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Final Report for Project 644

Dosimetric Evaluation of IEEE 802.11n and IEEE 802.11ac Devices

conducted by

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Executive Summary

The Swiss Federal Office for Public Health (Swiss FOPH) has identified that public information regarding radiofrequency (RF) exposure of humans to wireless local area network devices (WLAN) compliant with the latest communication standards is lacking. The Swiss FOPH mandated the IT'IS Foundation for Research on Information Technologies in Society (IT'IS) to dosimetrically assess WLAN devices that employ IEEE 802.11n/ac by measuring the specific absorption rate (SAR) values. This study was conducted in oder to respond to this lack of publicly available information, by:

- analysis of the IEEE 802.11n/ac technologies with respect to exposure relevant parameters, especially extended to [1, 2]
- selection of wireless access point (WAP) and tablet devices that can be reliably controlled with respect to RF parameters
- determination of test modes and device under test (DUT) control
- assessment of the influence of the new technological parameters (data rate, bandwidth) available in IEEE 802.11n/ac
- comparison of the exposure to that obtained with older IEEE 802.11 and other mobile communication technologies

Table 1 gives a summary of the maximum SAR value measured for each device and for each band. Specified in the table are the main factors that influence the SAR value: geometric configuration (i.e., the distance between the phantom and the antenna), the number of antennas selected – and to a lesser extent, the frequency – as well as the channel bandwidth. It should, however, be noted that WLAN-capable devices can differ widely in terms of how the IEEE 802.11 communication is implemented, e.g., limitations on output power per band, bandwidth, and modulation may be different. Thus, these measurement results cannot be generalized to other devices. The tablet exhibited higher SAR values, despite lower output power, due to the smaller distance between the antenna and the phantom. The maximum SAR values from the IEEE 802.11n/ac devices measured in this study are in the same range as those found in [1, 2] for older generations of the IEEE 802.11 standard.

Band (GHz)	BW (MHz)	Channel Freq. (MHz)	Mod. (DC)	Power (dBm)	Position	Antennas Transmitting	SAR 10 g (W/Kg)
Tablet							
2.4	20	13 2472	BPSK (0.99)	14.5	Front screen	main, aux	0.398
2.4	20	13 2472	BPSK (0.99)	14.5	Front screen	main, aux	0.398
5	20	165 5825	BPSK (0.99)	14.5	Front screen	main, aux	0.697
Wireless Access Point							
5	40	136 5680	64-QAM (0.83)	20	90°	2 out of 3 (NSS = 2)	0.096

Table 1: The maximum SAR measured for both of the devices and for both bands. In every case, IEEE 802.11n applies and all antennas were configured as active.

Contents

1 List of Abbreviations and Acronyms

BPSK	Binary Phase-Shift Keying
BW	Channel Bandwidth
CH	Channel
cSAR3D	Fast SAR measurement system
DAK	Dielectric Assessment Kit
DASY6	Dosimetric Assessment System Version 6
DC	Duty Cycle
DUT	Device Under Test
ELF	Extremely Low Frequency
EM	Electromagnetic
GI	Guard Interval
HT	High Throughput
IEEE	Institute of Electrical and Electronics Engineers
IEEE802.11x	Series of WLAN Standards
LF	Low Frequency
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MU-MIMO	Multi-User MIMO
NSS	Number of Spatial Streams
OFDM	Orthogonal Frequency-Division Multiplexing
PSK	Phase-Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RF	Radiofrequency
SAR	Specific Absorption Rate
SISO	Single-Input Single-Output
SPEAG	Schmid & Partner Engineering AG
TPC	Transmit Power Control
VHT	Very High Throughput
WAP	Wireless Access Point
WLAN	Wireless Local Area Network
Swiss FOPH	Swiss Federal Office for Public Health
IT'IS	IT'IS Foundation for Research on Information Technologies in Society

