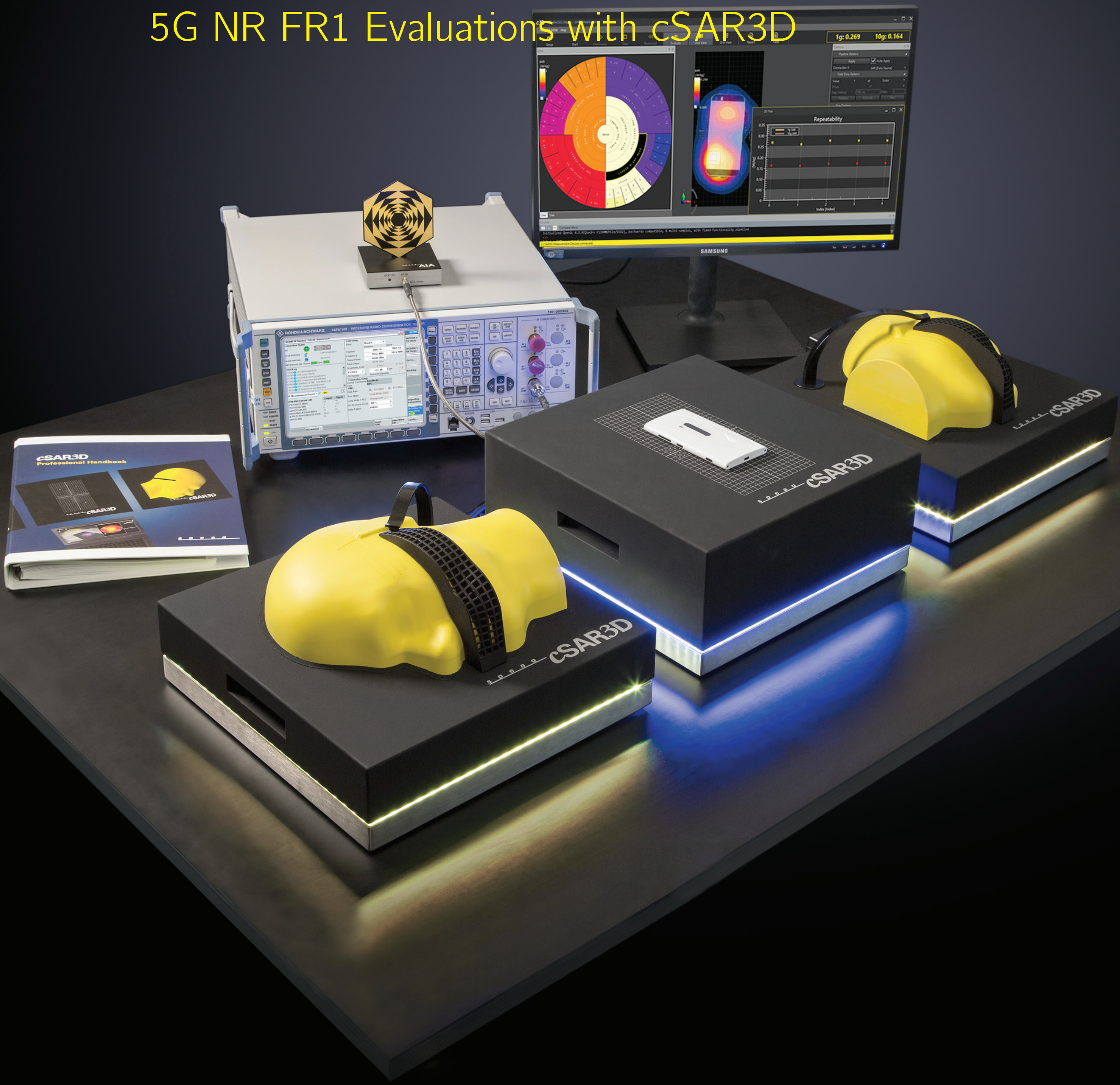
SAR Measurements with cSAR3D

APPLICATION NOTE

5G NR FR1 Evaluations with cSAR3D



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List of Abbreviations **45**

5G NR FR1 Evaluations with cSAR3D

1 Summary

This application note describes how to perform SAR measurements for 5G NR FR1 using the cSAR3D system. It is intended for users who are new to 5G NR SAR testing. It describes the measurement methods and system check procedures that are applicable to 5G SAR measurements. The measurement technique used are consistent with regulatory policies and the draft Technical Report under consderation by the IEC TC106 Joint Working Group 13 [9] on 5G NR SAR measurements.

5G NR SAR measurements in FR1 are supported by all cSAR3D systems with software version V3.0 or higher. The cSAR3D system has distinct advantages compared to frequency-selective technologies:

1. The broadband sensors pose no limits for very wide bandwidth signals.
2. The most effective method to demonstrate simultaneous transmission SAR compliance for the large number of wireless mode combinations and configurations used in 5G is to measure individual modes or configurations directly and combine the SAR distributions through post-processing to assess the maximum exposure for all applicable simultaneous transmission combinations.
3. The standard system check used by cSAR3D [8] is also applicable for 5G SAR measurements in FR1.

This following are included in this application note:

- a brief review of 5G operating parameters that are relevant for SAR measurement (Section 2),
- recommended SAR measurement procedures for 5G NR (Section 3),
- an updated SAR measurement uncertainty budget for 5G NR (Section 4),
- the procedures required for system check (Section 5),
- example 5G NR SAR measurements performed with cSAR3D (Section 6),
- references to list of test reports for 5G NR devices that have received recent regulatory approval (Section 7).

Additional information on measurement concerns, specific techniques applied and measurement uncertainty components are included in the Appendices.

Note that the 5G devices described in Section 7 have received regulatory approval for FR1 operations according to measurement method used by DASY (single-probe scanning system). From 5G NR setup point of view, the DUT configuration is the same. In addition, SPEAG is planning to issue a complimentary validation report on direct comparisons of DASY and cSAR3D measurements.

2 5G NR Background and Overview[1]

The demand for higher data rates has resulted in larger signal bandwidth for each new generation of communication system. The air interface defined by 3GPP for 5G is known as New Radio (NR). It consists of two frequency ranges; Frequency Range 1 (FR1) and Frequency Range 2 (FR2). In 3GPP Release 16 TS 38.101-1 [1], FR1 is specified for 410 MHz to 7125 MHz, and FR2 is specified for 24250 and 52600 MHz. These are shown in Table 1.1.

Frequency range designation	Corresponding frequency range
FR1	410 MHz - 7125 MHz
FR2	24250 MHz - 52600 MHz

Table 1.1: Definition of the 5G NR frequency ranges

For 5G NR, channel bandwidths up to 100 MHz are supported for FR1 and up to 400 MHz for FR2. Besides larger channel bandwidths, 5G NR also provides additional flexibility for carrier aggregation (CA) - a feature introduced in 4G LTE in 3GPP Release 10, where multiple component carriers (CC) are used to extend the transmission bandwidth. The 4G CA concept is expanded in 5G NR to enable higher data rates and larger transmission bandwidth, up to 100 MHz per CC or total of 400 MHz with a maximum of 8 CC in FR1 [1]. The CCs can use different combinations of signal modulations (up to 256 QAM), transmit power, resource block allocation, channel bandwidths and sub-carrier-spacing (SCS) etc.

The first commercial 5G networks were launched in South Korea and in the United States in April 2019. Many operators worldwide have commercially running networks at the end of 2019. These initial 5G deployments have been mostly in non-standalone (NSA) mode, that requires the LTE core to provide control and signalling for the 5G data transmission. LTE and 5G operate according to EN-DC requirements (E-UTRAN (Evolved Universal Terrestrial Radio Access) and New Radio - Dual Connectivity). This requires the so-called LTE anchor for 5G operations. As the number of 5G devices on the market continue to increase, 5G networks and devices will start transitioning to standalone (SA) mode, using 5G core network only; the LTE anchor will no longer be needed. A few OEMs have already made announcement to release such devices [25], [26]. The first SA networks are expected to be launched in Asia in the second half of 2020. Besides reducing the overall network and device implementation complexity, the SAR measurement requirements for device operating in SA mode are also expected to be simpler. The low latencies required for certain time-critical operations can be supported only in SA mode; for example in the medical field or time-critical IoT.

2.1 5G NR FR1 Operating Bands

The frequency bands for 5G NR are updated continuously through each 3GPP release. The table below reflects the frequency bands allocated for FR1 in 3GPP TS 38.101-1 (2020-03) [1]. Both FDD and TDD are supported and most of the bands may be shared with LTE. NR bands are identified with the leading letter n to distinguish them from LTE bands. For bands that cover a sufficiently wide frequency range, such as n40, n41, n48, n77, n78, n79 and n90, the maximum channel bandwidth can be up to 100 MHz. For example, n77 covers a frequency range of 900 MHz. As shown in the table below, certain frequency bands can support optional features, such as Supplementary Downlink (SDL) and Supplementary Uplink (SUL). SDL is used to increase downlink capacity through channel bonding. SUL employs an additional uplink FDD/TDD carrier, typically in a lower frequency band, to increase uplink cell edge coverage for the primary uplink band. Simultaneous transmission of the primary UL and SUL band is not supported in SUL, only one band may transmit at a time.

Although the frequency bands can be quite wide, the bandwidths of channels and component carriers within the band are limited to 100 MHz. Therefore, SAR measurement of the individual channels can be easily satisfied with DASY and cSAR3D systems.

Note: *SAR measurements of 160 MHz channel bandwidths for 802.11ac [5] have been performed using DASY systems since 2013.*

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[1] Section 2 reflects the knowledge as of July 2020 and will be continuously updated with inputs from the regulators and industry.

NR operating band	Uplink (UL) *operating band* BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) *operating band* BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
n18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n26	814 MHz – 849 MHz	859 MHz – 894 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n29	N/A	717 MHz – 728 MHz	SDL
n30[3]	2305 Mhz – 2315 MHz	2350 MHz – 2360 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n48	3550 MHz – 3700 MHz	3550 MHz – 3700 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD[1]
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n53	2483.5 MHz – 2495 MHz	2483.5 MHz – 2495 MHz	TDD
n65	1920 MHz – 2010 MHz	2110 MHz – 2200 MHz	FDD[4]
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780 MHz	N/A	SUL
n89	824 MHz – 849 MHz	N/A	SUL
n90	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD[5]
n91	832 MHz – 862 MHz	1427 MHz – 1432 MHz	FDD[9]
n92	832 MHz – 862 MHz	1432 MHz – 1517 MHz	FDD[9]
n93	880 MHz – 915 MHz	1427 MHz – 1432 MHz	FDD[9]
n94	880 MHz – 915 MHz	1432 MHz – 1517 MHz	FDD[9]
n95[8]	2010 MHz – 2025 MHz	N/A	SUL

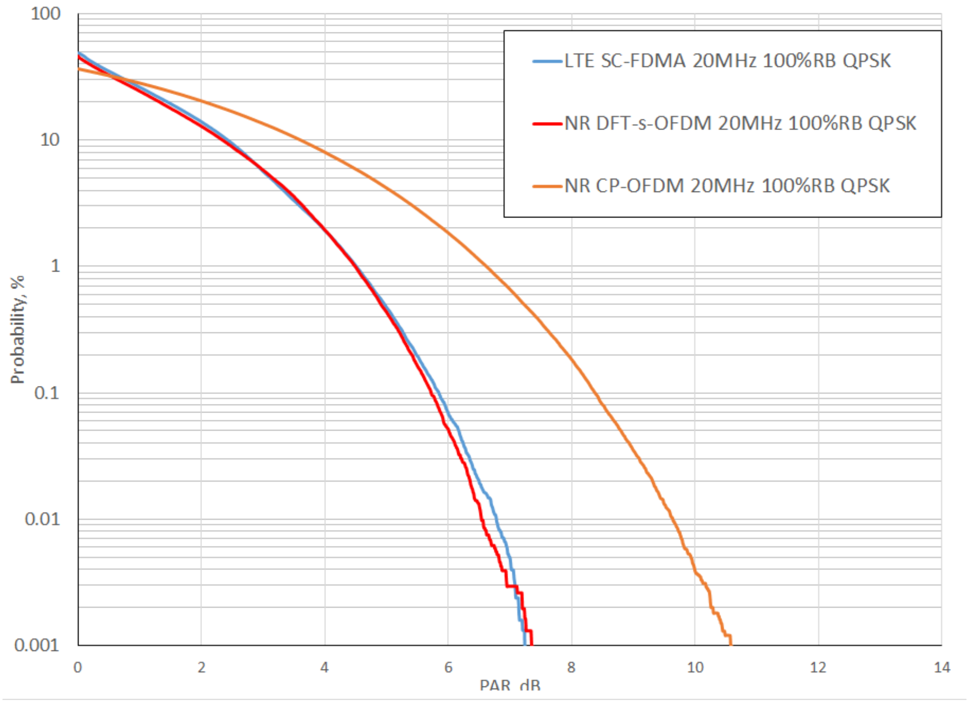


Figure 1.1: The CCDF of an LTE waveform and both types of 5G NR waveform. All signals have 15 kHz sub-carrier spacing, 20 MHz channel bandwidth and 100% resource blocks. SC-OFDM used in LTE has a very similar CCDF as DFT-s-OFDM used in 5G NR.

2.2 5G NR Bandwidths

Uplink channel bandwidths of 5, 10, 15, 20, 25, 30, 40, 50, 60, 80 and 100 MHz are supported in FR1; in addition, 70 and 90 MHz bandwidths are also supported in the downlink. These channel bandwidths are substantially higher than the 20 MHz specified for LTE.

2.3 5G Uplink Waveforms and PAR Considerations

Two uplink waveforms are used for 5G transmissions, CP-OFDM and DFT-s-OFDM. CP-OFDM is similar to that used in LTE downlink and DFT-s-OFDM is similar to SC-FDMA used in LTE uplink. As shown on Fig. 1.1, similar to SC-FDMA, DFT-s-OFDM has a relatively low PAR. It is illustrated in Figures 1.2 and 1.3 that CP-OFDM has a higher PAR; however, there is little PAR variation among modulations (QPSK, 16QAM, 64QAM, 256QAM). The PAR of a signal can impact power amplifier linearity and limit device output performance. Because of that, it has to be considered during conducted measurements and taken into account when selecting the configurations for SAR evaluations. 3GPP has implemented Maximum Power Reduction (MPR) criteria to limit UE output power, according to signal modulation, resource block (RB) allocations and channel bandwidth combinations. Due to MPE requirements, QPSK generally corresponds to the highest output power configurations that are considered for SAR evaluations. For DFT-s-OFDM, $\pi/2$ BPSK is also supported but it is optional.

