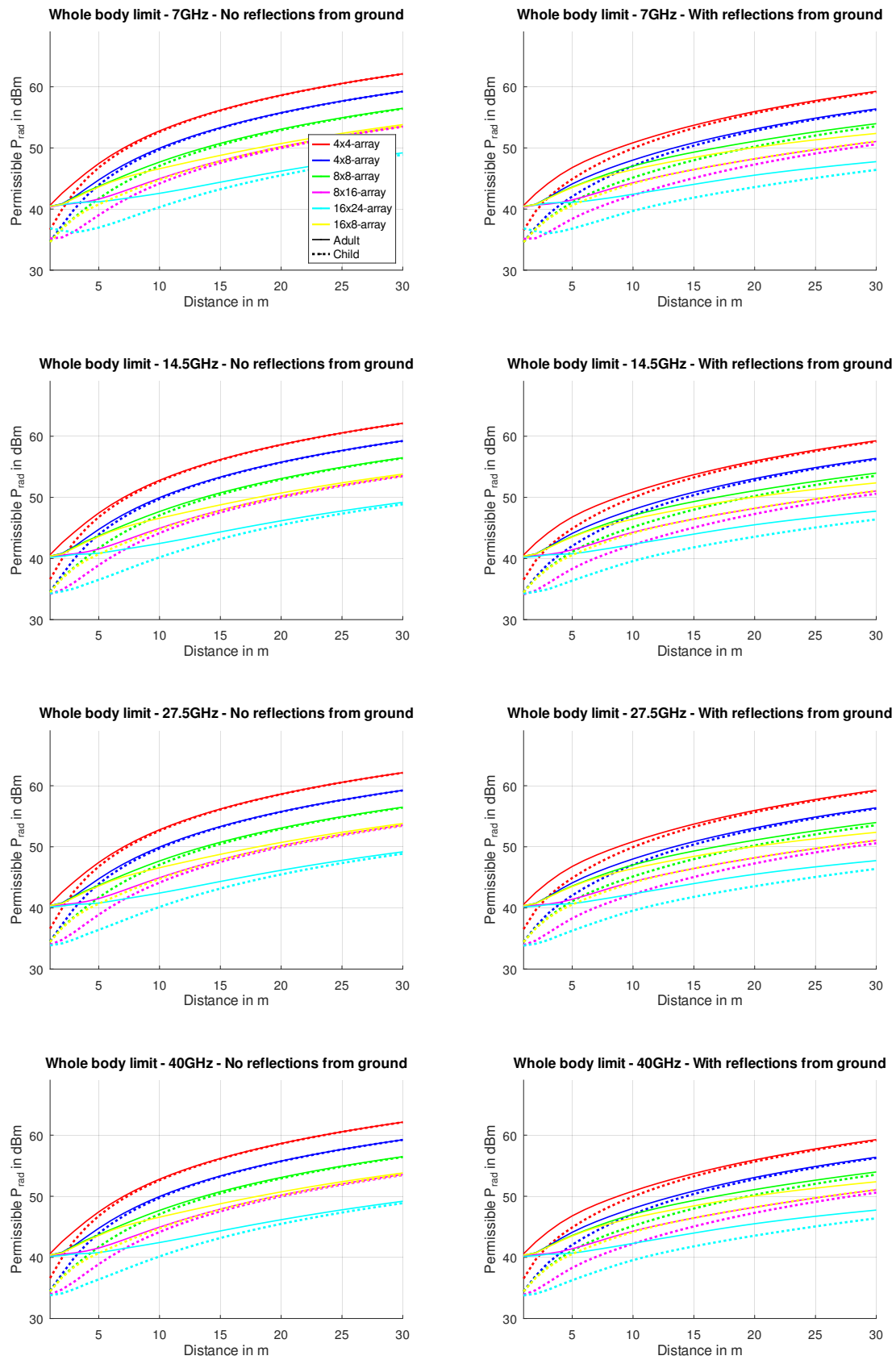


Figure 8: Maximum permissible radiated power to reach the whole body exposure limit as a function of the horizontal distance from the antenna mounting location for boresight radiation.