2 Introduction

In 2004, the Swiss Federal Office for Public Health (Swiss FOPH) mandated the IT'IS Foundation for Research on Information Technologies in Society (IT'IS) to develop test methods and to assess human exposure from general mobile devices used in home and office environments [1]. This work was supplemented in 2006 [2] with a specific focus on wireless data transfer technologies such as wireless local area networks (WLAN) based on the IEEE 802.11 standard series. At that time, IEEE 802.11b/g/a/h standards [3–6] were the commonly used WLAN technologies. With the evolution of WLAN technologies, newer standards have taken over WLAN communication. In particular, IEEE 802.11n [7] was introduced in 2009, followed by IEEE 802.11ac [8] in 2013. Both technologies aim to enhance the data rates in WLAN systems.
For these latest WLAN technologies, there is little public information available with respect to human exposure to electromagnetic (EM) fields, thus, the Swiss Federal Office for Public Health mandated the IT'IS Foundation for Research on Information Technologies in Society to carry out dosimetric assessment of IEEE 802.11n/ac devices.

3 Objective

The objective of this study was to assess the exposure from two IEEE 802.11n/ac capable devices dosimetrically, by:

- selection of an access point and a tablet that can be reliably controlled with respect to radiofrequency (RF) parameters.
- determination of test modes and device under test (DUT) control.
- assessment of the influence of the new technological parameters (data rate, bandwidth) available in IEEE 802.11n/ac.
- comparison of the exposure to that due to older IEEE 802.11 and other mobile communication technologies.

4 Technologies

The ever increasing demand for high-speed communication in wireless local area networks (WLANs) is addressed by new technologies, introduced with IEEE 802.11n/ac. Table 5 shows the channel numbers and the corresponding frequencies used in modern WLANs. Incorporation of older devices, which implement IEEE 802.11a/b/g/h, is ensured by backwards compatibility with these previous standards. The following sections give an overview of the recent standards IEEE 802.11n/ac and the specifications and regulations are summarized in Table 2.

4.1 IEEE 802.11n

The IEEE 802.11n standard, which was published in 2009, features a significantly increased data transmission rate with a theoretical maximum of 600 Mbps. The standard extends the previous IEEE 802.11g standard, enabling operation also in the 5 GHz bands and introducing new modulation schemes. The channel bandwidth can be extended from 20 to 40 MHz. Orthogonal frequency-division multiplexing (OFDM) is used to encode the data stream on multiple closely spaced sub-bands. Each sub-carrier is then modulated with phase-shift keying (PSK) or quadrature amplitude modulation (QAM), the highest data rate being achieved with 64-QAM. The modulation and coding scheme (MCS) (see Table 3) shows the various combinations and resulting data rates. Further, multiple-input multiple-output (MIMO) is introduced, with up to four spatial data streams, each with a maximum data rate of 150 Mbps. Also, the option of a shorter guard interval (GI) is included to achieve higher data rates, and spatial beam-forming is applied to improve signal quality.

4.2 IEEE 802.11ac

The IEEE 802.11ac standard, introduced in 2013, applies only to the 5 GHz bands and enhances various concepts of IEEE 802.11n. Channel bandwidths are increased to 80 and 160 MHz, which provides, together with denser modulation (256-QAM), an increased data rate of 866.7 Mbps per spatial stream (see Table 4). The maximum number of spatial streams (NSS) is increased to eight. The multi-user capabilities introduced, with downlink multi-user MIMO (MU-MIMO), allow independent transmission to up to four clients (i.e., one transmitter, multiple receivers).

Standard	IEEE 802.11n
RF Range	2.4 – 2.4835 GHz; 5.15 – 5.35 GHz; 5.47 – 5.825 GHz
Max. RF P_{out}	100 mW; 200 mW (100 mW); 1 W (500 mW) – these correspond to the above ranges (allowed values without transmit power control (TPC) in parentheses)
Power Control	Optional TPC
Spreading	OFDM
Modulation	BPSK, QPSK, 16-QAM, 64-QAM (variable coding rates)
Max. NSS	4
Bandwidth	20 MHz, 40 MHz
ELF / LF	0 ... ~10 (beacon) ... 4.42 kHz
Standard	IEEE 802.11ac
RF Range	5.15 – 5.35 GHz; 5.47 – 5.825 GHz
Max. RF P_{out}	200 mW (100 mW); 1 W (500 mW). – these correspond to the above ranges (allowed values without TPC in parentheses)
Power Control	Optional TPC
Spreading	OFDM
Modulation	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM (variable coding rates)
Max. NSS	8
Bandwidth	20 MHz, 40 MHz, 80 MHz, 160 MHz
ELF / LF	0 ... ~10 (beacon) ... 4.42 kHz

Table 2: Specifications and Swiss regulations for IEEE 802.11n/ac.