2.4 5G Subcarrier Spacing and Flexible Numerology

One of the advantages of OFDM is its ability to support wide-band channels by sub-dividing the channel into orthogonal narrow spectral segments called subcarriers. The combinations of 5G waveform parameter configurations is called numerology. It is identified by the Greek letter μ. Different numerologies are considered for the OFDM-based subcarriers, according to parameters such as subcarrier spacing (SCS), symbol duration, cyclic prefix (CP) etc. The corresponding SCS for each numerology is summarized in Table 1.2. The SCS for 5G are specified in multiples of 15 kHz to provide backward compatibility with LTE. The lower SCS configurations are more suitable for larger cell sizes and low frequency bands, which may limit channel bandwidth due to a larger number of subcarriers.

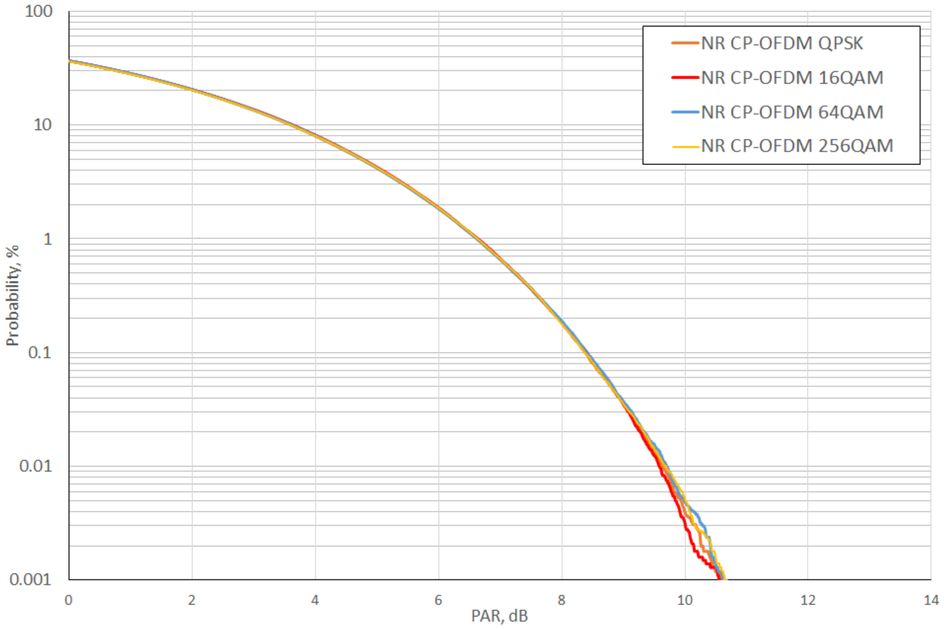


Figure 1.2: CCDF of 5G NR using CP-OFDM waveforms with different modulations: QPSK, 16QAM, 64QAM, and 256QAM. All signals have15 kHz, sub-carrier spacing, 20 MHz channel bandwidth and 100% resource blocks. The PAR of the signal is not changing with the increasing the modulation order - the curves are almost overlapping each other.

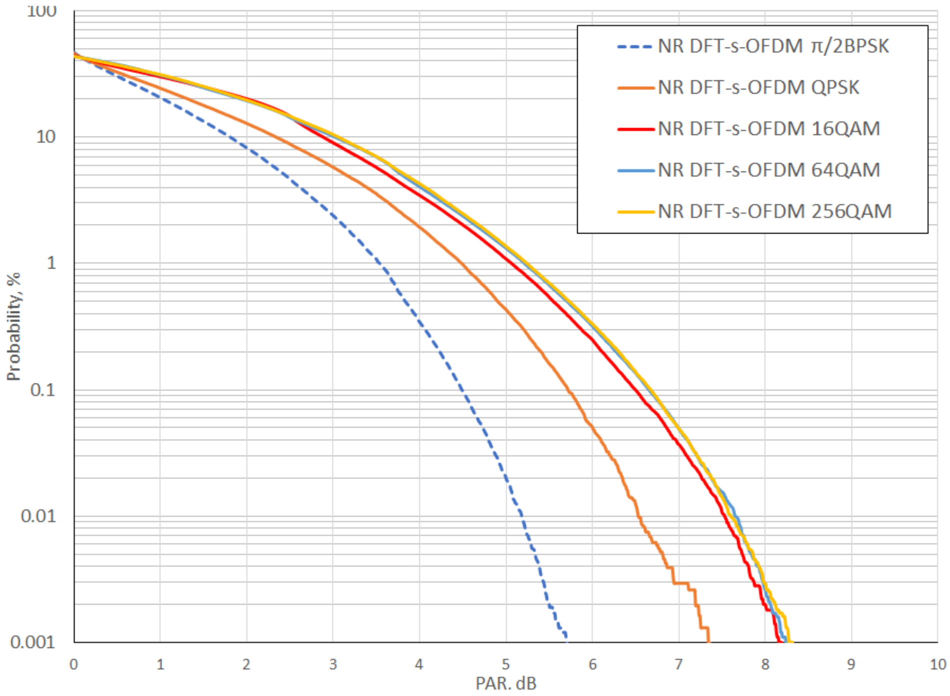


Figure 1.3: CCDF of 5G NR using DFT-s-OFDM waveforms with different modulations: $\pi/2$ BPSK, QPSK, 16QAM, 64QAM, 256QAM. All signals have 15 kHz sub-carrier spacing, 20 MHz channel bandwidth and 100% resource blocks. The PAR of the signal is changing with increasing the modulation order.

μ	SCS $\Delta f = 2^{\mu} * 15[kHz]$	Availability in FR1
0	15	Yes
1	30	Yes
2	60	Optional
3	120	No
4	240	No

Table 1.2: Numerology and corresponding SCS in 5G NR

The higher SCS configurations have shorter symbol durations with improved Doppler spread immunity, which can support higher channel bandwidths. A typical SCS of 15 kHz is used for frequency bands below 1 GHz and 30 kHz is used at above 1 GHz. The 60 kHz SCS is optional and is intended for frequency bands above 1 GHz, since the low frequency bands cannot support wide-enough channels.

2.5 5G NR Resource Blocks

Similar to LTE, 5G NR also allocates physical resources with respect to both frequency and time, according to defined resource block (RB) allocation criteria. One resource block corresponds to 12 consecutive subcarriers. The selection of SCS is directly related to the number of RBs that can fit in a given channel bandwidth. RB allocation with respect to channel bandwidth and SCS according to 3GPP TR 38.817-1 [4] is summarized in Table 1.3 for CP-OFDM and Table 1.4 for DFT-s-OFDM. To simplify precoder implementation, 3GPP has included certain RB allocation restrictions for DFT-S-OFDM; however, these are not applicable to CP-OFDM because it does not use precoder. The RB allocation for DFT-s-OFDM uses the closest number of RBs lower than or equal to the maximum RB allocation for CP-OFDM. It is calculated according to $N_{RB} = 2^X * 3^Y * 5^Z$; where X, Y, Z are integers. When partial RB allocation is used for SAR measurements; for example, 50% RB allocation, the selected RB configuration must conform to this equation. Hence, the number of RBs allocated for CP-OFDM and DFT-s-OFDM waveforms are slightly different.

SCS [kHz]	BS / UE Channel bandwidths [MHz]												
	5	10	15	20	25	30	40	50	60	70[1]	80	90[1]	100
15	25	52	79	106	133	160	216	270	N.A.	N.A.	N.A.	N.A.	N.A.
30	11	24	38	51	65	78	106	133	162	189	217	245	273
60	N.A.	11	18	24	31	38	51	65	79	93	107	121	135
Note 1: 70MHz and 90MHz are defined only as BS channel bandwidths.													

Table 1.3: NR FR1 BS and UE maximum RB allocations for CP-OFDM

SCS [kHz]	Channel bandwidths [MHz]										
	5	10	15	20	25	30	40	50	60	80	100
15	25	50	75	100	128	160	216	270	N.A.	N.A.	N.A.
30	10	24	36	50	64	75	100	128	162	216	270
60	N.A.	10	18	24	30	36	50	64	75	100	135

Table 1.4: NR FR1 UE maximum RB alocation for DFT-s-OFDM

2.6 5G NR Modulations

The uplink modulations used for 5G waveforms include QPSK, 16QAM, 64QAM and 256QAM, with $\pi/2$-BPSK being optional for DFT-s-OFDM. Because of MPR requirements, QPSK typically corresponds to the maximum output power configurations in typical UE implementations. This is the main reason why this modulation is typically selected as a starting point for SAR evaluations. Conducted power measurements are usually performed for various waveforms, modulations, SCSs, RB allocations and channel bandwidth combinations to determine SAR measurement configurations, similar to the SAR test reduction criteria used for LTE.

2.7 5G Dual connectivity, power sharing

Until 5G networks are fully built-out, the initial deployments have been mostly using NSA mode, according to EN-DC requirement that require an LTE anchor channel to support 5G transmissions. EN-DC has been used in other wireless technology combinations prior to 5G. According to recent updates in 3GPP Release 15, NR-NR (NR-DC) dual connectivity between FR1 and FR2 may be supported in SA mode. FR1 is the anchor that provides relatively wide coverage and FR2 is intended for connections closer to the base station; for example, an indoor mm-wave hotspot. SAR is required for FR1 and power density (PD) evaluation is applicable to FR2 for NR-DC. SAR and PD are evaluated separately and aggregate exposure is combined during post-processing according to exposure ratios computed using the corresponding SAR and PD limits.

For inter-band and intra-band CA or EN-DC in 5G, transmissions from the CCs or dual-connected technologies are on different frequency bands or channels. Unless array antennas are used for beam-forming or beam-steering, as described in the IEC TR 62630:2010 [6], the signals at different frequencies are uncorrelated; therefore, the normally required procedures for combining SAR distributions are applied to determine SAR compliance.

The output power levels of the CCs are determined according to available headroom from the maximum allowed aggregate power (P_{cmax}), which is managed by the same cell site. In NSA mode, under EN-DC, the LTE anchor and 5G channels are managed by different cell sites according to specific power sharing schemes and specifications to ensure the maximum allowed aggregated power (P_{cmax}) shared by both connections is not exceeded. These power sharing schemes are described in the following:

- Equal Power Sharing (EPS): The allowed aggregated maximum power (P_{cmax}) is divided equally between LTE and NR. For example, the maximum output power of a Class 3 UE for LTE and NR are both limited to 20 dBm to satisfy the 23 dBm aggregate output requirement. Each transmitter is allowed equal shares of the aggregated maximum power (P_{cmax}); therefore, simultaneous transmission SAR can be evaluated according to the normally required procedures in IEC/IEEE 62209-1528 [7]; by either summing of the individually measured psSAR or combining the SAR distributions to determine total psSAR.

- Dynamic Power Sharing (DPS): The allowed aggregated maximum power (P_{cmax}) is shared between LTE and NR; where LTE is in the master cell group (MCG) and NR is in the secondary cell group (SCG). Priority is given to MCG to allocate its share of output power and the remaining portions can be allocated to the SCG to ensure P_{cmax} is not exceeded. Support of DPS on teh UE side will become mandatory after the initial deployment. Provided P_{cmax} is not exceeded at any given instance, each transmitter may transmit up to P_{cmax}. While the SAR for each transmitter may be measured at P_{cmax}, for purpose of demonstrating simultaneous transmission SAR compliance according to the aggregate maximum output power (P_{cmax}), either the psSAR or the individual SAR distribution of the transmitters can be scaled according to various combinations of LTE and NR power to determine simultaneous transmission SAR compliance for DPS at the aggregate maximum power of P_{cmax}. Summing the psSAR of each transmitter measured at P_{cmax} can substantially overestimate the worst-case combined SAR. By proportionally scaling the measured SAR of each transmitter to different output power levels, using either psSAR or SAR distribution, different combinations of the scaled psSAR or distributions may be derived to determine the combined psSAR of the transmitters at P_{cmax}. For example, with the output of one transmitter increasing and the other decreasing, while maintaining the aggregated output at Pmax, the combined psSAR can be determined for a range of power levels for the individual transmitters. Hence, simultaneous transmission SAR compliance can be determined according to the highest of psSAR among the range of power level combinations used for the transmitters.

The power sharing scheme used by the device should be documented for the SAR evaluation. SAR combining methods are further described in Appendix B.7 SAR combining methods. Details of other 5G NR interworking combinations, such as EN-DC, NE-DC (anchor is 5G instead of LTE), NR-DC (dual 5G connectivity) etc., are available in TS 38.101-3 [2].

While CA and EN-DC may be viewed conceptually as simultaneous transmission of multiple component carriers, the power control mechanisms used by the network to limit output power are different for these configurations. Therefore, there will be differences in setting up a device to ensure that the appropriate power settings for the corresponding simultaneous transmission operating modes are used for the SAR measurement. For intra-band CA, if the frequency band is larger than the bandwidth of the measurement system, instead of measuring SAR with all CCs transmitting, additional considerations would be necessary for CC configurations that may span across a wide frequency range. This applies to both contiguous and non-contiguous CA configurations. When measuring the SAR of the CCs separately, it should be ensured that each SAR distribution is scaled according to the maximum output allowed for the individual CC combinations in that CA configuration before combining the SAR distributions. More or less CCs in the combination can change the maximum power allowed for each CC. For inter-band CA, SAR is measured for each CC independently; however, the SAR scaling according to the maximum output power allowed for the individual CC combinations in that CA configuration should be ensured before combining the SAR distributions. NSA under EN-DC can be treated similar to inter-band CA with 2 CCs; however, the psSAR should be determined according to the specific power sharing schemes (EPS vs. DPS) used in the dual cell or connectivity configuration, which is not applicable to CA.

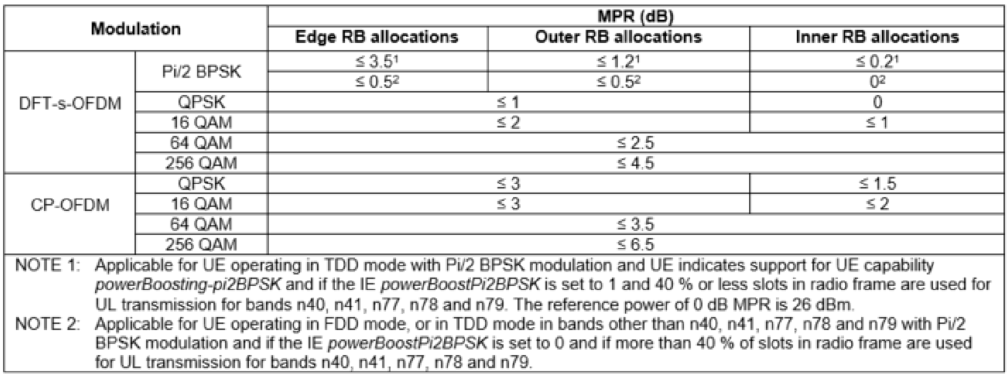
2.8 5G NR power reduction considerations

The UE output power is determined according to the following conditions:

1. UE power class - 5G NR devices operating in FR1 typically follow power class 3 requirements, with a nominal maximum output power of 23 dBm. However, some frequency bands may allow up to 26 dBm for power class 2 HPUE (High Power/Performance User Equipment) devices.