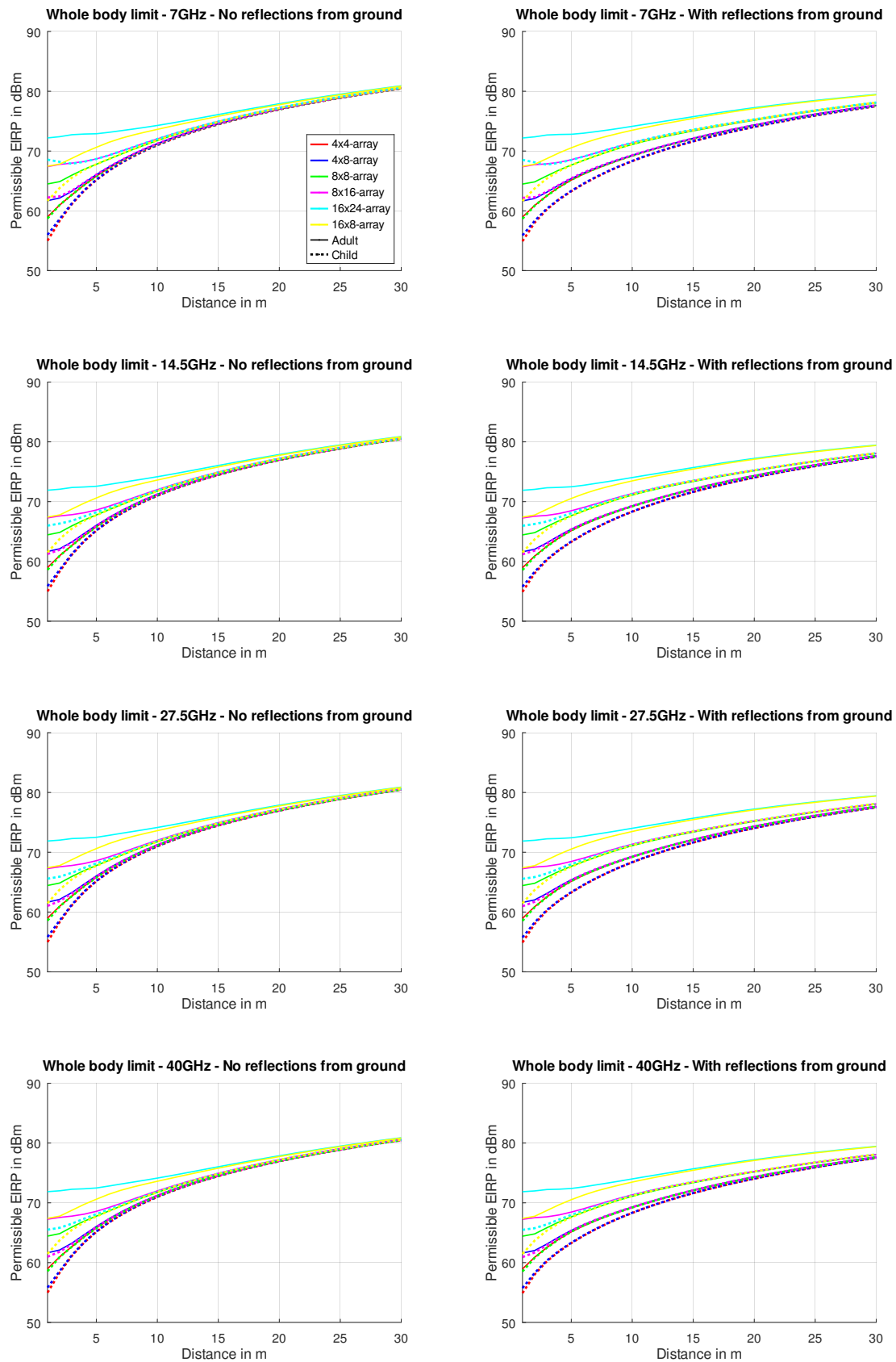


Figure 9: Maximum permissible EIRP to reach the whole body exposure limit as a function of the horizontal distance from the antenna mounting location for boresight radiation.

7.2.2 Local psIPD

Figure 10 shows the permissible radiated power required to reach the 4 cm^2 psIPD limit for the 4×4 -, the 8×8 - and the 8×16 -array operating at 27.5 GHz. General tendencies with respect to distance, mounting height, array size and deflection angle are similar to those observed for the whole body limit (Section 7.2.1). Due to the significantly smaller averaging area for the local psIPD, the additional reduction of the permissible radiated power due to reflection from the ground can be observed mainly for a particular distance-dependent angle of exposure, but in general, the highest exposure occurs for boresight radiation. At larger distances, the permissible power to reach the local limit is higher than for the power for the whole body limit (Section 7.2.3).

Figure 11 shows the maximum permissible power to reach the 4 cm^2 psIPD limit at all four frequencies and for all antenna arrays given in Table 10 operating with boresight radiation. Without reflections from ground, the maximum permissible power depends directly on the array size and ranges from approximately 54 dBm to 70 dBm at the maximum evaluated distance of 30 m. At 1 m distance, it can be less than 30 dBm.

The differences between adults and children observed for the whole-body IPD (Section 7.2.1) are due to the smaller body cross-section of children, i.e., a smaller averaging area. For the evaluation of the local exposure, the averaging area is 4 cm^2 for both adults and children. Hence, the maximum permissible radiated power is identical for both age groups if no reflections from the ground are considered. With reflections, a reduction of up to approximately 2 dB can be observed for children compared to adults. This can be explained by the different body heights, which leads to a different angle of incidence and, in the case of the children, to a slight reduction of the distance that the reflected fields travel.

Figure 12 shows the maximum permissible EIRPs to reach the 4 cm^2 psIPD limit. Barring effects due to reflections from the ground and strongly inhomogeneous exposure at close distances from the 16×24 -element array at 7 GHz, the maximum permissible EIRP to reach the psIPD limit does not depend on the antenna topology.