HT MCS Index	NSS	Modulation	Coding rate	Data Rate (Mbps) Bandwidth 20 MHz 800 ns GI	Bandwidth 20 MHz 400 ns GI	Bandwidth 40 MHz 800 ns GI	Bandwidth 40 MHz 400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15
1	1	QPSK	1/2	13	14.4	27	30
2	1	QPSK	3/4	19.5	21.7	40.5	45
3	1	16-QAM	1/2	26	28.9	54	60
4	1	16-QAM	3/4	39	43.3	81	90
5	1	64-QAM	2/3	52	57.8	108	120
6	1	64-QAM	3/4	58.5	65	121.5	135
7	1	64-QAM	5/6	65	72.2	135	150
8	2	BPSK	1/2	13	14.4	27	30
9	2	QPSK	1/2	26	28.9	54	60
10	2	QPSK	3/4	39	43.3	81	90
11	2	16-QAM	1/2	52	57.8	108	120
12	2	16-QAM	3/4	75	86.7	162	180
13	2	64-QAM	2/3	104	115.6	216	240
14	2	64-QAM	3/4	117	130.3	243	270
15	2	64-QAM	5/6	130	144.4	270	300

Table 3: Excerpt of the modulation and coding scheme (MCS) and data rates for IEEE 802.11n. Up to two (out of four) spatial streams are shown. The high throughput (HT) MCS index uniquely identifies the communication mode at any given bandwidth. Adapted from [7].

VHT MCS Index	NSS	Modulation	Coding rate	Data rate (Mbps) Bandwidth 20 MHz 800 ns GI	Bandwidth 20 MHz 400 ns GI	Bandwidth 40 MHz 800 ns GI	Bandwidth 40 MHz 400 ns GI	Bandwidth 80 MHz 800 ns GI	Bandwidth 80 MHz 400 ns GI	Bandwidth 160 MHz 800 ns GI	Bandwidth 160 MHz 400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65
1	1	QPSK	1/2	13	14.4	27	30	58.5	65	117	130
2	1	QPSK	3/4	19.5	21.7	40.5	45	87.8	97.5	175.5	195
3	1	16-QAM	1/2	26	28.9	54	60	117	130	234	260
4	1	16-QAM	3/4	39	43.3	81	90	175.5	195	351	390
5	1	64-QAM	2/3	52	57.8	108	120	234	260	468	520
6	1	64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585
7	1	64-QAM	5/6	65	72.2	135	150	292.5	325	585	650
8	1	256-QAM	3/4	78	86.7	162	180	351	390	702	780
9	1	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7
0	2	BPSK	1/2	13	14.4	27	30	58.5	65	117	130
1	2	QPSK	1/2	26	28.9	54	60	117	130	234	260
2	2	QPSK	3/4	39	43.3	81	90	175.5	195	351	390
3	2	16-QAM	1/2	52	57.8	108	120	234	260	468	520
4	2	16-QAM	3/4	78	86.7	162	180	351	390	702	780
5	2	64-QAM	2/3	104	115.6	216	240	468	520	936	1040
6	2	64-QAM	3/4	117	130.3	243	270	526.5	585	1053	1170
7	2	64-QAM	5/6	130	144.4	270	300	585	650	1170	1300
8	2	256-QAM	3/4	156	173.3	324	360	702	780	1404	1560
9	2	256-QAM	5/6	N/A	N/A	360	400	780	866.7	1560	1733.4

Table 4: Excerpt of the MCS and data rates for IEEE 802.11ac. Up to two (out of eight) spatial streams are shown. The very high throughput (VHT) MCS index and NSS together uniquely identify the communication mode at any given bandwidth (different usage in IEEE 802.11n, see. Table 3). Adapted from [8].