2. Maximum Power Reduction (MPR) - Similar to LTE, MPR also applies to 5G NR for maintaining UE output and PA linearity. Power back-off criteria are specified according to OFDM waveform, signal modulation, channel bandwidth and RB allocation requirements. This is illustrated in Figure 1.4, according to Table 6.2.2-1 of TS 38.101-1 [1] for power class 3 devices. The power reduction is with respect to the nominal output power. Different MPR thresholds are applied to DFT-s-OFDM and CP-OFDM due to PAR requirements of the waveforms (as discussed in Subsection 2.3). QPSK has the least MPR and higher MPR is specified for the other modulations, including $\pi/2$ BPSK. Depending on the location of RBs allocated within the channel bandwidth, different MPR requirements apply. This is explained in 3GPP TR 38.817-1 [4]. Higher MPR is specified for RBs allocated near the edge or away from the center of the channel bandwidth to minimize interference concerns. RBs concentrated at the middle of the channel bandwidth have the least MPR; therefore, QPSK with inner RB allocations should generally correspond to the highest output power configurations used for SAR evaluation. Since lower output power does not always correspond to the highest SAR, conducted power measurements in various combinations of channel bandwidth, waveform, modulation and RB allocation are usually performed to determine the subset of test configurations for SAR measurements. In addition, since MPR is not mandatory, conducted power measurement is also used to confirm if 3GPP recommended or non-standard MPR is supported by the device. The power measurement results are used to support the selected SAR test configurations and the applicable test reduction considerations.

3. Additional MPR (A-MPR) - This is the optional power reduction that may be triggered according to various network signaling (NS) conditions/configurations and is applied in addition to the 3GPP recommended MPR. A-MPR is used under certain network conditions where additional power reduction is necessary to mitigate interference or similar concerns. Since A-MPR is an optional feature for addressing local or regional concerns, it should be disabled during SAR testing. It is achieved by setting *NS_1* (default network signalling value) in the base station simulator.



Modulation		MPR (dB)		
		Edge RB allocations	Outer RB allocations	Inner RB allocations
DFT-s-OFDM	Pi/2 BPSK	≤ 3.5[1]	≤ 1.2[1]	≤ 0.2[1]
		≤ 0.5[2]	≤ 0.5[2]	0[2]
	QPSK	≤ 1		0
	16 QAM	≤ 2		≤ 1
	64 QAM	≤ 2.5		
	256 QAM	≤ 4.5		
CP-OFDM	QPSK	≤ 3		≤ 1.5
	16 QAM	≤ 3		≤ 2
	64 QAM	≤ 3.5		
	256 QAM	≤ 6.5		

NOTE 1: Applicable for UE operating in TDD mode with Pi/2 BPSK modulation and UE indicates support for UE capability *powerBoosting-pi2BPSK* and if the IE *powerBoostPi2BPSK* is set to 1 and 40 % or less slots in radio frame are used for UL transmission for bands n40, n41, n77, n78 and n79. The reference power of 0 dB MPR is 26 dBm.

NOTE 2: Applicable for UE operating in FDD mode, or in TDD mode in bands other than n40, n41, n77, n78 and n79 with Pi/2 BPSK modulation and if the IE *powerBoostPi2BPSK* is set to 0 and if more than 40 % of slots in radio frame are used for UL transmission for bands n40, n41, n77, n78 and n79.

Figure 1.4: Maximum power reduction for power class 3. Source: Table 6.2.2-1 from TS 38.101-1 [1]

2.9 Beam-forming, beam-steering and MIMO

Beam-forming, beam-steering and MIMO techniques are generally applied in the downlink at the base station. Due to the typical $\lambda/4$ antenna spacing requirement, these are not anticipated in the typical UE or portable devices for operation in FR1. However, when such techniques are implemented, the SAR evaluation procedures for uncorrelated signals may be considered on a case-by-case basis, for certain small SAR test distance configurations, less than $\lambda/4$, and when it can be demonstrated that SAR is dominated by individual source coupling in such conditions. This is under consideration by SPEAG, according to investigations performed at the ITâĂŹIS Foundation, to evaluate the uncertainty associated with this simplification.

3 SAR Measurement Procedure

3.1 General

5G NR imposes some additional SAR measurement considerations that have not been directly addressed in IEC/IEEE 62209-1528 [7] or IEC 62209-3 [8] for 5G SAR measurements using the cSAR3D:

(a) Simultaneous transmission of LTE and NR in NSA mode under EN-DC, including time-division between NR and LTE for single uplink operation (SUO) and Dynamic Power Sharing (DPS) of LTE and NR,

(b) Inter-band and Intra-band CA configurations for FDD and TDD operations,

(c) Channel bandwidth up to 100 MHz per CC and 400 MHz for a maximum of 8 CCs, and

(d) High-order signal modulations (up to 256-QAM).

The aforementioned features of 5G NR can impose specific requirements for the SAR measurement procedures. Some additional regulatory guidance might be required to properly address these. The SAR measurement system and test setup should be properly configured to ensure that SAR of simultaneous transmission configurations involving different channel or signal bandwidths are satisfying the measurement system calibration requirements. These concerns are described with respect to the spectral integration method in Appendix A for 5G SAR measurements in FR1. Additional information on CA is provided in Appendix C 4G and 5G Carrier Aggregation, including specific examples of CA combinations for LTE and 5G NR for SA and NSA modes.

3.2 Procedures

As described earlier in this application note, 5G FR1 SAR testing (NSA or SA) is not fundamentally different from what was done in 4G. The general approach is to adapt them to the 5G test scenarions. For example, NSA SAR measurements are treated in a similar way as carrier aggregation in LTE. The procedure allows the measurement of the individual carrier signals separately. For 5G NSA, base station simulators are configured to test the 5G NR signal separately from the 4G LTE signal.

The following procedure is applied for 5G NSA:

1. Switch on both LTE and NR cells. Wait until the DUT attaches to both LTE and NR in dual-connectivity (EN-DC) mode.
2. Ensure that 5G NSA call is established (connected mode).
3. Configure the 5G uplink as desired (number of resource blocks, modulation, subcarrier spacing (SCS), etc.)
4. Turn off the 4G anchor by setting 0 RB in uplink and downlink.
5. Measure the SAR for the 5G uplink signal using cSAR3D.
6. Set NR to idle.
7. Set LTE on. Configure and measure the SAR for the 4G uplink signal. Alternatively, if standalone LTE SAR for the same configuration with the same power is already available, or can be scaled, then the LTE SAR measurement would not need to be repeated.
8. Combine the SAR distributions using one of the alternatives presented in Appendix B.7 SAR combining methods. Power sharing schemes according to Section 2.7 have to be taken into consideration here.

Note: *the 4G and 5G uplink can be monitored with a spectrum analyzer, to confirm that the DUT is properly configured. This information is also available from the base station simulator.*

A large number of 5G NR phones have been tested in NSA mode for FR1 and approved by applying similar procedures using single-probe scanning systems. The similar test setup for these devices are applicable for SAR measurements with the cSAR3D. Certain details of the testing are included in test reports for these devices, which are publicly available and can be downloaded from the links listed in the following references: A large number of 5G NR FR1 NSA phones has been tested and approved using procedures very similar to this. Some detailed measurement reports from OEMs are publicly available and can be downloaded from the links listed in the following references: [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24].

The following procedure is applied for 5G SA:

1. Switch on the NR cell to attach the DUT in SA mode.
2. Ensure that 5G SA call is established (connected mode).
3. Configure the 5G uplink as desired (number of resource blocks, modulation, subcarrier spacing (SCS), bandwidth, etc.)
4. Measure the SAR for the 5G uplink signals.

4 Measurement Uncertainty Estimation

The measurement uncertainty of cSAR3D for 5G NR is estimated by analyzing the SAR distribution and uncertainty components described in Annex D. In addition to the uncertainty budget defined in IEC/IEEE 62209-1528, four additional uncertainty terms are specified for 5G SAR measurements using cSAR3D. These are described in the following:

MB Uncertainty due to data acquisition bandwidth. For cSAR3D, this uncertainty term is negligible because it is a broadband spectral-integration technique.

SCB Uncertainty due to combining of SAR distributions for uncorrelated signals. For cSAR3D, this uncertainty is not negligible due to the uncertainty in the individual SAR distributions. However, it is relatively low because the SAR distributions are combined at each interpolated point by simple summation. This process is independent of the transmitter operating frequencies.

BBS Uncertainty due to frequency dependence of probe response and frequency dependence of tissue-equivalent medium dielectric properties. For cSAR3D, this uncertainty has been estimated to be less than 0.12 dB (2.9 %) for unequal spectral distributions (see Appendix D.4.29 for explanation) and less than 0.02 dB (0.5 %) for equally-distributed signals.

PSH Uncertainty of the measured output power used for SAR scaling according dynamic power sharing scheme described in Section 2.7. This uncertainty term is independent of the cSAR3D system. Conducted output power measurement with a power meter is typically about 0.1 dB. Care should be taken to ensure a calibrated power meter/sensor is used and cable losses are account for.

For frequencies below 6 GHz, the combined uncertainty due to the above terms for 5G SAR measurement is less than 0.5 % larger than that reported in Appendix D. The estimated uncertainty calculated at the end of each cSAR3D measurement based on SAR distribution and measurement parameters will be updated for 5G signals in Version 3.2. Until then, it is recommended that 0.5 %, while overly conservative, should be added to the reported uncertainty.

5 System Check

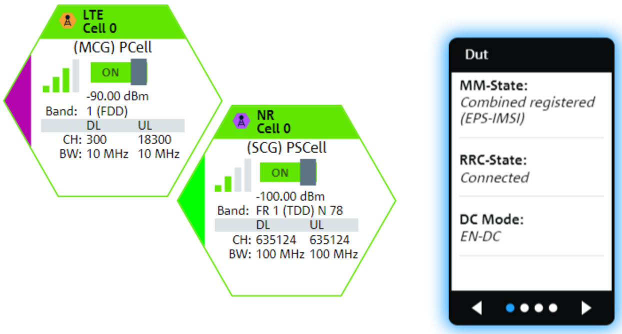
System check should be performed by the user according to IEC/IEEE 62209-1528 and regulatory requirements to ensure system performance is acceptable. System check requirements are described in the cSAR3D Application Note “System Check or Verification.” No additional system check is required for 5G SAR measurements.

System check is performed using a CW signal, at five frequencies (835 MHz, 1950 MHz, 2450 MHz, 5200 MHz and 5800 MHz) to cover measurements in the range of 650 MHz to 6 GHz. When a cSAR3D system has been calibrated for 6 âĂŞ 10 GHz range and system validation is performed according to Appendix F, the same system check procedures also apply to measurements in the 650 MHz to 10 GHz range.

6 5G NSA FR1 Measurement Example with cSAR3D

The 5G NSA procedure described in Section 3 is illustrated in the following cSAR3D measurement example. A commercially available phone is configured for testing with a 4G/5G base station simulator.

1. The LTE and NR cells are switched on and the DUT is attached to both cells in EN-DC mode. This can be seen from the base station simulator screen in Figure 1.5 and is independently confirmed with an external spectrum analyzer, as shown in Figure 1.6.



LTE Cell 0
(MCG) PCell
ON
-90.00 dBm
Band: 1 (FDD)

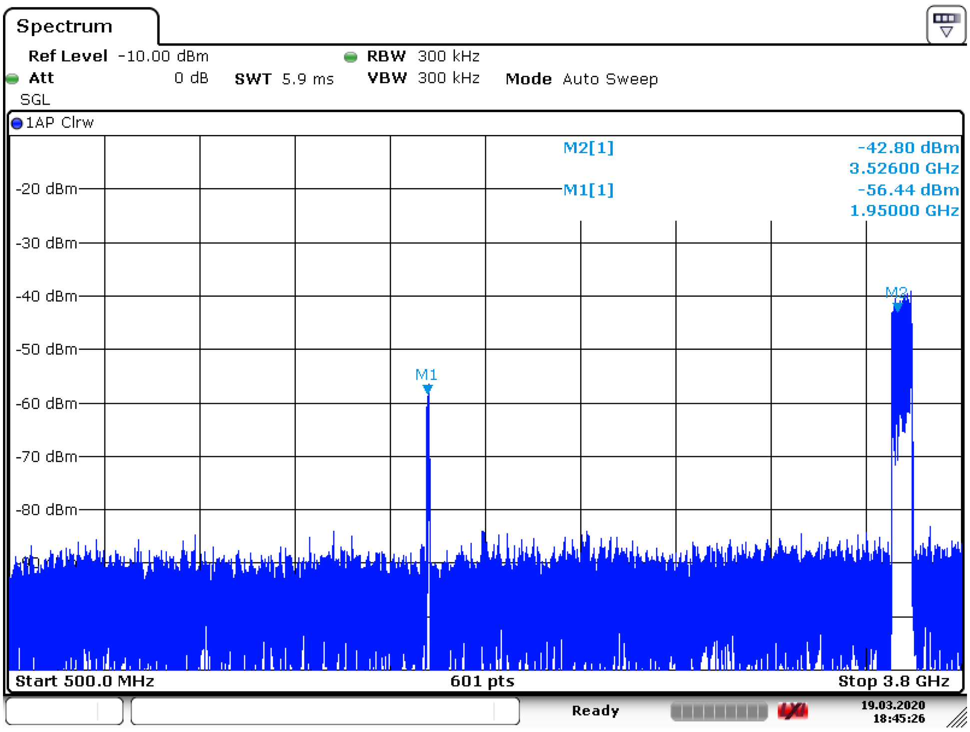
	DL	UL
CH:	300	18300
BW:	10 MHz	10 MHz

NR Cell 0
(SCG) PSCell
ON
-100.00 dBm
Band: FR 1 (TDD) N 78

	DL	UL
CH:	635124	635124
BW:	100 MHz	100 MHz

Dut
MM-State: *Combined registered (EPS-IMSI)*
RRC-State: *Connected*
DC Mode: *EN-DC*

Figure 1.5: Base Station Simulator screen showing the DUT connected in EN-DC mode.