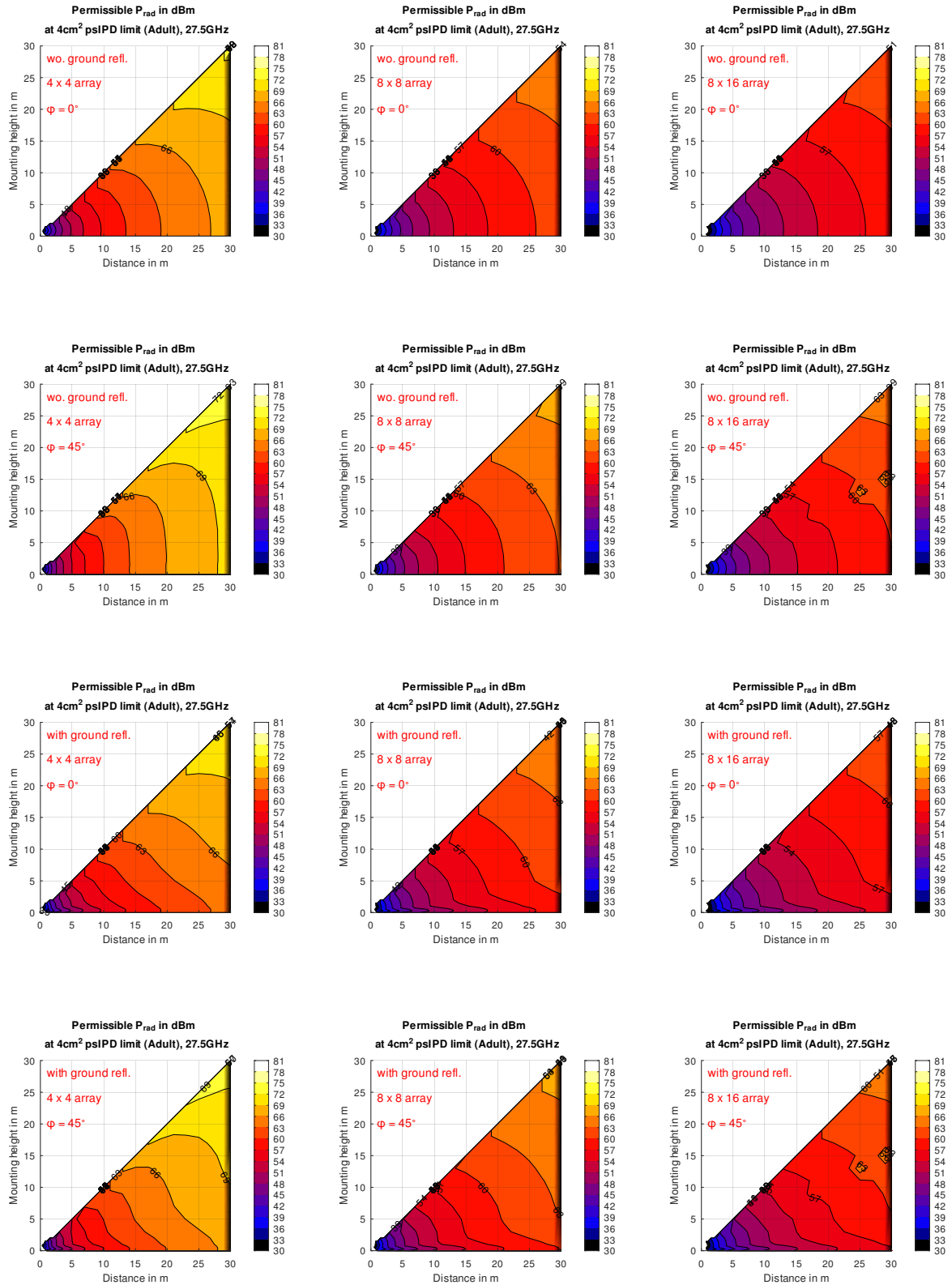


Figure 10: Maximum permissible radiated power to reach the 4 cm² psIPD limit for the 4 × 4-, the 8 × 8- and the 8 × 16-array operating at 27.5 GHz as a function of the horizontal distance from the antenna mounting location and of the mounting height.

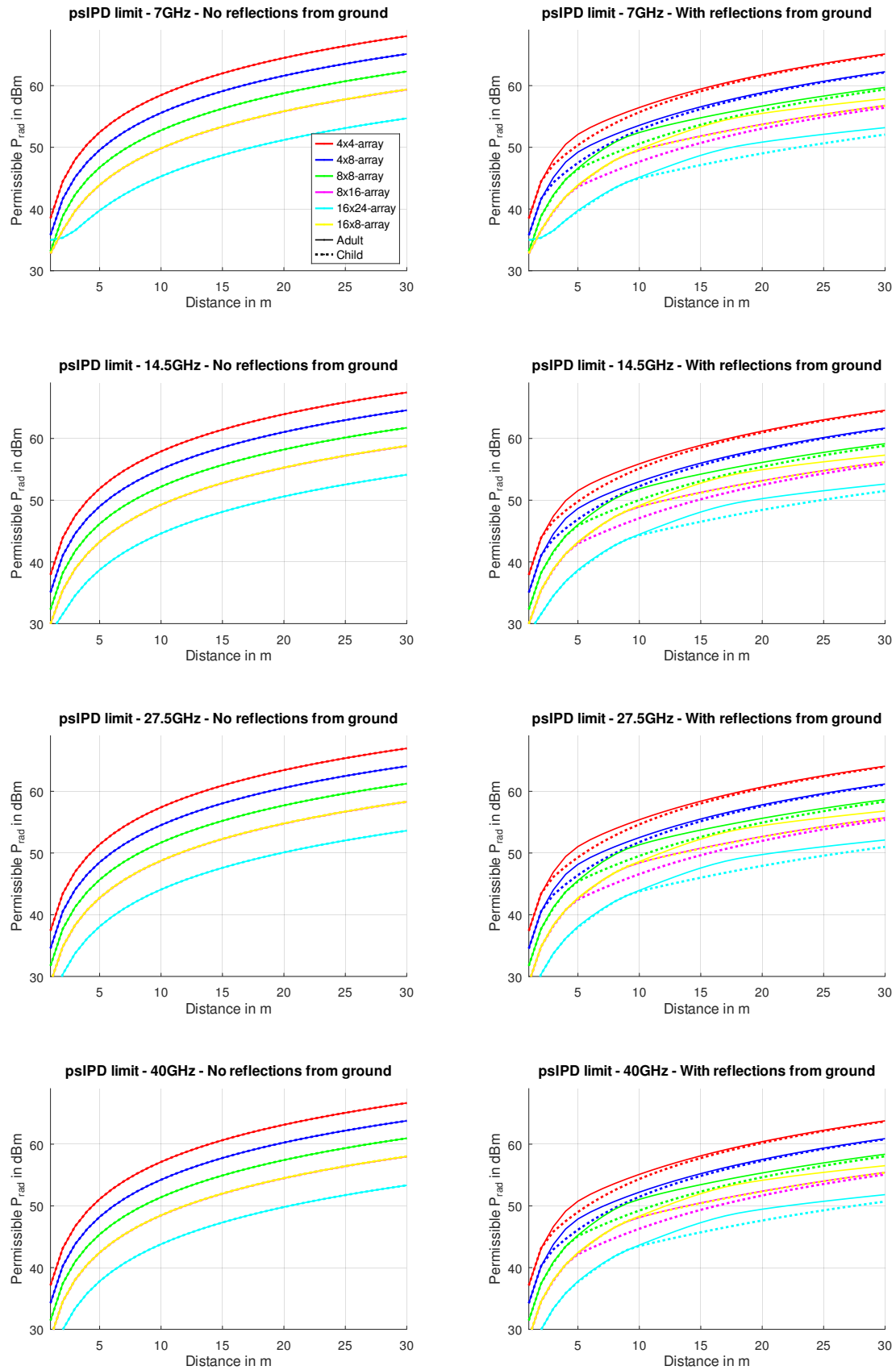


Figure 11: Maximum permissible radiated power to reach the 4 cm^2 psIPD limit as a function of the horizontal distance from the antenna mounting location.