2.4 GHz band		5 GHz bands	
Channel number	Frequency / MHz	Channel number	Frequency / MHz
1	2412	36	5180
2	2417	38	5190
3	2422	40	5200
4	2427	42	5210
5	2432	∼	∼
6	2437	100	5500
7	2442	102	5510
8	2447	104	5520
9	2452	106	5530
10	2457	∼	∼
11	2462	136	5680
12	2467	138	5690
13	2472	140	5700
		∼	∼
		155	5775
		157	5785
		159	5795
		161	5805
		165	5825

Table 5: Channels and corresponding center frequencies in the 2.4 GHz and 5 GHz bands (excerpt).

5 Test Equipment and Test Procedures

5.1 Dosimetric Assessment Systems

5.1.1 Robotic Scanning System

The measurements were performed with the automated Dosimetric Assessment System Version 6 (DASY6) from Schmid & Partner Engineering AG (SPEAG). DASY is currently the most widely used system for dosimetric evaluations and specific absorption rate (SAR) type approval of mobile devices [9]. The detailed specifications are provided in Tables 6 and 7. The measurement system is displayed in Figure 1.

Figure 1: DASY6 dosimetric assessment system with the SAM and flat phantoms for SAR assessments according to [10], [11].

5.1.2 Tissue Simulating Liquid

For measurements in the frequency ranges 2.4 – 2.5 GHz and 5.1 – 5.8 GHz, the tissue simulating liquid HBBL600-6000V6, according to IEC 62209-2 Ed.1, was chosen. The dielectric parameters of the liquid were determined with a calibrated open-ended coaxial probe of the SPEAG Dielectric Assessment Kit (DAK3.5) prior to the dosimetric evaluation. The results are compared with those of the tissue parameters of IEC 62209-2 [10] in Table 8.

5.1.3 Fast SAR System

A vector array system (cSAR3D QUAD, from SPEAG) was used to conduct preliminary fast SAR measurements, to determine the worst case orientation and antenna settings of one device, the wireless access point. The detailed specifications of the cSAR3D QUAD measurement system, shown in Figure 2, are provided in Table 9.

System	Type: Software Version:	DASY6 6.4.0.12171
Data Acquisition System	Type: Serial No: Calibrated On: Manufacturer:	DAE4 1262, 355 01/07/2016, 15/06/2016 Schmid & Partner Engineering AG (CH)
Positioner	Robot: Serial No: Repeatability: Controller: Serial No: Manufacturer:	TX60L F15/5Z0NB1/A/01 0.04 mm CS8C F11/5H1ZA1/C/01 Stäubli (France)
Phantom	Type: Serial No: Manufacturer:	Oval Phantom ELI4 1010 Schmid & Partner Engineering AG (CH)

Table 6: Measurement system for SAR measurements.

Dosimetric Probe	Type: Serial Number: Manufacturer: Calibrated On: Tip Diameter: Frequency Range: Dynamic Range:	EX3DV4 7459 Schmid & Partner Engineering AG (CH) 03/05/2016 2.5 mm 10 MHz to 6 GHz 5 μW/g to >100 mW/g

Table 7: Probe used with the DASY system.

f	IEC 62209-2		Measured		Deviation from target	
(GHz)	ε_r'	σ /(S/m)	ε_r'	σ /(S/m)	ε_r' (%)	σ (%)
2400	36.3	1.76	40.6	1.83	3.3	4
2500	39.1	1.85	40.4	191	3.3	2.8
5150	36	4.6	35.6	4.59	−1.1	−0.4
5800	35.3	5.27	34.4	5.43	−2.5	2.9

Table 8: Measured dielectric parameters of the tissue simulating liquid compared to the targets of IEC 62209-2 Ed.1.