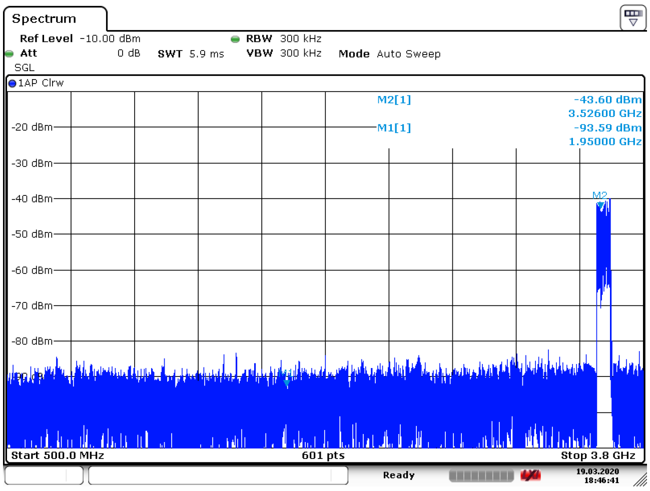
Spectrum
Ref Level -10.00 dBm **RBW** 300 kHz
Att 0 dB **SWT** 5.9 ms **VBW** 300 kHz **Mode** Auto Sweep
SGL
1AP Clrw
M2[1] -42.80 dBm 3.52600 GHz
M1[1] -56.44 dBm 1.95000 GHz
Start 500.0 MHz **601 pts** **Stop 3.8 GHz**
Ready **19.03.2020 18:45:26**

Figure 1.6: Spectrum plot showing the 4G anchor at 1950 MHz and the 5G NR at 3526 MHz

2. The 5G uplink is configured with the following settings:
   - Waveform: CP-OFDM
   - Channel Bandwidth: 100 MHz
   - Operating band: n78

   - Subcarrier Spacing: 30kHz
   - Modulation: QPSK
   - NR-ARFCN: 635124 (Frequency: 3526.86 MHz)
   - Number of RBs: 273

3. The LTE anchor is switched off by setting 0 RB in uplink and downlink. This can be confirmed by looking at the resulting spectrum on Figure 1.7.


Ref Level -10.00 dBm
Att 0 dB
SWT 5.9 ms
RBW 300 kHz
VBW 300 kHz
Mode Auto Sweep
SGL

M2[1] -43.60 dBm 3.52600 GHz
M1[1] -93.59 dBm 1.95000 GHz

Start 500.0 MHz
601 pts
Stop 3.8 GHz

Ready
19.03.2020 18:46:41

Figure 1.7: Separate 5G uplink at 3526 MHz

4. SAR is measured for the 5G uplink signal using cSAR3D and the SAR distribution is shown in Figure 1.8.


1g: 0.251 10g: 0.089
U1g: ±1.14 dB (-23.1%, 30.1%)
U10g: ±1.10 dB (-22.4%, 28.9%)

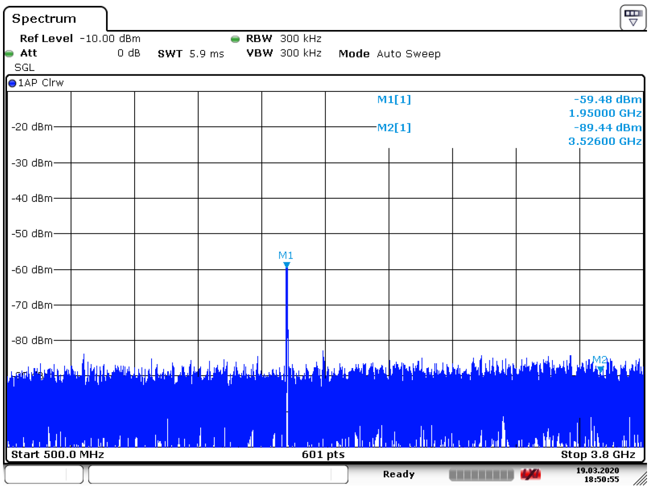
Figure 1.8: 5G carrier's SAR distrubution in cSAR3D

5. The 5G signal is turned off and the LTE anchor is configured as follows and switch on to perform LTE SAR measurement.

   - Channel Bandwidth: 10 MHz

- Operating band: 1
- Modulation: QPSK
- EARFCN: 18300 (Frequency: 1950 MHz)
- Number of RBs: 50

Again, the signal is confirmed with a spectrum analyzer, as shown in Figure 1.9 and the SAR distribution is shown in Figure 1.10:



Spectrum

Ref Level -10.00 dBm RBW 300 kHz

Att 0 dB SWT 5.9 ms VBW 300 kHz Mode Auto Sweep

SGL

1AP Clrw

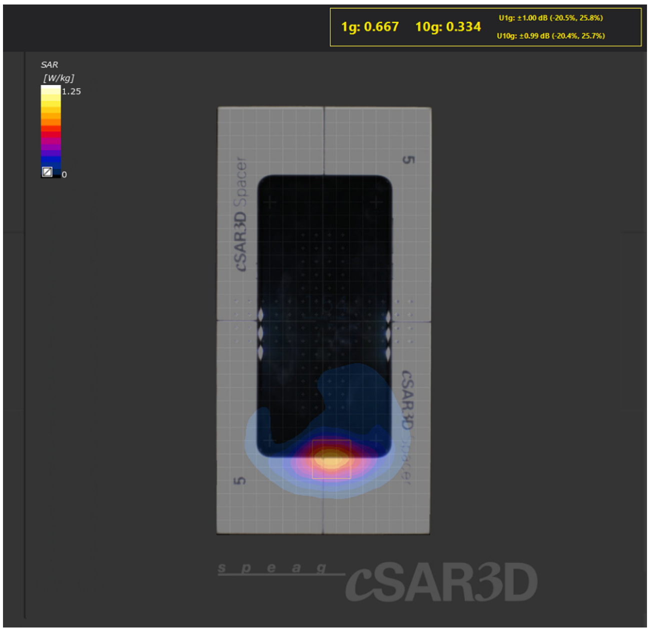
M1[1] -59.48 dBm 1.95000 GHz

M2[1] -89.44 dBm 3.52600 GHz

Start 500.0 MHz 601 pts Stop 3.8 GHz

Ready 19.03.2020 18:50:55

Figure 1.9: Separate 4G uplink at 1950 MHz



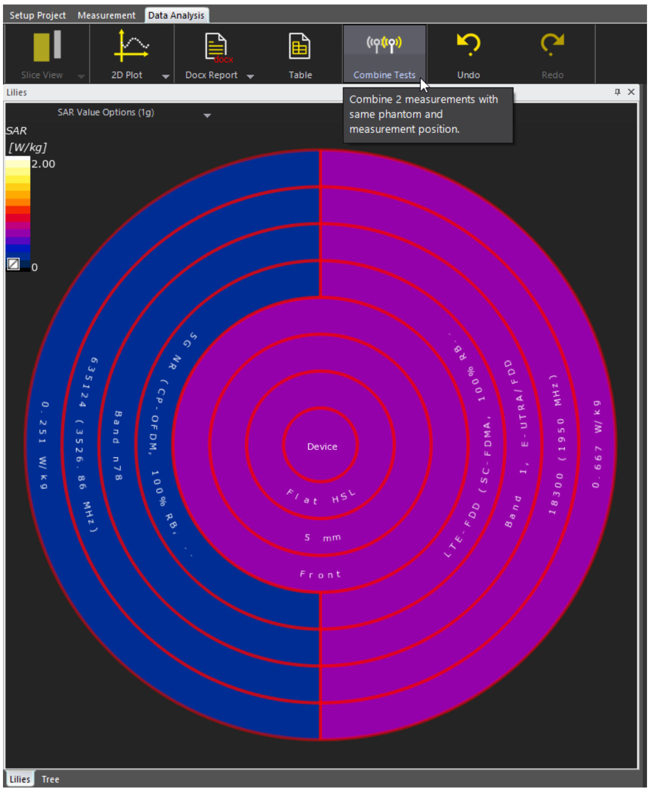
1g: 0.667 10g: 0.334

U1g: ±1.00 dB (-20.5%, 25.8%)

U10g: ±0.99 dB (-20.4%, 25.7%)

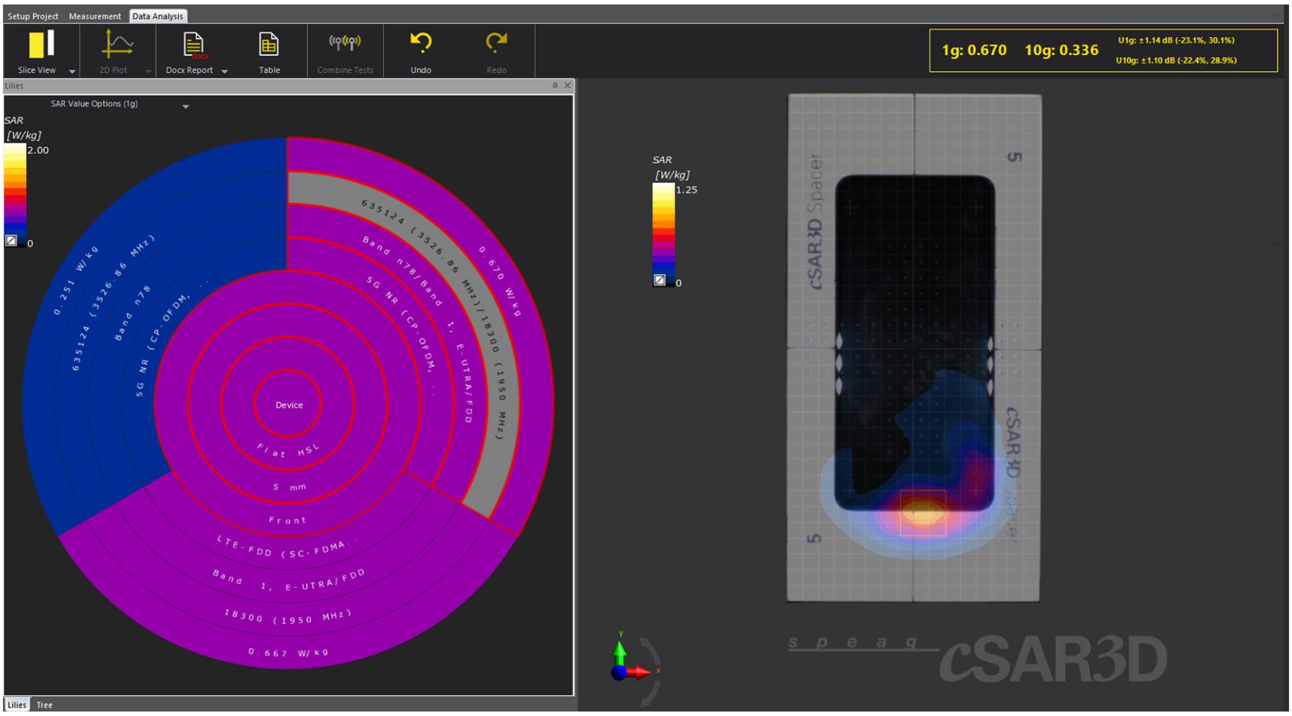
Figure 1.10: 4G carrier's SAR distrubution in cSAR3D

The 4G and 5G distributions are combined with post-processing using the Combine Tests button in the Data Analysis tab of cSAR3D. A new sector in the Lilies Wheel containing the combined result is created and shown in Figure 1.11 and Figure 1.12.



Combine 2 measurements with same phantom and measurement position.

Figure 1.11: Combine Tests button in the Data Analysis tab



1g: 0.670 10g: 0.336
U1g: ±1.14 dB (-23.1%, 30.1%)
U10g: ±1.10 dB (-22.4%, 28.9%)

Figure 1.12: A new sector in the Lilies Wheel containing the combined results is created

A summary of the cSAR3D results is shown in Figure 1.13.

	4G only	5G only	4G and 5G
SAR value, 1g [W/kg]	0.667	0.251	0.670
SAR value, 10g [W/kg]	0.334	0.089	0.336

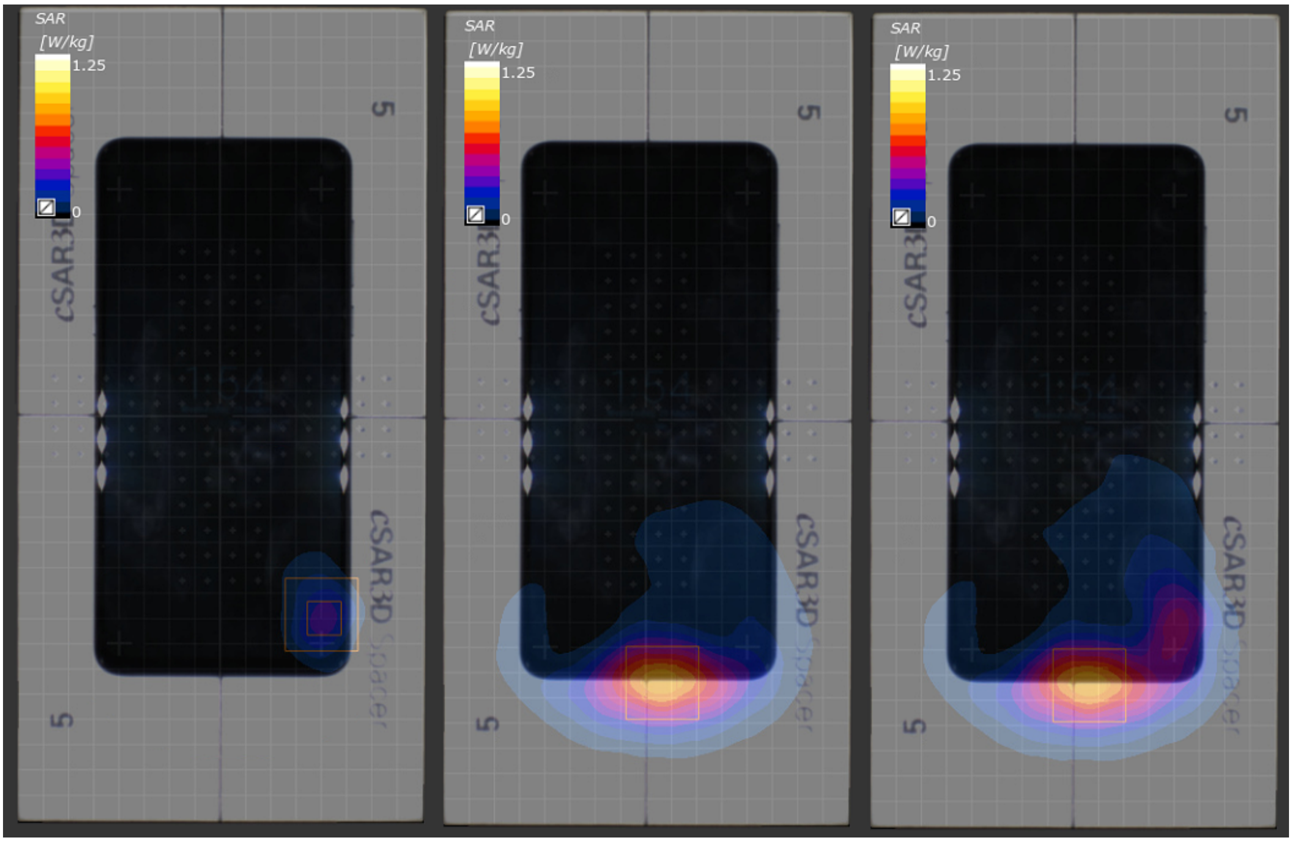


Figure 1.13: Side by side comparison of the measurement results. From left to right: 5G, 4G, 4G combined with 5G. All plots have the same color scaling.