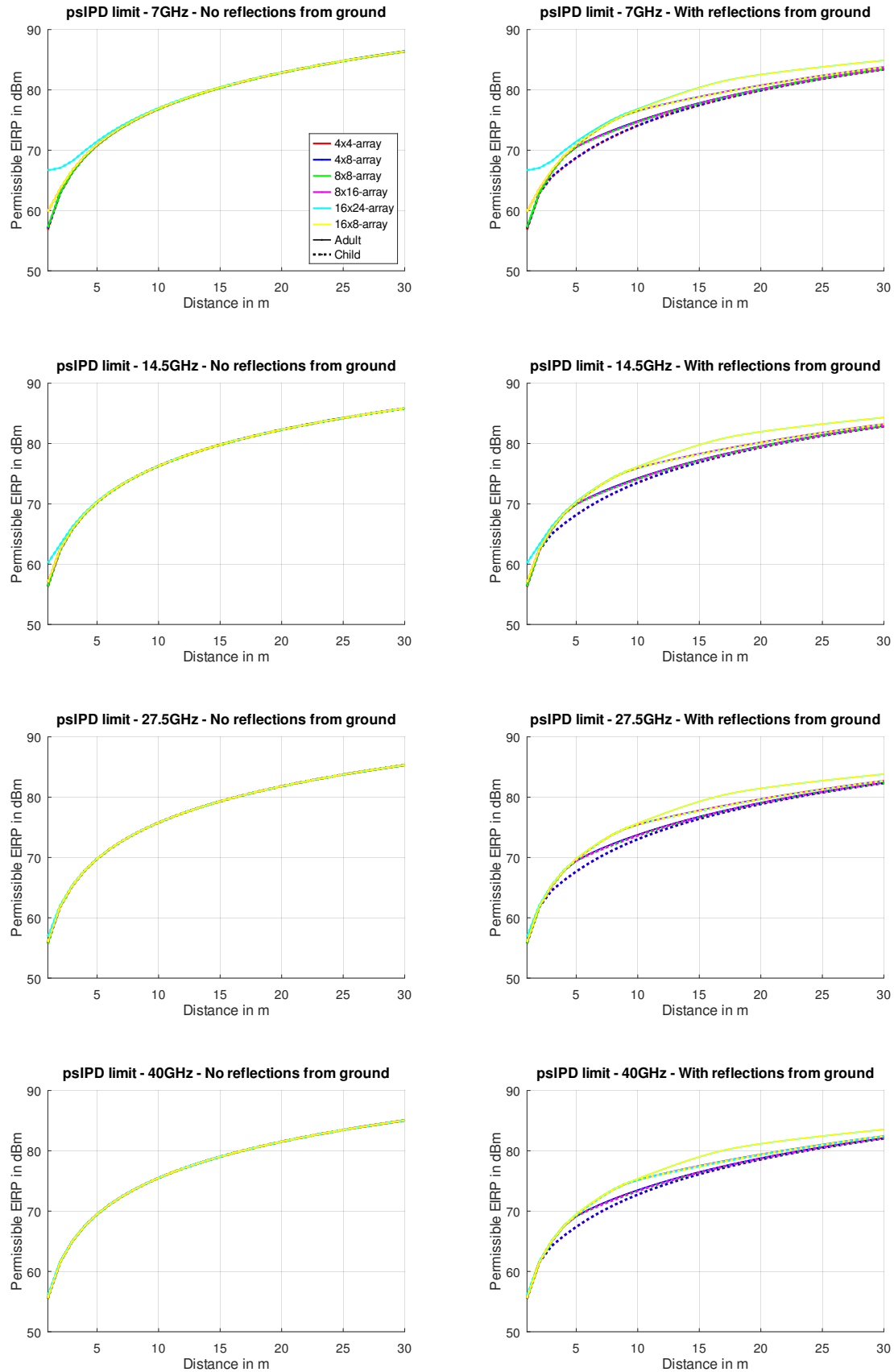


Figure 12: Maximum permissible EIRP to reach the 4 cm^2 psIPD limit as a function of the horizontal distance from the antenna mounting location.

7.2.3 Limiting Exposure Metric

Figure 13 shows the ratio of the maximum permissible power level required to reach the whole body limit to the maximum permissible power limit required to reach the psIPD limit. For values below 0 dB, the whole body limit is more restrictive. In general, this is the case at distances greater than 7 m for the antenna topologies considered (Table 10). For smaller arrays, the whole body limit is more restrictive at shorter distances because of the more homogeneous exposure. This is also true for the smaller body cross section of children.

At larger distances, the whole body limit is generally 5 dB more restrictive. At shorter distances, the psIPD limit can be more restrictive by > 10 dB depending on the array size. It should be noted that the ratio of the maximum permissible power level shown in Figure 13 is identical to the ratio of the maximum permissible EIRP because the directivity required to convert one into the other cancels out.