For this specific phone, separate antennas are used for LTE band 1 and NR n78. The distributions have very little overlap and there is no significant change to the combined peak spatial-average SAR.

7 Examples of Test Reports

A large number of 5G phones with SAR measurements in NSA mode have been approved using the same method and procedures described in this Application Note. Certain measurement details are included in publicly available test reports, which can be downloaded from links listed in the following references: [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. While these are measured using single-probe scanning systems, the same 5G NR test configurations also apply to SAR measurements using cSAR3D.

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[3] 3GPP TS 36.101 V16.5.0 (2020-03) Technical Specification Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE) radio transmission and reception (Release 16)

[4] 3GPP TR 38.817-01 V16.1.0 (2019-09) Technical Report - General aspects for User Equipment (UE) Radio Frequency (RF) for NR (Release 16)

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[6] IEC TR 62630:2010 Guidance for evaluating exposure from multiple electromagnetic sources

[7] IEC/IEEE 62209-1528 Recommended Practice for Measurement Procedures for the Assessment of Specific Absorption Rate (SAR) of Human Exposure to Radio Frequency Fields From Hand-Held and Body-Worn Wireless Communication Devices (Frequency Range of 4 MHz to 10 GHz)

[8] IEC 62209-3:2019 Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices - Part 3: Vector measurement-based systems (Frequency range of 600 MHz to 6 GHz)

[9] TC106/JWG13 TR 5G NR FR1 and Inter-laboratory Comparison Study

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[18] Samsung Electronics Co. Ltd. FCC ID:A3LSMG976U (Galaxy Note 10 5G variant) Portable Handset RF Exposure Info https://fccid.io/A3LSMN976U/RF-Exposure-Info/SAR-Report-1-4509491

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Appendices

A SAR Measurement Considerations

A.1 Expression of SAR

Specific Absorption Rate (SAR) is a measurement of the rate at which energy is absorbed by the human body when exposed to an RF electromagnetic field. The SAR in the tissue-equivalent medium can be determined by the rate of temperature increases or by E-field measurements according to the following formula specified in the IEC 62209 series of standards. For low power wireless devices, SAR is measured using E-field techniques due to the low temperature rise. The following formula is valid for a single and narrow-band spectrum:

$$SAR = c\frac{\Delta T}{\Delta t} = \sigma\frac{E_{RMS}^2}{\rho} \tag{1}$$

Where:

SAR: is the specific absorption rate in [W/kg]

c is the specific heat capacity, in joule per kilogram per kelvin

ΔT is the change in temperature, in kelvin

Δt is the exposure duration

E_{RMS}: is the RMS value of the electric strength in the tissue-equivalent medium in [V/m]

σ: is the electrical conductivity of the tissue-equivalent medium in [S/m]

ρ: is the mass density of the tissue-equivalent medium in [kg/m^3].

For signals with broad bandwidths, the measurement uncertainty is influenced by the frequency dependence of both tissue dielectric parameters and probe sensitivity. The measurement of induced E-field is a function of frequency, tissue-equivalent medium conductivity and permittivity. These dependencies must be considered in the uncertainty budget and according to the measurement protocol to optimize the precision of the evaluation for the applied technique.

A.2 SAR Measurement Background

cSAR3D and DASY are implementations of broadband frequency-integration methods. These are methods capable of measuring SAR by integrating all the signals throughout the systemâĂŹs operating frequency range. DASY is a broadband frequency-integration method using a single probe as defined in IEC/IEEE 62209-1528 [7]. It is designed to provide accurate RMS values over a very broad frequency range by spectral integration. cSAR3D is a broadband frequency-integration method using an array of probes that complies with the requirements of IEC 62209-3 [8] and is also a vector measurement-based SAR system.

These systems are designed to provide accurate RMS field measurements over a very broad frequency range using spectral integration with minimal scattering from the probe. A diode detector is used to measure the square of the E-field with an electrically small dipole sensor. Minimally reflective materials are used for the transmission lines and mechanical supporting material to minimize field scattering by the probes embedded within the phantom, which may cause field distortions, secondary reception, and interactions with the DUT. This also has the advantage that the fields close to the boundary can be measured and boundary effects can be compensated. Therefore, high accuracy is achieved for amplitude at the expense of loss of phase information, although some systems use phase retrieval techniques. SAR is a scalar quantity that is associated with magnitude but not phase. However, phase information can be used to combine simultaneous transmission of correlated signals (see IEC to apply TR 62630:2010 [6]). For multiple carriers that are uncorrelated and transmit simultaneously, the typical approach is to measure each signal separately and combine the SAR distributions during post-processing, as illustrated in Figure 14.

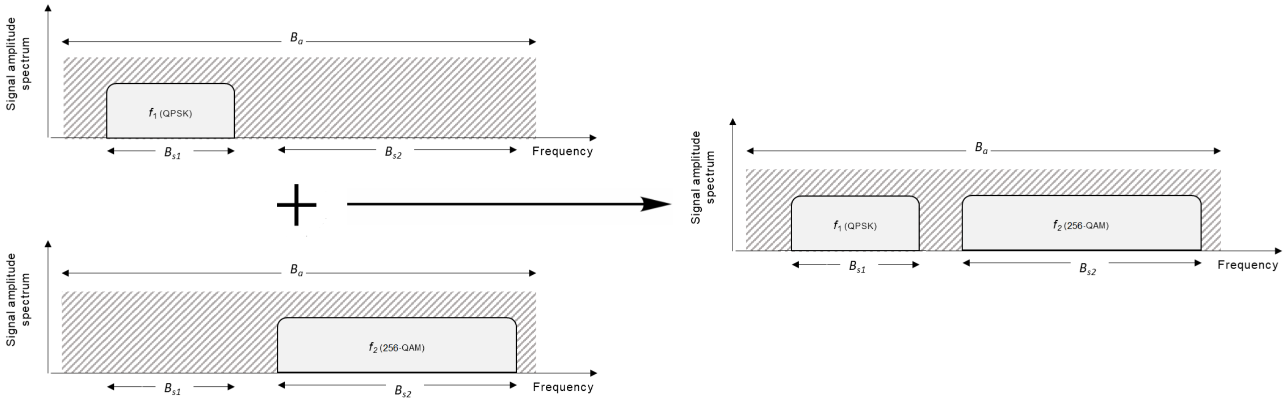


Figure 14: Two SAR measurements are performed, the first measurement is done when the desired signal f_1 with a bandwidth B_{s1} is turned ON while the desired signal f_2 with a bandwidth B_{s1} is OFF; then the second measurement is done when the desired signal f_1 is turned OFF while the desired signal f_2 is ON.

B SAR Measurement Protocol

B.1 Preparation of tissue-equivalent medium

The requirements of clause 7.1.2 in IEC 62209-3 [8] are applicable to the hermetically sealed cSAR3D phantoms. Broadband tissue simulating liquid is used to cover the frequency bands supported by 4G and 5G FR1 for SAR measurement.

B.2 System check

The requirements of clause 7.1.3 in IEC 62209-3 are applicable. To complement the system check defined in this standard, additional frequencies can be evaluated.

B.3 Preparation of the DUT

The requirements of clause 7.2.2 in IEC/IEEE 62209-1528 should be applied to prepare the DUT for SAR measurement.

B.4 DUT operating mode requirements

The requirements of clause 7.2.3 in IEC/IEEE 62209-1528 are applicable.

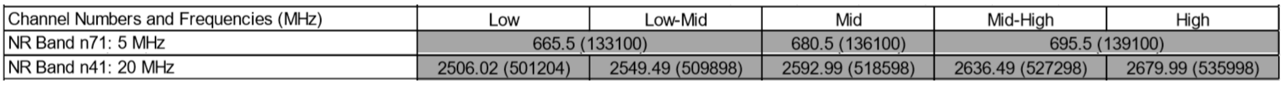
B.5 Positioning the DUT relative to the phantom

The requirements of clause 7.2.4, 7.2.5, 7.2.6 and 7.2.7 in IEC/IEEE 62209-1528 [7] are applicable.
Note: *Note: DUT test separation distances and required device test positions specified by national regulations should be applied.*

B.6 Test frequencies for DUTs

The number of channels that need testing are specified in IEC/IEEE 62209-1528 and regulatory requirements. At least the channel with the highest output power is tested. The channels at the lowest and highest frequencies may also need to be tested. For wider frequency bands such as n41, n77, n78, n79, additional channels are generally required.

It is possible that there could be sufficient variations in antenna performance across a wide frequency band that the additional channels are needed to demonstrate SAR compliance; for example, n41 with approximately 200 MHz of spectrum. An example of test channel selection is illustrated in Figure 15 for a recently approved device [21]. There could be circumstances that the frequency band is wider than the antenna bandwidth; therefore, multiple antennas would be required to cover the entire band; for example, n77 with 900 MHz of spectrum. Due to tissue medium property and CA/CC configurations across the band, additional considerations and regulatory guidance are necessary to evaluate SAR for such wide frequency bands.



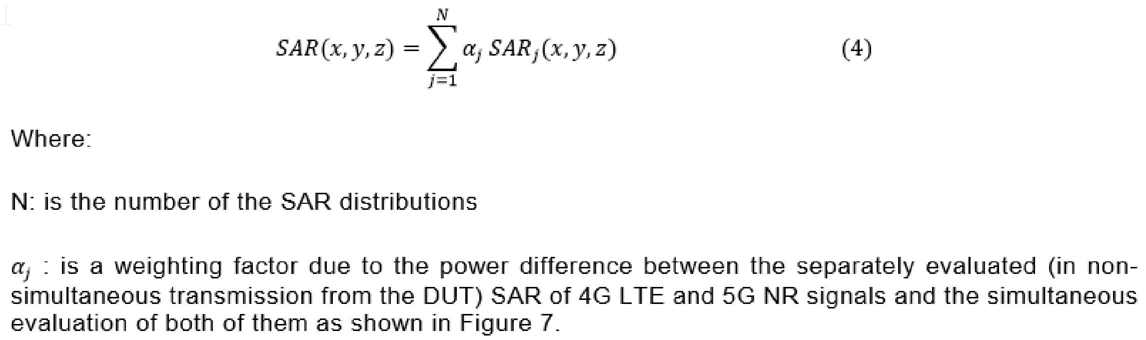
Channel Numbers and Frequencies (MHz)	Low	Low-Mid	Mid	Mid-High	High
NR Band n71: 5 MHz	665.5 (133100)		680.5 (136100)	695.5 (139100)	
NR Band n41: 20 MHz	2506.02 (501204)	2549.49 (509898)	2592.99 (518598)	2636.49 (527298)	2679.99 (535998)

Figure 15: DUT test channels for 2 different 5G NR bands. Only 3 test channels are required for the narrow n66 band (low, mid and high). On the other hand, for the relatively wider n41, 5 channels are tested (low, low-mid, mid, mig-high, high).

Note: *Regulatory policies may require a different number of channels for testing, according to spectrum allocations and wireless technology used for the frequency band.*

B.7 SAR combining methods

SAR is determined according to formula (1) in Section A.1 by applying one of the four alternative methods described in clause 7.4.4.2 of IEC/IEEE 62209-1528 for simultaneous transmission SAR evaluation. SAR combining should take into account the power control scheme used in the specific wireless operating mode and technology. As appropriate, SAR should be measured at a fixed output power level for each component carrier, and then scaled to the maximum power used in the wireless mode and power control scheme configuration; for example, CA/CC, NSA etc. The following formula (4) is applied to determine the aggregate SAR based on the weighted (properly scaled) SAR distributions.



$$SAR(x,y,z) = \sum_{j=1}^{N} \alpha_j \, SAR_j(x,y,z) \qquad (4)$$

Where:

N: is the number of the SAR distributions

α_j : is a weighting factor due to the power difference between the separately evaluated (in non-simultaneous transmission from the DUT) SAR of 4G LTE and 5G NR signals and the simultaneous evaluation of both of them as shown in Figure 7.

C 4G and 5G Carrier Aggregation

C.1 Introduction

Additional bandwidth and higher data rates can be achieved with carrier aggregation (CA). Frequency blocks, or component carriers (CCs) are assigned to the device and aggregated according to the following schemes:

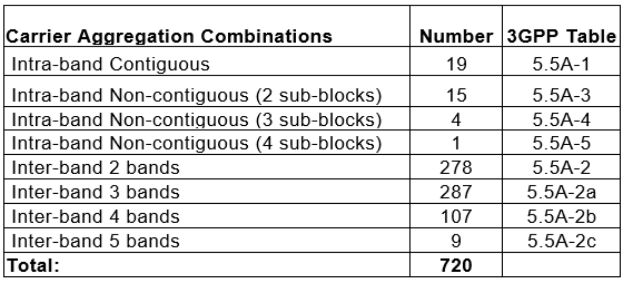
- intra-band contiguous: two or more CCs are assigned adjacent to each other within the same frequency band,
- intra-band non-contiguous: two or more CCs are assigned to non-adjacent channels within the same band, and
- inter-band: two or more channels from different frequency bands are used.

The number of carrier aggregation combinations for 4G LTE, 5G NSA and 5G SA are described in Sections C.2 - C.4. As 5G NR standard continues to evolve to meet network deployment and spectrum allocation requirements, the list of CA combinations will continue to grow at a rapid pace.

Different simplifications have been considered to reduce the number of SAR measurements required to demonstrate compliance. For simultaneous transmission, the different signals can be measured independently and SAR is aggregated by combining distributions through post-processing. The same technique can be applied to 5G NR NSA, where LTE and NR are tested separately. An initial connection is established for LTE as the MCG before 5G is connected as the SCG. For 5G NR SA, the LTE anchor is not required; all transmissions are controlled by the 5G NR cell site. As shown by the example in Figure 19, the total evaluation requires 51 frequency bands (26 NR bands, 25 LTE bands), and 238 combinations to generate the combined SAR distributions through post-processing to cover all combinations.

C.2 4G LTE Carrier Aggregation

For 4G LTE (TS 36.101 [3]), the total number of carrier aggregation combinations, including intra-band contiguous, intra-band non-contiguous and inter-band, is 720, as shown on Figure 16.

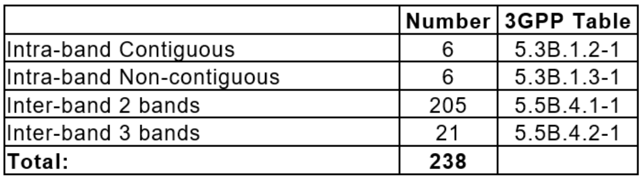


Carrier Aggregation Combinations	Number	3GPP Table
Intra-band Contiguous	19	5.5A-1
Intra-band Non-contiguous (2 sub-blocks)	15	5.5A-3
Intra-band Non-contiguous (3 sub-blocks)	4	5.5A-4
Intra-band Non-contiguous (4 sub-blocks)	1	5.5A-5
Inter-band 2 bands	278	5.5A-2
Inter-band 3 bands	287	5.5A-2a
Inter-band 4 bands	107	5.5A-2b
Inter-band 5 bands	9	5.5A-2c
Total:	**720**	

Figure 16: 4G LTE carrier aggregation combinations

C.3 5G NR NSA Carrier Aggregation

For purpose of SAR measurement, NSA mode in EN-DC can be addressed according to existing simultaneous transmission SAR testing requirements; provided the proper procedures are applied to configure the LTE anchor and NR transmission for independent SAR measurement. As appropriate, the standalone SAR results of the LTE configurations that are applicable to the LTE anchor in NSA mode may be scaled accordingly to the required power level to obtain combined SAR distribution for NSA. There are 238 combinations for 5G NR NSA (see Figure 17). Reference: TS38.101-3 [2].



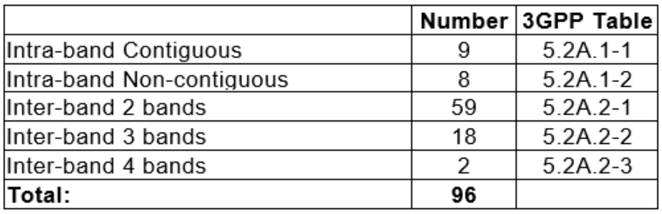
	Number	3GPP Table
Intra-band Contiguous	6	5.3B.1.2-1
Intra-band Non-contiguous	6	5.3B.1.3-1
Inter-band 2 bands	205	5.5B.4.1-1
Inter-band 3 bands	21	5.5B.4.2-1
Total:	**238**	

Figure 17: 5G NR NSA carrier aggregation

Figure 19 provides a more detailed overview of the 238 carrier aggregation combinations that are allowed. X indicates that only one configuration between the corresponding bands is allowed; XX indicates that multiple combinations are allowed. TS38.101-3 [1] lists all possible Dual Connectivity (DC) modes for NSA. The basic combination is two component carriers (2CC), with 1CC in NR and 1 CC in LTE band. Three band (3CC), four band (4CC) and five band (5CC) are also defined in the same standard.

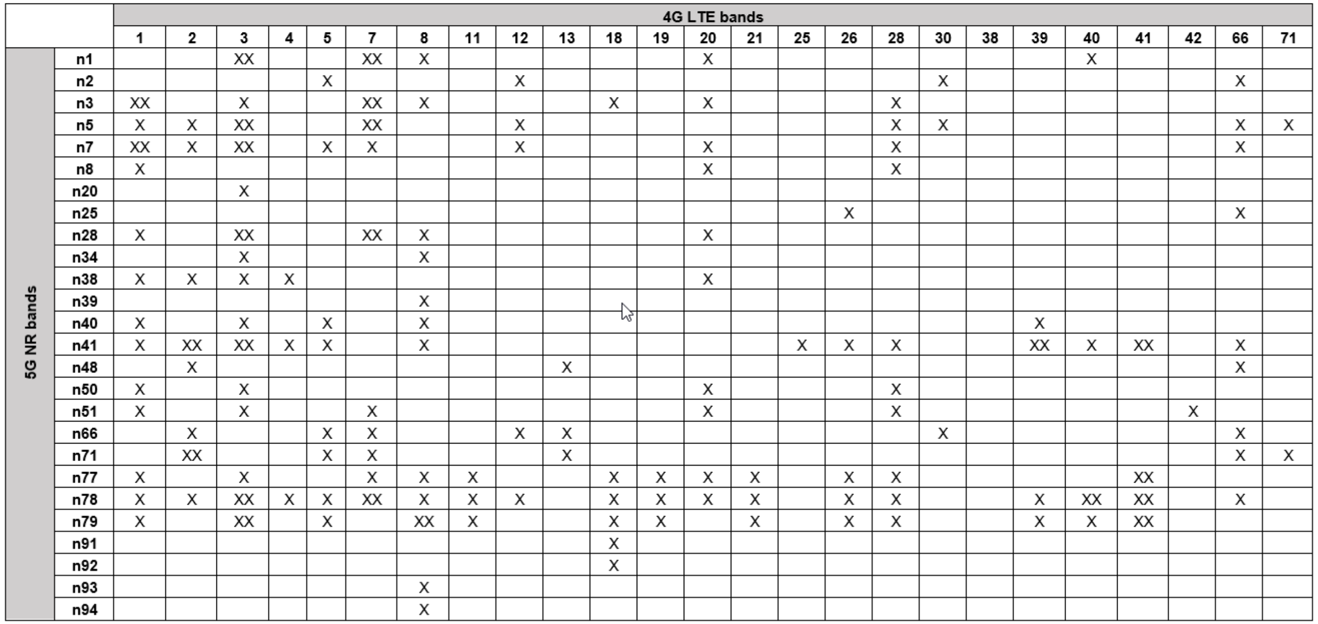
C.4 5G NR SA Carrier Aggregation

5G NR also has a standalone (SA) operation, where no LTE anchor is needed. As shown in Figure 18, there are 96 carrier combinations for 5G NR SA. Reference: TS38.101-1 [1].



	Number	3GPP Table
Intra-band Contiguous	9	5.2A.1-1
Intra-band Non-contiguous	8	5.2A.1-2
Inter-band 2 bands	59	5.2A.2-1
Inter-band 3 bands	18	5.2A.2-2
Inter-band 4 bands	2	5.2A.2-3
Total:	**96**	

Figure 18: 5G NR SA (no LTE anchor)



		4G LTE bands																								
		1	**2**	**3**	**4**	**5**	**7**	**8**	**11**	**12**	**13**	**18**	**19**	**20**	**21**	**25**	**26**	**28**	**30**	**38**	**39**	**40**	**41**	**42**	**66**	**71**
5G NR bands	**n1**			XX			XX	X						X								X				
	n2					X				X									X						X	
	n3	XX		X			XX	X				X		X				X								
	n5	X	X	XX			XX			X								X	X						X	X
	n7	XX	X	XX		X	X			X				X				X							X	
	n8	X												X				X								
	n20			X																						
	n25																X								X	
	n28	X		XX			XX	X						X												
	n34			X				X																		
	n38	X	X	X	X									X												
	n39							X																		
	n40	X		X		X		X													X					
	n41	X	XX	XX	X	X		X								X	X	X			XX	X	XX		X	
	n48		X								X														X	
	n50	X		X										X				X								
	n51	X		X			X							X				X						X		
	n66		X			X	X			X	X								X						X	
	n71		XX			X	X				X														X	X
	n77	X		X			X	X	X			X	X	X	X		X	X					XX			
	n78	X	X	XX	X	X	XX	X	X	X		X	X	X	X		X	X			X	XX	XX		X	
	n79	X		XX		X		XX	X			X	X		X		X	X			X	X	XX			
	n91											X														
	n92											X														
	n93							X																		
	n94							X																		

Note to table: X means that one configuration within the corresponding bands is allowed; XX means that multiple combinations are allowed

Figure 19: Overview of 5G FR1 NSA combinations, as listed in TS 38.101-3 [1]

D Measurement Uncertainty Estimation

cSAR3D software calculates the uncertainty of each measurement from the measured SAR distribution and other parameters. The uncertainty is displayed in the software, next to the measured SAR. It can also be exported in the table and report outputs.

D.1 Prerequisites

The budgets are applicable for all laboratories using cSAR3D provided the following requirements are met:

- the cSAR3D has been calibrated within the last 12 months;
- the system verification has been performed within the last 12 months.
- the environmental noise and reflection are less than 12 μW/g;
- the system is used by an experienced user who has followed the cSAR3D System Handbook;

D.2 Uncertainty Calculation

The combined expanded uncertainties for $psSAR_{1g}$ and $psSAR_{10g}$ are calculated as:

$$U_{1g} = k \cdot u_{c,1g} = 2 \cdot u_{c,1g} \tag{1}$$

$$U_{10g} = k \cdot u_{c,10g} = 2 \cdot u_{c,10g} \tag{2}$$

A coverage factor of $k = 2$ is used, corresponding to a 95% confidence interval. The combined standard uncertainties, $u_{c,1g}$ [dB] and $u_{c,10g}$ [dB], having log normal distributions, are calculated as follows:

$$u_{c,1g} = \sqrt{\sum_{i=1}^{N} \left(a_{i,1g} \cdot c_i/q_i\right)^2} = \sqrt{\sum_{i=1}^{N} u_{i,1g}^2} \tag{3}$$

$$u_{c,10g} = \sqrt{\sum_{i=1}^{N} \left(a_{i,10g} \cdot c_i/q_i\right)^2} = \sqrt{\sum_{i=1}^{N} u_{i,10g}^2} \tag{4}$$

where

- $a_{i,1g}$ and $a_{i,10g}$ are the uncertainty values of the i^{th} uncertainty component having a probability density function PDF_i. These are determined from the measured SAR distribution, other measurement parameters, phantom type, and system characteristics.
- q_i is the divisor corresponding to the probability density function PDF_i.
- c_i is the sensitivity coefficient associated with the i^{th} uncertainty component. It describes how the total uncertainty varies with small changes in the uncertainty component.
- $u_{i,1g} = a_{i,1g} \cdot c_i/q_i$ is standard uncertainty of the i^{th} uncertainty component. It is normalized so that it has a lognormal distribution.

The uncertainty model is combined from components described in IEC 62209-3 [8]. Each uncertainty component has corresponding uncertainty values $a_{i,1g}$ and $a_{i,10g}$. The main terms of the model are:

MM Measuring system uncertainties to be specified by the manufacturer,

MN Uncertainties in post-processing and corrections,

MD Measuring system uncertainties which are dependent on the device under test,

ME Uncertainties related to the user handling or the laboratory environment in which the measuring system will be used.

For measurements of a wireless device, the total uncertainty, ΔSAR, combined from all terms in the model:

$$\Delta SAR_{meas} = \sqrt{MM^2 + MN^2 + MD^2 + ME^2} \tag{5}$$

where

$$\begin{aligned} MM^2 =& CF^2 + ISO^2 + MSC^2 + AS^2 + LIN^2 + SL^2 + BE^2 + RE^2 + RT^2 + \\ & PP^2 + SE^2 + AB^2 + PS^2 + SH^2 + MAT^2 + HOM^2 + MSI^2 + MB^2 \end{aligned} \tag{6}$$

$$MN = \sqrt{REC^2 + POL^2 + SAV^2 + SARS^2 + SC^2 + SCB^2} \tag{7}$$

$$MD = \sqrt{PC^2 + MOD^2 + IT^2 + SD^2 + BBS^2 + PSH^2} \tag{8}$$

$$ME = \sqrt{DH^2 + DP^2 + AC^2 + DN^2} \tag{9}$$

For repeatability of the SAR measurement of a DUT, many of the uncertainty terms are zero. The total uncertainty for this case is the root-sum-squared of the remaining terms:

$$\Delta SAR_{repeat} = \sqrt{AS^2 + PP^2 + POL^2 + SC^2 + PC^2 + DN^2 + DP^2 + DH^2 + SD^2 + AC^2 + MSI^2} \tag{10}$$

For system check, the measurement uncertainty includes all above terms plus three additional terms for the system validation antenna (DEX, PMU, OVS).

$$\Delta SAR_{syscheck} = \sqrt{MM^2 + MN^2 + MD^2 + ME^2 + MV^2} \tag{11}$$

where

$$MV = \sqrt{DEX^2 + PMU^2 + OVS^2} \tag{12}$$

D.3 Uncertainty Budget

All uncertainty components are shown in Table 5. Description of the uncertainty terms is provided the next section.

Table 5: cSAR3D uncertainty budget

Symbol	Input quantity	PDF_i	$a_{i,1g}$ / $a_{i,10g}$ [dB]	q_i	c_i	$u_{i,1g}$ / $u_{i,10g}$ [dB]
Measuring system uncertainties to be specified by the manufacturer (MM)						
CF	Calibration	N		1	1	
ISO	Isotropy	R		$\sqrt{3}$	1	
MSC	Mutual sensor coupling	R		$\sqrt{3}$	1	
AS	Scattering due to the array	R		$\sqrt{3}$	1	
LIN	System linearity	R		$\sqrt{3}$	1	
SL	Sensitivity limit	R		$\sqrt{3}$	1	
BE	Boundary effect	N		1	1	
RE	Readout electronics	N		1	1	
RT	Response time	N		1	1	
PP	Probe positioning	N		1	1	
SE	Sampling error	R		$\sqrt{3}$	1	
AB	Array boundaries	R		$\sqrt{3}$	1	
PS	Phantom shell	N		1	1	
SH	Phantom shape	R		$\sqrt{3}$	1	
MAT	Material Parameters	R		$\sqrt{3}$	1	
HOM	Phantom homogeneity	R		$\sqrt{3}$	1	
MSI	Measurement system immunity	R		$\sqrt{3}$	1	
MB	Data acquisition bandwidth	R		$\sqrt{3}$	1	
Uncertainty of post-processing algorithms and corrections (MN)						
REC	Reconstruction	R		$\sqrt{3}$	1	
POL	Impact of noise on reconstruction	N		1	1	
SAV	SAR averaging	R		$\sqrt{3}$	1	
SARS	SAR scaling	N		1	1	
SC	SAR permittivity correction	N		1	1	
SCB	SAR combining	R		$\sqrt{3}$	1	
Measuring system uncertainties which are dependent on the DUT (MD)						
PC	Probe-array coupling with DUT	N		1	1	
MOD	Modulation response	R		$\sqrt{3}$	1	
IT	Integration time	R		$\sqrt{3}$	1	
SD	Measured SAR drift	R		$\sqrt{3}$	1	
BBS	Broadband signal	N		2	1	
PSH	Power sharing scheme	R		$\sqrt{3}$	1	
DUT-related uncertainties and environmental factors (ME)						
DH	Device holder	N		1	1	
DP	Device positioning	N		1	1	
AC	RF ambient conditions	R		$\sqrt{3}$	1	
DN	Drift and noise	R		$\sqrt{3}$	1	
U_{1g}, U_{10g}	Expanded uncertainty					

D.4 Uncertainty Components for DUT Measurement

D.4.1 CF – Calibration

Uncertainty of the calibration of the measurement system. The uncertainty value for CF is reported in the calibration report.

D.4.2 ISO – Isotropy

Isotropy is the change in sensitivity of the SAR probe due its rotation and inclination relative to the field vector being measured. The uncertainty value was evaluated from measurements of validation antennas rotated in different orientations and was determined to be 0.06 dB and 0.03 dB for $psSAR_{1g}$ and $psSAR_{10g}$, respectively.