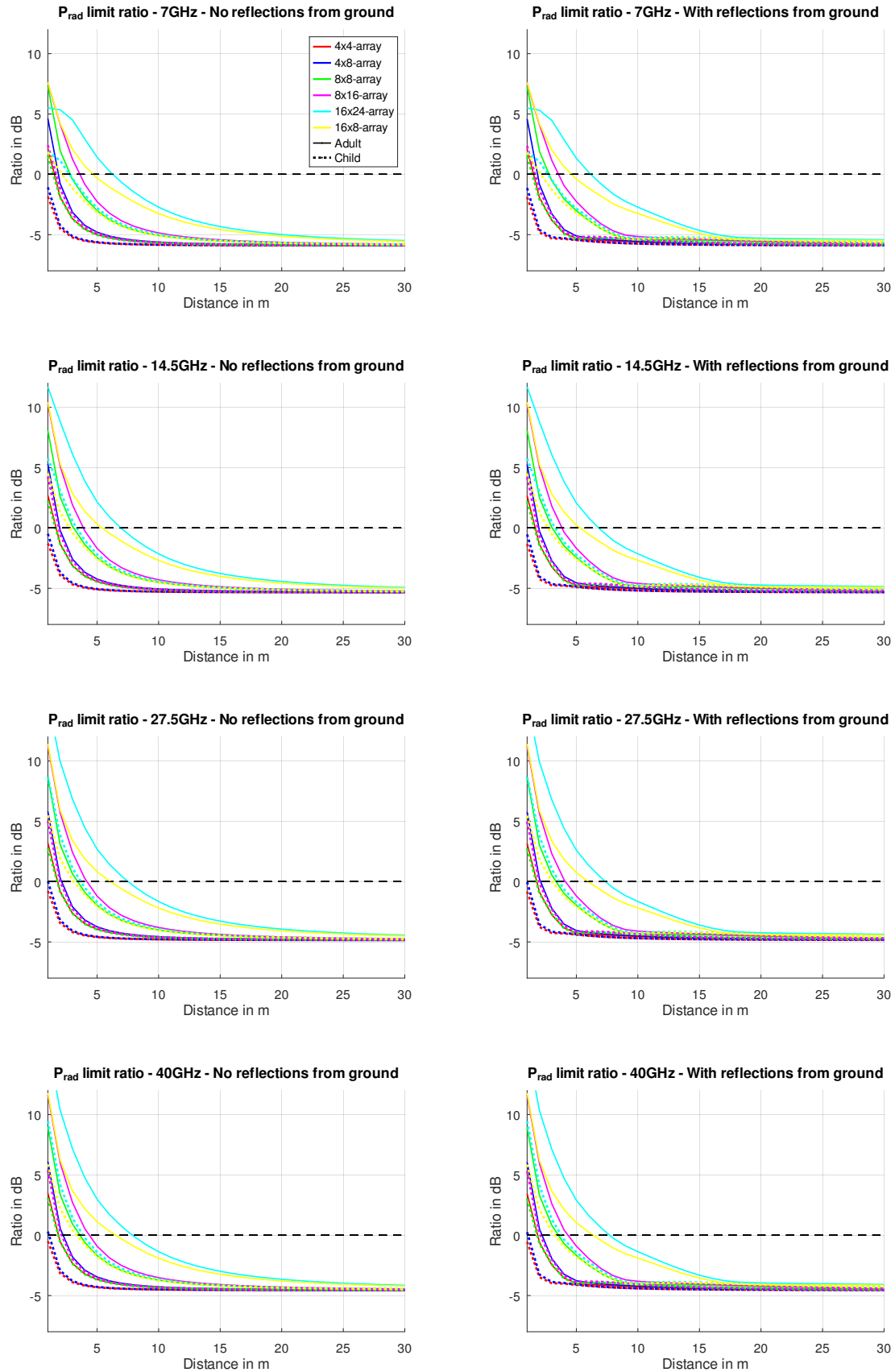


Figure 13: Ratio of the maximum permissible radiated power to reach the whole body limit to the maximum permissible radiated power to reach the psIPD limit as a function of the horizontal distance.

7.3 Relevance of the Short-Term Exposure Limits for mmWave Communication Signals

Fixed mmWave installations do not radiate continuously at maximum power. The signals are shaped by the PAPR of the OFDM waveform, by TDD gating, and by traffic- and beam-dependent scheduling. The ICNIRP 2020 guidelines restrict the energy density accumulated in any window shorter than six minutes, as outlined in the brief-exposure limits of Section 4.2.4 [1] in addition to the six-minute averaged limits. This subsection investigates for which duty cycles these short-term restrictions may be stricter than the six-minute average.

The assessment uses a linear time-invariant thermal model, in which the local peak temperature rise follows from the convolution of the time-variant exposure $S(t)$, i.e., the absorbed power density averaged over 4 cm^2 , with the temperature response $T_r(t)$ of the tissue to a unit step of exposure: $\Delta T_{\max} = \max_t [(S * dT_r/dt)(t)]$. One step response per configuration therefore predicts the peak heating of any pulse train, without a transient co-simulation. The evaluation was performed for the 4 cm^2 quantity. As shown in Section 6.3, the incident power density at the separations considered is nearly uniform across the averaging squares, so that the 1 cm^2 and 4 cm^2 averages nearly coincide, while the 1 cm^2 brief-exposure limits are never lower than the 4 cm^2 limits and converge for $t \rightarrow 0$ (Table 2).

Rectangular pulse trains of pulse width w and inter-pulse interval p , i.e., of duty cycle w/p or peak-to-average power ratio p/w , were evaluated in two scenarios (Figure 14): i) a pair of pulses within the 360 s averaging window (Scenario 1), and ii) a continuous periodic pulse train (Scenario 2).

$\Delta T_{\max}$ is then evaluated when i) the energy density just meets the short-term limit in every sliding window up to 360 s; and ii) the mean incident power density over 360 s just meets the six-minute average limit.

The ratio of the two $\Delta T_{\max}$ distributions, i.e., brief-exposure-limited divided by 6-minute-average-limited defines for which configurations the brief-exposure or 6-minute-average are limiting ($\Delta T_{\max}^{\text{ST}}/\Delta T_{\max}^{6\text{min}}$). A ratio of one means that both limits are equivalent for that pulse shape; a ratio below one means that the short-term limit is the more restrictive one.