D.4.3 MSC – Mutual Sensor Coupling

This uncertainty is due to coupling between the probe sensors from imperfect isolation of the sensors. It is caused by port-to-port coupling where the readout at a given sensor port is influenced by the voltage and/or current at another sensor port. It is dependent on polarization, distribution and angle of incidence. The uncertainty value for MSC has been measured and was found to be a function of phantom type and frequency.

D.4.4 AS – Scattering Due to the Array

The presence of the array (sensors, transmission lines) scatters the fields inside the phantom, which can distort the SAR pattern, leading to errors in $psSAR_{1g}$ and $psSAR_{10g}$. A source was moved to several locations on the phantom. A broad source was used so that Sampling Error (SE) is not included. The uncertainty value was found to be 0.05 dB.

D.4.5 LIN – Linearity

This uncertainty term is the deviation in the SAR vs power characteristic. Non-linearities in the measurement system (e.g., due to diodes, amplifiers) are compensated during calibration. This is the left-over deviation after compensation. Power sweeps were performed covering a local SAR in the range of 0.12 W/kg to 100 W/kg (RMS for CW signals) in steps of 3 dB or less. The linearity uncertainty is the maximum deviation in the SAR vs. power characteristic from the best-fit straight reference line going through zero. MOD and LIN uncertainty terms are evaluated together in MOD component, so it is reported as 0 dB here.

D.4.6 SL – Sensitivity Limit

This uncertainty term is due to the signal to noise ratio at the lower bound of the system dynamic range. A formula for this uncertainty is applied, using the measured signal as compared to the average noise level that has been measured in over 100 cSAR3D units.

D.4.7 BE – Boundary Effect

The probe proximity to the shell introduces over-estimation due to capacitive coupling between the probe and the shell. For cSAR3D, this uncertainty is negligible because sensors are calibrated in-situ and sensors are at fixed locations.

D.4.8 RE – Readout Electronics

This uncertainty accounts for the error due to non-linearities in the electronics (e.g., amplifiers) used to read the signal from the probes. Since cSAR3D is calibrated as a complete system, with the same sensors and readout electronics as used for measurements, any loading of the sensors is accounted for during calibration. Therefore this uncertainty term is negligible.

D.4.9 RT – Response Time

This is the measurement error caused by movement of the probe during measurement. For systems having fixed probes, this uncertainty is zero by definition.

D.4.10 PP – Probe Positioning

Mechanical tolerances in the locations of the sensors introduce measurement uncertainty. This uncertainty is calculated numerically by sampling reference functions at the sensor locations and applying the field reconstruction algorithm to calculate $psSAR_{1g}$ and $psSAR_{10g}$. The sensor locations are first set to their nominal positions to calculate the reference psSAR. Then the sensor locations are varied from their nominal locations according to the mechanical tolerance, which is 1 mm in x and y directions for cSAR3D ($k = 2$, Normal distribution). The field values at these locations are passed through the field reconstruction to calculate the modified psSAR and normalize it to the reference psSAR. This is run several times until the standard deviation of the normalized psSAR has converged. Applying this procedure yields a standard deviation of 0.04 dB when the SAR distribution is sharp. The standard deviation is reduced for broader SAR distributions.

D.4.11 SE – Sampling Error

This is the measurement error due to the fixed sensor resolution. For sharp SAR distributions, the SAR may be underestimated when the peak SAR is located between the sensors. This uncertainty component is evaluated by injecting a numerical SAR distribution into cSAR3D and normalizing the psSAR after field reconstruction to the analytical psSAR value. The normalized psSAR is calculated thousands of times for different SAR distributions and peak locations. The results have been fit to a formula that varies based on the sharpness of the SAR distribution, the averaging mass, and the phantom type. cSAR3D Quad has a much lower Sampling Error uncertainty due to its high resolution.

D.4.12 AB – Array Boundaries

Uncertainties at the boundary of the measurement area are due to the truncation of the field and extrapolation of the field distribution beyond the measurement area. This uncertainty has been carefully evaluated by injecting numerical SAR distributions close to the boundary of the measurement area and comparing the psSAR (after field reconstruction) to the psSAR when the same SAR distribution is located at the center of the measurement region. cSAR3D software provides warnings when the averaging volume touches the boundary of the measurement region. When the border warning is triggered, the uncertainty is not displayed (shown as 'n/a'). Therefore, any locations of the SAR distribution that trigger the border warning are not counted in the uncertainty evaluation. For the remaining locations, the uncertainty has been determined to be negligible compared to the REC and SE uncertainty terms.

D.4.13 PS – Phantom Shell

The variations in the thickness, permittivity and loss tangent of the phantom shell from the nominal values influence the psSAR value. This has been determined from numerical simulations. To determine the uncertainty value, first the reference psSAR was calculated in the Flat phantom from a numerical distribution when the phantom thickness, permittivity and loss tangent are all set to their nominal values. Next, the psSAR was calculated in the same condition as above, using different values according to the mechanical tolerances of the shell thickness, permittivity, and loss tangent, which have been determined to be ±0.2 mm, ±10% and ±0.01, respectively. Normalize this psSAR value to the reference psSAR. Take the standard deviation among all cases. The results show an uncertainty value below 0.1 dB that is applied in the software as a function of frequency.

D.4.14 SH – Phantom Shape

This uncertainty component accounts for variation in SAR due to the production tolerances in the phantom shape. This uncertainty component is not covered in IEC 62209-3 [8] but it affects the measured psSAR. For Head phantoms, the phantom shape uncertainty has been assessed by measuring deviations in the Head and Flat phantoms among several production units. The SAR varies with the square of the separation distance from a current source to the phantom:

$$a_{SH}[\%] = ((z + \Delta z)^2/z^2 - 1) \cdot 100\% \approx (2\Delta z/z) \cdot 100\% \tag{13}$$

$$a_{SH}[dB] = 10 \cdot log_{10}(1 + 2\Delta z/z) \tag{14}$$

This uncertainty component is independent of frequency. It is also the same for SAR_{1g} and SAR_{10g}. A rectangular probability distribution is used because the maximum range of the shape tolerance is applied. The divisor is therefore $q_{SH} = \sqrt{3}$. The weighting factor is $c_{SH} = 1$. For Head phantoms, $a_{SH} = 0.2$ dB. For Flat phantoms, this uncertainty component was found to be negligible.

D.4.15 MAT – Tissue-Equivalent Material Parameters

This uncertainty is the psSAR variation due to changes in permittivity, conductivity, density and temperature of the tissue-equivalent medium. Temperature variation during measurements changes the permittivity and conductivity of the medium. It also may affect the performance of the hardware. It is therefore important to carefully evaluate this uncertainty using the cSAR3D hardware under worst-case conditions. Repeat measurements have been conducted over a 24-hour period using reference sources. A difference in psSAR of up to 0.2 dB has been recorded.

D.4.16 HOM – Phantom Homogeneity

This uncertainty term accounts for the influence on psSAR of the inhomogeneity of the phantom. The phantom inhomogeneities are due to several causes, which are the spatial variation of the tissue-equivalent medium parameters, thermal gradients in the phantom, and back-scattering from the electronics and other materials in the phantom. This uncertainty term has been evaluated using sources with broad SAR distributions at different locations, polarizations, and distances to the phantom. The results are compared with their respective numerical reference values. The results have been fitted to a function that depends on phantom type and location.

D.4.17 MSI – Measurement System Immunity

During measurement, the field radiated by the DUT may be picked up by parts of the measurement system other than the field sensors. This uncertainty is evaluated by using the validation antennas in specified test positions and blocking the direct field reception from the probe or probe-array supposed to perform the measurement.

D.4.18 MB – Data acquisition bandwidth

cSAR3D is a broadband spectral integration method. This uncertainty term, due to the finite data acquisition bandwidth of the measurement system, is negligible for cSAR3D.

D.4.19 REC – Reconstruction

This measurement uncertainty component is caused by errors in the reconstruction algorithm. It is evaluated by applying the field reconstruction algorithm to analytical SAR distributions that have been sampled at the sensor locations. This is performed repeatedly for different locations of the source on the phantom. As stated in IEC 62209-3 [8], the uncertainty contributions for sampling error, array boundaries, reconstruction algorithms may be correlated. Therefore, they can be evaluated in a combined fashion. This uncertainty term has been combined with SE and therefore REC is reported as 0 dB.

D.4.20 POL – Impact of Noise on Reconstruction

Noise in the measurement system causes errors in the field reconstruction algorithm. To evaluate this uncertainty term, component noise was added to reference field distributions and the processed psSAR was normalized to the reference psSAR without noise. The component noise was determined as the maximum allowable noise for the cSAR3D hardware, which is applied during quality checks prior to shipment. The noise is applied having a Normal distribution. Over 100 measurements were performed with injected noise until the standard deviation stabilized. The resulting uncertainty is a function of the psSAR level.

D.4.21 SAV – SAR Averaging

This uncertainty term is due to the orientation of the 1-gram or 10-gram averaging cube. The SAR may be underestimated if the cube is not oriented to capture the highest psSAR. To evaluate this uncertainty, numerical test functions were evaluated numerically, and the psSAR was evaluated for different cube orientations from 0° to 45° in steps of 5°. The uncertainty has been evaluated for SAR distributions having different variations in x and y directions.

D.4.22 SARS – SAR Scaling

This uncertainty is caused by non-linearities in the measured signal when the SAR is measured applying a different modulation than that used by the signal of the DUT. This uncertainty term does not apply to cSAR3D if the user applies the correct modulation to the measurements. cSAR3D is calibrated for all modulations. The modulation response uncertainty, MOD, is covered separately.

D.4.23 SC – SAR Correction for Deviations in Permittivity and Conductivity

This uncertainty arises when the system corrects the SAR value for changes in the permittivity and conductivity of the tissue-equivalent medium. It is not applicable to cSAR3D because these corrections are not applied. cSAR3D is calibrated in situ in the hermetically-sealed final assembly, the same dielectric parameters are in the phantom during calibration and measurements of the DUT. Temporal variation in dielectric parameters due to heating and aging of the system are considered in DN and MAT.

D.4.24 SCB – SAR Combining

For simultaneous transmission of uncorrelated signals, the signals are measured separately and the combined SAR distribution is made by spatially adding the individual SAR measurements. This uncertainty term is low because each SAR distribution is calculated at the same points after interpolation and therefore the combining is a straightforward summation. It is independent of whether the simultaneous transmitters are within the same band or between different bands.

D.4.25 PC – Probe Coupling with DUT

The probe of the scanning system scatters the power deposited into the phantom from the DUT. The scattered field may modify the loading of the DUT compared to a phantom without the probe present. This uncertainty has been evaluated by measuring the return loss of validation antennas on the phantom with the sensors present in the phantom and comparing against the return loss without sensors present. The uncertainty is the maximum value of $(1 - S_{11,with})^2$ / $(1 - S_{11,without})^2$.

D.4.26 MOD – Modulation Response

This uncertainty is due to errors in calibration of modulated signals. Sensor model calibration (SMC) is applied to cSAR3D. The error in the model has been evaluated over a large range of 2G, 3G and 4G signals and over the full dynamic range of the system. The error has been found to be small (0.05 dB) for psSAR values up to 1 W/kg and increases for higher values. It can exceed 0.1 dB for psSAR values of 10 W/kg for some modulations. The uncertainty value is calculated as a function of the psSAR value.

D.4.27 IT – Integration Time

This is the uncertainty due to finite measurement time and sampling of signals with non-continuous amplitude. Due to this effect, cSAR3D adjusts the integration time of the SAR measurement based on the signal modulation. The uncertainty term has been evaluated by measuring the modulated signal at integration time, then repeatedly doubling the integration time and remeasuring until the psSAR values are within 0.1 dB of each other. Pulsed signals have integration time uncertainties less than 0.2 dB.

D.4.28 SD – Measured SAR Drift

This uncertainty term is due to the drift in the output power of the DUT. Uncertainty is negligible due to short measurement acquisition time ($\lesssim$ 1 second) of cSAR3D.

D.4.29 BBS – Broadband Signal

This uncertainty is due to the variable response of the intrinsic parameters of the probe as a function of frequency. It is also due to the frequency dependence of the dielectric properties.

If the transmission spectrum is equally distributed around the center frequency of the channel, the uncertainty term for the broadband signal is less than 0.5 %, independent of signal bandwidth. This is due to the relatively flat frequency-dependence of conductivity and cSAR3D probe sensitivity.

For unequal spectral distributions, the maximum uncertainty can be calculated by assuming the mean of the spectral power has an offset with respect to the center of the channel over 75 % of the channel bandwidth. This has been calculated for the maximum bandwidth per frequency band in Figure 20. For example, above 6 GHz for a maximal channel bandwidth of 320 MHz (± 160 MHz), the error may be calculated for an offset of 120 MHz. Figure 20 shows a maximum value of 2.9 % (0.12 dB). A Gaussian distribution with k = 2 is applied. If the evaluation frequency offset to account for equal spectral weighting, the uncertainty is less than 0.5 %. For intra-band contiguous CA and non-contiguous CA, the measurement uncertainty can be reduced by using test protocols that allow the CCs to be measured separately.

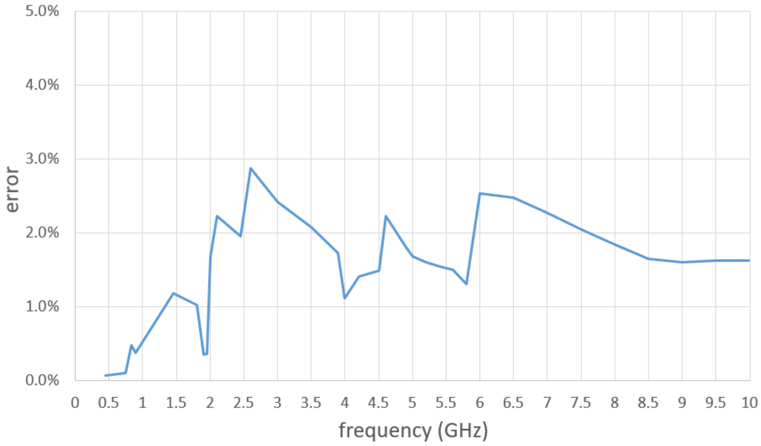


Figure 20: BBS uncertainty for an offset with respect to the center of the channel of 75 % of the channel bandwidth, calculated for the maximum signal bandwidth per frequency as specified in 3GPP and other standards.

D.4.30 PSH – Power Sharing Scheme

When simultaneous transmission is used, the signals are combined. The signals may be scaled according to their relative output power levels. Measurement of the output power and scaling of the SAR levels is performed by the user.