Figure 15 shows the results at 30 GHz for the incident power-density reference level. Under the short-term scaling (left), the peak temperature rise remains low and nearly uniform over all pulse shapes, since the limit directly bounds the energy delivered within short windows. Under the six-minute average scaling (middle), it grows substantially for narrow pulses with long intervals, because a low duty cycle permits a high instantaneous amplitude at the same average power. The ratio (right) is therefore close to one for wide pulses and near-continuous transmission and below one for narrow pulses with long intervals. Realistic downlink communication waveforms exhibit microsecond-scale OFDM envelope peaks, at a PAPR of about 8 dB after crest-factor reduction [57], and millisecond-scale TDD gating, at a downlink duty cycle of about 0.75. Therefore, such signals would fall in the bottom left corner of the ratio plot ($\Delta T_{\max}^{\text{ST}}/\Delta T_{\max}^{6\text{min}}$) of Scenario 2, with $w \ll 1\text{ s}$ and $p \ll 10\text{ s}$ in Figure 15. In this area, the ratios are all unity.

An independent analysis of base station exposure [62] reaches the same conclusion. At a realistic peak-to-average power ratio of about 10 dB, the power within a symbol time would have to be about 57 dB above realistic values to breach the short-term limits while the six-minute average is met [62].

Waveforms with narrow pulses and long intervals could instead occur in the pulsed operation of radar and possibly of ISAC, whose sensing transmissions may be independent of user traffic [34, 37].

In summary, for fixed mmWave communication installations, the six-minute average will be the binding constraint, but brief exposure limits may have to be considered for radar and ISAC applications.

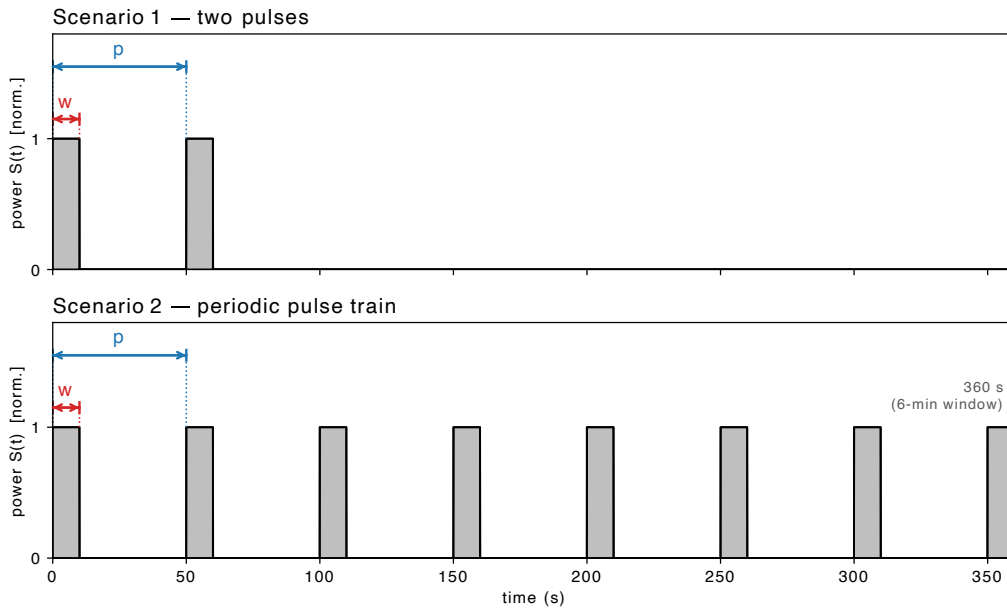


Figure 14: The two rectangular pulse-train scenarios, each parameterized by the pulse width w and the inter-pulse interval (period) p . Scenario 1 (top) is a pair of pulses within the 360 s (six-minute) averaging window; Scenario 2 (bottom) is a continuous periodic pulse train.

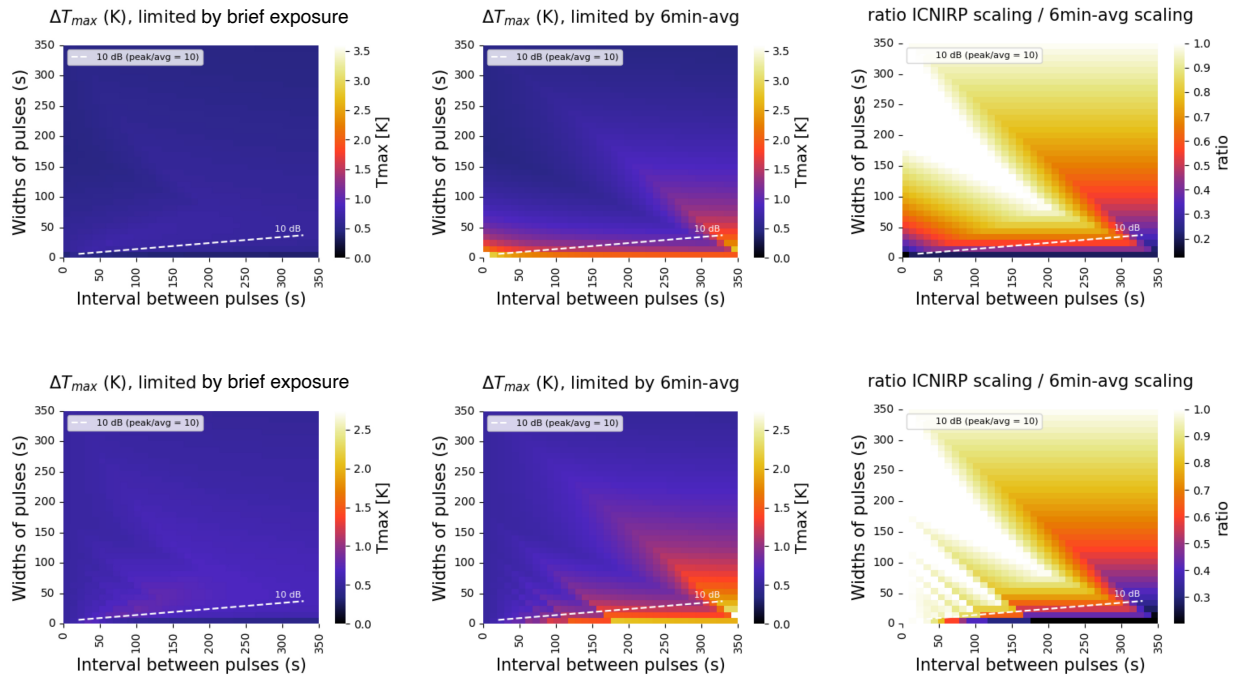


Figure 15: Local peak temperature rise $\Delta T_{\max}$ at 30 GHz for rectangular pulse trains as a function of pulse width and inter-pulse interval, for the two pulse-train scenarios of Figure 14 (top row: Scenario 1, a pair of pulses resembling a RADAR scenario; bottom row: Scenario 2, a periodic pulse train resembling a TDD scenario). Each row shows $\Delta T_{\max}$ when the exposure is scaled to just meet the ICNIRP 2020 short-term limit (left), the six-minute average limit (middle), and the ratio of the two (right). A ratio at or close to 1 means that the 6-minute average is limiting.

8 Discussion and Conclusions

8.1 Discussion

The potential to predict the future adoption of public mmWave communication systems in Switzerland is limited. Worldwide, the FR2 deployment has remained confined to high-capacity hotspots and to FWA in markets lacking wired broadband, and operators have largely shifted their growth to the mid-band (Section 5). In Switzerland, no mmWave frequencies have been assigned yet; the 26 and 40 GHz ranges remain populated with incumbent services until at least the end of 2028, and a public consultation will precede any award. The FR3 bands are not yet a standardized 3GPP frequency range, so the parameters underlying this study are taken from coexistence studies [19, 20, 63] rather than from deployed hardware. However, should future products deviate from these assumptions, the wavelength-normalized exposure results transfer directly. Frequencies above the bands considered here, including sub-terahertz operation, cannot be assessed realistically before candidate bands and technical parameters emerge from the WRC process at the earliest 2030s. Additionally, considering the slow and even decreasing adoption of FR2 bands worldwide, adoption of sub-terahertz communication in public wireless networks is considered highly unlikely at this point.

The upcoming revision of the ONIR may have to address several boundary cases related to mmWave communication systems. Exposure from non-terrestrial networks is currently excluded from the assessment of fixed terrestrial installations (Section 5.1.1), yet fixed user uplink terminals for satellite communications could resemble FWA customer-premises installations in mounting and operation. Similarly, the FWA CPE itself constitutes a fixed transmitter with a peak EIRP of up to 55 dBm for FR2 power class 1 [38], comparable to a pico base station allowing exposure at short distances to persons; its treatment under the ONIR should be clarified. Reconfigurable intelligent surfaces that may transmit as well as reflect may deliberately open outdoor-to-indoor propagation paths, weakening the building attenuation for mmWave signals, and may require attention in future assessment guidelines.

The assessment combines several worst-case assumptions: the beam is continuously directed at the center of the exposed body at maximum radiated power, ground reflection is assumed total and constructively interfering, free-space propagation is assumed, and the evaluation surface is oriented for the maximum of the incident power density (Section 6.3). Actual exposures are further reduced by power control, scheduling, and traffic statistics, which may be taken into account in compliance assessments through the actual transmitted power [13]. The results therefore constitute upper bounds for a single installation; however, the summation of co-located antennas is not addressed here.

8.2 Limitations

The analytical array model assumes an infinitely large ground plane, neglects mutual coupling between the elements as well as radome and casing, and has been validated against full-wave simulations to within 1 dB down to distances comparable to a single patch element [74]. The arrays are generic uniform lattices; the sub-array structures and pre-set down-tilts of the 3GPP parameter sets (Table 9) are not reproduced. The exposed person is represented by box-shaped averaging surfaces rather than anatomical models, which is conservative for the whole-body average of the incident power density.

The short-term assessment uses a linear time-invariant thermal model of the local heating at 30 GHz and, as justified in Section 7.3, the 4 cm^2 quantity. The conclusions on the short-term limits hold for communica-

tion signals and for sensing functions sharing the communication transmit chain; radar-like transmitters with separate high-peak-power chains would require a dedicated assessment.

The study is computational; no measurements were performed. Established measurement methods [14, 16] are available for the compliance assessment of actual installations.

All results and discussions are with respect to the ICNIRP exposure limits. However, where precautionary limits are defined as scaled versions of the ICNIRP limits, the results can be readily adapted by applying the corresponding scaling factor.

8.3 Conclusions

The exposure from fixed mmWave installations relative to the ICNIRP 2020 limits is governed mainly by the distance from the antenna, its mounting height, its directivity, and power radiated. The whole-body incident-power-density limit becomes the decisive quantity at distances beyond approximately 7 m, at an EIRP of approximately 65 to 75 dBm depending on array type. In the far-field, it is approximately 5 dB more restrictive than the local psIPD limit for adults and children alike, so that compliance with the local limit does not guarantee whole-body compliance. The smaller body cross section of children reduces the permissible power by up to approximately 5 dB; ground reflections and horizontal beam steering each reduce it further, by up to approximately 3.5 dB for larger arrays and up to 6 dB for smaller arrays.

The local psIPD limit becomes decisive only within approximately 5 m of the antenna, at an EIRP above approximately 55 dBm at 1 m, rapidly increasing to approximately 65 dBm at 5 m. At the minimum base-station-to-person distances of the scenarios (35 m for the macro, 2 m for the pico TS 38.104 base-station class), the whole-body limit permits a maximum EIRP of approximately 80 dBm and 65 dBm, respectively; the emissions therefore approach the limits only for combinations of high EIRP and short separation, as for pico installations or antennas mounted at the level of an opposite balcony or window.

Regarding the brief-exposure limits, the six-minute average is generally more restrictive for realistic communication waveforms; the brief-exposure energy-density limits become binding only for exposures with a high peak-to-average ratio and a low duty cycle. Such properties are unrealistic for fixed mmWave communication installations. As long as integrated sensing functionality (ISAC) reuses the communication signal and amplifier chain, this conclusion holds; only a separate, radar-like transmit chain generating substantially higher peak powers may require consideration of the brief-exposure limits.