D.4.31 DH – Device Holder

Any material used to hold the DUT or provide spacing of the DUT to the phantom during measurement can influence the measured SAR. This has been evaluated for the device holder and 15° mask for cSAR3D Head, the foam and rigid spacers used for cSAR3D Flat and cSAR3D Quad, and the robot gripper used for cSAR3D-A. The influence has been found to be within 0.1 dB for a range of sources.

D.4.32 DP – Device Positioning

This uncertainty term is the influence of the device position on the phantom due to operator. DUT measurements have been repeated with different trained operators and the results have been made available to regulators. The device positioning uncertainty has been found to be less than 0.2 dB and depends on the phantom type.

D.4.33 AC – RF Ambient Conditions

This is influence of nearby RF sources on SAR of the DUT. It depends on the lab setup, not on the cSAR3D hardware or software. It is the responsibility of the user to evaluate this effect and keep other RF sources away from the phantom during measurement.

D.4.34 DN – Drift and Noise

This uncertainty term accounts for noise in the SAR measurement system. There are three causes of this uncertainty: component noise (over seconds), short-term drifts (over minutes or hours) due to equipment heating or changes in ambient conditions, and long-term drifts (over the calibration period) due to changes in the electronics and the dielectric parameters. Repeated measurements have been performed with different intervals to separately evaluate the three effects. The measurements were performed at high SAR levels (e.g., 1 W/kg) so that this uncertainty is not correlated with the SL uncertainty. It was also evaluated for x-, y- and z-dominated polarization. The long-term drift has been found to be up to 0.05 dB over the recommended 1-year calibration period. The short-term drift is accounted for in the MAT component. The component noise has been found to be 0.02 dB.

D.5 Uncertainty Components of Validation Antennas

When system check is performed, measurement uncertainties of the validation antennas shall be additionally accounted for. The following three additional uncertainty terms are defined, as described in IEC 62209-3 [8].

D.5.1 DEX – Deviation of Experimental Antennas

Mechanical and electrical tolerances of the validation antennas cause uncertainty in the psSAR. These tolerances affect the current distribution on the antenna, the feed-point impedance, and the near field distribution. Type A uncertainty analysis has been conducted of the variations in psSAR from more than 20 dipole antennas at different frequencies on both Flat and Head phantoms. The worst-case uncertainty has been found to be 0.5 dB. This term has a rectangular distribution.

D.5.2 PMU – Power Measurement Uncertainty

The power fed to the antenna is measured using a setup that includes cables, attenuators, a directional coupler and a power meter. The total uncertainty of the power measurement includes the calibration uncertainty of the power meter, drift in the power meter reading, coupler mismatch, and drift in the insertion losses of the cable and attenuator. The power measurement uncertainty has been found to be 0.1 dB. This term has a normal distribution.

D.5.3 OVS – Other Uncertainty Contributions for Validation Antennas

This uncertainty term accounts for all other uncertainies in addition to DEX and PMU when using validation antennas. The primary contributions to this uncertainty are the mechanical tolerances in the mask and spacer. These affect the distance from the antenna to the phantom surface and diffraction of the electric field. The combined influences of these uncertainty components has a maximum value of 0.2 dB. This term has a rectangular distribution.

D.6 Example Uncertainty Budget

An example uncertainty budget is shown in Table 6. Results are typical for measurement of 5G signals at frequencies below 3 GHz at a SAR level of 1 W/kg on a cSAR3D Flat. The actual uncertainty depends on many parameters of the system and wireless device which are calculated during SAR measurement.

Table 6: Example cSAR3D uncertainty budget for cSAR3D Flat.

Symbol	Input quantity	PDF_i	$a_{i,1g}$ / $a_{i,10g}$ [dB]	q_i	c_i	$u_{i,1g}$ / $u_{i,10g}$ [dB]
Measuring system uncertainties to be specified by the manufacturer (MM)						
CF	Calibration	N	0.43 / 0.43	1	1	0.43 / 0.43
ISO	Isotropy	R	0.06 / 0.03	$\sqrt{3}$	1	0.03 / 0.02
MSC	Mutual sensor coupling	R	0.13 / 0.13	$\sqrt{3}$	1	0.08 / 0.08
AS	Scattering due to the array	R	0.05 / 0.05	$\sqrt{3}$	1	0.03 / 0.03
LIN	System linearity	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
SL	Sensitivity limit	R	0.03 / 0.03	$\sqrt{3}$	1	0.02 / 0.02
BE	Boundary effect	N	0.00 / 0.00	1	1	0.00 / 0.00
RE	Readout electronics	N	0.00 / 0.00	1	1	0.00 / 0.00
RT	Response time	N	0.00 / 0.00	1	1	0.00 / 0.00
PP	Probe positioning	N	0.03 / 0.03	1	1	0.03 / 0.03
SE	Sampling error	R	0.25 / 0.05	$\sqrt{3}$	1	0.14 / 0.03
AB	Array boundaries	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
PS	Phantom shell	N	0.03 / 0.03	1	1	0.02 / 0.02
SH	Phantom shape	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
MAT	Material Parameters	R	0.20 / 0.20	$\sqrt{3}$	1	0.12 / 0.12
HOM	Phantom homogeneity	R	0.20 / 0.20	$\sqrt{3}$	1	0.12 / 0.12
MSI	Measurement system immunity	R	0.04 / 0.04	$\sqrt{3}$	1	0.02 / 0.02
MB	Data acquisition bandwidth	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
Uncertainty of post-processing algorithms and corrections (MN)						
REC	Reconstruction	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
POL	Impact of noise on reconstruction	N	0.00 / 0.00	1	1	0.00 / 0.00
SAV	SAR averaging	R	0.01 / 0.01	$\sqrt{3}$	1	0.01 / 0.01
SARS	SAR scaling	N	0.00 / 0.00	1	1	0.00 / 0.00
SC	SAR permittivity correction	N	0.00 / 0.00	1	1	0.00 / 0.00
SCB	SAR combining	R	0.03 / 0.03	$\sqrt{3}$	1	0.02 / 0.02
Measuring system uncertainties which are dependent on the DUT (MD)						
PC	Probe-array coupling with DUT	N	0.10 / 0.10	1	1	0.10 / 0.10
MOD	Modulation response	R	0.04 / 0.04	$\sqrt{3}$	1	0.02 / 0.02
IT	Integration time	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
SD	Measured SAR drift	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
BBS	Broadband signal	N	0.02 / 0.02	2	1	0.01 / 0.01
PSH	Power sharing scheme	R	0.00 / 0.00	$\sqrt{3}$	1	0.00 / 0.00
DUT-related uncertainties and environmental factors (ME)						
DH	Device holder	N	0.10 / 0.10	1	1	0.10 / 0.10
DP	Device positioning	N	0.12 / 0.12	1	1	0.12 / 0.12
AC	RF ambient conditions	R	0.05 / 0.05	$\sqrt{3}$	1	0.03 / 0.03
DN	Drift and noise	R	0.05 / 0.05	$\sqrt{3}$	1	0.03 / 0.03
U_{1g}, U_{10g}	Expanded uncertainty					1.06 / 1.02

E System Validation for Frequencies Up To 6 GHz

System validation is performed by SPEAG to verify that the system performs within its stated uncertainty. It is performed after calibration and before the system is delivered.

E.1 Antennas for System Validation

IEC/IEEE 62209-1528 [7] and IEC 62209-3 [8] describe the antennas and procedure for system check and system validation.

In collaboration with the regulators and the IEC JWG13, SPEAG has extended the system validation dipoles to cover the 5G NR FR1 bands. For the 3 GHz to 5 GHz frequency range, Table 7 shows the dipole dimensions and Table 7 shows the corresponding SAR target values. These requirements are also compatible with [9]. More might be added during the development of the JWG13 Technical Report on 5G NR FR1 SAR measurement and SPEAG is also committed to support these requirements.

Frequency [MHz]	L **[mm]**	h **[mm]**	d_1 **[mm]**
3300	38.0	28.5	3.6
3500	37.0	26.4	3.6
3700	34.7	26.4	3.6
3900	32.0	21.0	3.6
4200	30.1	22.5	3.6
4600	27.0	21.7	3.6
4900	25.0	19.1	3.6
NOTE 1 The L, h and d_1 dimensions shall be within ±2 % tolerance.			

Table 7: Mechanical dimensions of validation dipoles in the 3 GHz to 5 GHz frequency range.

Frequency MHz	**Phantom shell thickness mm**	**1 g SAR W/kg**	**10 g SAR W/kg**
3300	2.0	66.9	25.4
3500	2.0	65.8	24.6
3700	2.0	65.2	23.5
3900	2.0	67.5	23.3
4200	2.0	66.4	22.2
4600	2.0	66.7	21.5
4900	2.0	68.4	21.2

Table 8: Numerical target SAR values (W/kg) for standard dipole (see Table 7) and flat phantom, normalized to 1 W forward power. The SAR values are sensitive to the dipole and phantom geometry (dipole length, spacer length and permittivity, and phantom shell permittivity) and can vary by as much as ± 10 % (see IEC/IEEE 62209-1528 [7]).

E.2 System Validation Procedure

cSAR3D is fully validated in accordance with IEC 62209-3. In addition, SPEAG has also identified specific 5G modulations and frequencies for cSAR3D validation. Two additional modulations, as shown in Table 9, have been added to the validation to cover the range of 5G signal types. QPSK and 256QAM modulations are used respectively for DFT-s-OFDM and CP-OFDM waveforms to represent a range of low and high PAR configurations, with 100 MHz maximum channel bandwidth. The test configurations are shown in Table 10.

No.	**Description**	**PAR**	**UID**
M15	5G NR (DFT-s-OFDM, 100 % RB, 100 MHz, QPSK, 30 kHz)	5.9	10868
M16	5G NR (CP-OFDM, 100 % RB, 100 MHz, 256QAM, 30 kHz)	8.4	10971

Table 9: Modulations added to cSAR3D Validation in addition to those defined in IEC 62209-3.

The test configurations for cSAR3D validation are those defined in IEC 62209-3 plus those described in Table 10.

No.	**Ant.**	f **[MHz]**	P_f **[dBm]**	**Mod.**	**Loc., Angle**	s **[mm]**	SAR_{1g} **[W/kg]**	SAR_{10g} **[W/kg]**	U_{sa} **(k=1) [dB]**
1	D4200	4200	20	M1, M15	B1, 22.5	10	6.64	2.22	0.2
2	D4200	4200	13	M1, M16	B2, 67.5	10	1.33	0.443	0.2

Table 10: Test configurations added to cSAR3D Validation for frequencies below 6 GHz, in addition to those defined in IEC 62209-3.

F System Validation for the Frequency Range 6 - 10 GHz

F.1 Antennas for System Validation

As specified in 3GPP Release 16 TS 38.101-1, 5G NR has been extended to 7125 MHz for FR1. There is the possibility that this may be extended to higher frequencies in the future. System validation dipoles are already defined in IEC/IEEE 62209-1528 for 6 - 10 GHz. The dimensions of these dipoles are shown in Table 11 and the SAR target values are shown in Table 12.

Frequency [MHz]	L **[mm]**	h **[mm]**	d_1 **[mm]**
6500	14.5	35.1	2.2
7000	14.5	35.1	2.2
8000	12.2	25.0	2.2
9000	12.2	25.0	2.2
NOTE 1 The L, h and d_1 dimensions shall be within ±2 % tolerance.			

Table 11: Mechanical dimensions of validation dipoles in the 6 GHz to 10 GHz frequency range.

Frequency MHz	**Phantom shell thickness mm**	**1 g SAR W/kg**	**10 g SAR W/kg**
6500	2.0	298	52.8
7000	2.0	275	47.0
8000	2.0	273	44.5
9000	2.0	243	40.0

Table 12: Numerical target SAR values (W/kg) for standard dipole (see Table 11) and flat phantom, normalized to 1 W forward power. The SAR values are sensitive to the dipole and phantom geometry (dipole length, spacer length and permittivity, and phantom shell permittivity).

F.2 System Validation Procedure

For cSAR3D Flat phantoms that are calibrated for 6 - 10 GHz, system validation is performed at 7 GHz and 9 GHz with a CW signal. Table 13 shows the system validation test configurations for frequencies above 6 GHz using the X10 combiner. A sufficient number of measurements, at least 5, is performed to maintain an expanded uncertainty less than 30%.

No.	**Ant.**	f **[MHz]**	P_f **[dBm]**	**Mod.**	**Loc., Angle**	s **[mm]**	SAR_{1g} **[W/kg]**	SAR_{10g} **[W/kg]**	U_{sa} **($k = 1$) [dB]**
1	D7000	7000	10	M1	D1, 0	5	2.75	0.47	0.3
2	D9000	9000	20	M1	D2, 0	5	24.3	4	0.3

Table 13: Test configurations added to cSAR3D Validation for frequencies above 6 GHz.

List of Abbreviations

3GPP	Third Generation Partnership Project
4G LTE	Fourth Generation Long Term Evolution
5G NR	Fifth Generation New Radio
A-MPR	Additional - Maximum Power Reduction
BS	Base Station
BSS	Base Station Simulator
CA	Carrier Aggregation
CC	Component Carrier
CCDF	Complementary Cumulative Distribution Function
CP	Cyclic Prefix
CP-OFDM	Cyclic Prefix âĂŞ Orthogonal Frequency Division Multiplexing
CW	Continuous Wave
DFT-s-OFDM	Discrete Fourier Transform - spread - Orthogonal Frequency Division Multiplexing
DPS	Dynamic Power Sharing
DUT	Device Under Test
E-UTRA	Evolved Universal Terrestrial Radio Access
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
EN-DC	E-UTRA - NR Dual Connectivity
EPS	Equal Power Sharing
FDD	Frequency Division Duplex
FR1	Frequency Range 1
FR2	Frequency Range 2
HPUE	High Power/Performance UE
JWG 13	Joint Working Group 13
LTE	Long Term Evolution
MCG	Master Cell Group
MIMO	Multiple Input Multiple Output
MPE	Maximum Permissible Exposure
MPR	Maximum Power Reduction
NE-DC	NR - EUTRAN Dual Connectivity
NR	New Radio

NR-ARFCN	New Radio Absolute Radio Frequency Channel
NR-DC	NR Dual Connectivity
NS_1	Network Signalling 1
NSA	Non-Standalone Access
OEM	Original Equipment Manufacturer
QAM	Quadrature Amplitude Modulation
PAR	Peak to Average Ratio
PDF	Probability Density Function
$\pi/2$-**BPSK**	$\pi/2$ - Binary Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RF	Radio Frequency
RMS	Root Mean Square
SA	Standalone Access
SAR	Specific Absorption Rate
SC-OFDM	Single-Carrier Orthogonal Frequency Division Multiplex
SCG	Secondary Cell Group
SCS	Subcarrier Spacing
SDL	Supplementary Downlink
SUL	Supplementary Uplink
SUO	Single Uplink Operation
TDD	Time Division Duplex
UE	User Equipment