For the revision of the ONIR, a subset of the ICNIRP 2020 limits is therefore sufficient for fixed mmWave communication installations: the whole-body incident-power-density limit, complemented by the local psIPD limit at short separations.

If precautionary limits are defined as scaled versions of the ICNIRP limits, the results can be adapted by applying the corresponding scaling factor. In addition, future assessment guidelines should consider whole-body averaging areas that are representative of children.

9 About Us

Z43 (www.z43.swiss)

Zurich43 (Z43) is a strategic alliance composed of four partner organizations: the nonprofit Foundation for Research on Information Technologies in Society (IT'IS) and three commercial SMEs – Schmid and Partner Engineering AG (SPEAG), ZMT Zurich MedTech AG (ZMT) and TI Solutions AG (TI Solutions). Z43's dedicated mission is to expand the boundaries of (i) accurate evaluation of electromagnetic (EM) near- and far-fields from static to optical frequencies and (ii) predictive modeling in validated anatomical and physiological environments for precision medicine. Z43 is a leading global player that collaborates with over 100 R&D centers and serves more than 500 customers worldwide. In addition, Z43 maintains two ISO17025 accredited laboratories to better serve its research partners and customers, i.e., the SPEAG Calibration Laboratory and the IT'IS Test Laboratory (accredited since 27 September 2024).

IT'IS – Foundation for Research on Information Technologies in Society (www.itis.swiss)

The IT'IS Foundation was established in 1999 through the initiative and with the support of the Federal Institute of Technology (ETH) Zurich and the global wireless communications industry, together with several governmental agencies. IT'IS is the leading independent nonprofit research institute dedicated to improving the quality of people's lives by advancing personalized medicine and computational life sciences and beneficial applications of EM energy and wireless communications (EM Research). IT'IS supports the R&D efforts of the alliance members, as well as its many academic and industrial partners, to advance precompetitive and non-competitive research initiatives; and offers a variety of customized research solutions to the wireless and medical device industries, to academic and national institutions, and to governments and regulatory bodies. IT'IS is very active in numerous standards, including IEC 62209, 62232, 62704, 63195, and 63184 (wireless transmitting devices), and IEC 60601-2-33, ISO 10974, and ASTM F2182 (magnetic resonance systems and implant safety).

SPEAG – Schmid & Partner Engineering AG (www.speag.swiss)

SPEAG was founded in 1994 to develop and manufacture EM systems and components as a spin-off of the ETH Zurich's Bioelectromagnetics/EM Compatibility research group (which later became the IT'IS Foundation). SPEAG is the leading developer and manufacturer of advanced, efficient, and reliable test equipment for the evaluation of the EM near- and far-fields at frequencies from a few kHz up to 110 GHz. SPEAG's key products are: DASY8 – specific absorption rate (SAR) measurements for safety compliance; cSAR3D – fast SAR testing; ICEy – automated near-field scanning for EM interference and compatibility (EMI/EMC); MAGPy – exposure assessments below 10 MHz; DAK – dielectric measurement systems; EM Phantoms – body simulators for radiofrequency (RF) testing; and SEMCAD X – RF performance modeling of devices used in and on the human body.

ZMT – ZMT Zurich MedTech AG (www.zmt.swiss)

ZMT was founded in 2006 as a spin-off company of ETH Zurich and the IT'IS Foundation, with the mission to develop innovative and validated simulation tools and best practices for the analysis and prediction of complex, multifaceted, and dynamic biological processes and interactions. ZMT's flagship product is Sim4Life, a state-of-the-art simulation platform that combines computable human phantoms with powerful physics solvers and the most advanced tissue models. Sim4Life is used to analyze real-world biological phenomena and complex technical medical devices and therapies in validated computational biological and anatomical environments. ZMT also provides fully characterized and ISO17025-calibrated measurement systems for model generation, verification, and validation of *in silico*-based evaluations.

TI Solutions – TI Solutions AG (www.temporalinterference.com)

TI Solutions is a young start-up developing highly flexible stimulation devices and planning tools to support investigations of non-invasive temporal interference stimulation of brain and peripheral nervous system activity. The long-term goal is to enable personalized treatments by providing the most advanced stimulation devices.

IT'IS Test Laboratory (www.itis.swiss/customized-research/)

The IT'IS Test Laboratory performs accurate electromagnetic near-field evaluations. Its scope is to (i) design, validate and perform electromagnetic and temperature measurements in free space and in lossy media, (ii) characterize test items and materials relating to such measurements, and (iii) provide service assistance in the areas of testing and verification. The primary applications are in areas of wireless and medical devices in which product standards have not been established yet. ISO 17025 calibrated probes, verified test equipment, and validated methodologies are utilized to ensure quality and traceability of tests. In 2022, the IT'IS Laboratory formally applied to the Swiss Accreditation Service for ISO 17025 Type C accreditation with the main objective to develop new robust and validated test procedures which extend the scope and methodology beyond what is addressed by current norms or technical specifications and to work with the relevant standards organizations and national regulators to introduce these techniques into the next generation of standards and national regulations. Formal accreditation was granted on 27 September 2024.

SPEAG Calibration Laboratory (<https://speag.swiss/services/cal-lab/accreditation/>)

To better serve Z43 partners and customers, SPEAG established a calibration Laboratory in 2001 that is certified by the Swiss Accreditation Service for ISO/IEC 17025 Accreditation and multilaterally recognized by EA, IFA, and ILAC. The laboratory provides extensive calibration services to the entire Z43 family for systems, probes, antennas, dielectric probe kits, phantoms, materials, etc. A number of satellite facilities have been co-founded, such as the SPEAG Calibration Laboratory Korea, established in 2011 in collaboration with DYMSTEC, in order to bring calibration services closer to SPEAG's global customer base.

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