System	Type: Software Version: Serial No: Manufacturer: Calbibrated on: Frequency Range: Dynamic Range:	cSAR3D QUAD 2.8.4.13120 9402 Schmid & Partner Engineering AG (CH) 29/10/2014 300 MHz to 6 GHz <0.01 − >100 W/Kg
	Probe Isotropy: Repeatability: Uncertainty (95% CI)	< 0.2 dB 0.1 dB < 30%

Table 9: Measurement system for fast SAR measurements.

Figure 2: cSAR3D QUAD fast SAR system.

5.2 IEEE 802.11n/ac test modes

Two devices were selected for the tests, a wireless access point (WAP) and a tablet. The tablet was chosen as an alternative to a second WAP, since it allowed more control over the transmission modes compared to the WAP, which has restricted configuration possibilities.

5.2.1 Tablet

The tablet was set to a forced transmission mode during measurements, with channel, bandwidth, modulation, and duty cycle (DC) fixed. The output power was set to maximum, 14.5 dBm. Tested were the lowest and highest available channels (the choice of which depends on other settings, e.g., the bandwidth) and a channel in the middle of the band. The modulation was set to the lowest and highest settings supported by the device (binary phase-shift keying (BPSK) and 64-QAM, respectively). Bandwidths of 20 and 40 MHz (IEEE 802.11n), as well as 80 MHz (IEEE 802.11ac) were tested. The DC chosen was the maximum possible for each case, while keeping a fixed transmission frame size of 1528 bytes. The tablet features both main and auxiliary antennas. Most of the measurements were conducted with only the main antenna enabled, and only for the resulting worst-case scenarios was the auxiliary antenna, alone and in combination with the main antenna, tested additionally. Table 10 provides details regarding the settings at which the tablet measurements were conducted.

5.2.2 Wireless Access Point

The WAP was connected to a client, and a continuous stream of data was sent to the client during the measurement. Due to the limited possibilities for configuration of the WAP's wireless driver, the modulation could be enforced only in the 2.4 GHz band. In the other cases, the modulation was automatically set by the driver to obtain the maximum data rate. The maximum output power is achieved with multiple antennas enabled, where the 2.4 and 5 GHz radio chains allow 17 and 20 dBm, respectively. The DC was estimated according to the maximum possible at a fixed transmission frame size of 1528 bytes. However, the actual DC may differ somewhat from the estimated values, as the mode of operation was a realistic data transmission (in contrast to the forced transmission mode in the case of the tablet). Table 10 provide details regarding the settings at which the WAP measurements were conducted.

Standard IEEE	Band /GHz	BW /MHz	Channel, Frequency /MHz, (DC)					
			Low		Mid		High	
802.11n	2.4	20	1 2412 (0.99)	1 2412 (0.92)	7 2442 (0.99)	-	**13** **2472** **(0.99)**	13 2472 (0.92)
802.11n	2.4	40	-	-	-	-	**11** **2462** **(0.98)**	11 2462 (0.88)
802.11n	5	20	36* 5180 (0.99)	-	100* 5500 (0.99)	100 5500 (0.92)	**165*** **5825** **(0.99)**	165 5825 (0.92)
802.11n	5	40	-	-	102 5510 (0.98)	102 5510 (0.88)	**159** **5795** **(0.98)**	159 5795 (0.88)
802.11ac	5	80	42 5210 (0.96)	-	106 5530 (0.96)	-	**155** **5775** **(0.96)**	155 5775 (0.82)
			BPSK	64-QAM	BPSK	64-QAM	BPSK	64-QAM
			Modulation					

Table 10: Test modes for the tablet. Marked in bold are the worst cases (for which also the auxiliary antenna was tested, see Table 15). Typically, two positions of the tablet were measured; cases for which all six positions were measured are marked with * (see Table 13).

<table>
<tr><th rowspan="2">Standard
IEEE</th><th rowspan="2">Band
/GHz</th><th rowspan="2">BW
/MHz</th><th rowspan="2">Power
|dBm</th><th colspan="4">Channel, Frequency (MHz)
(DC)</th></tr>
<tr><th>Low</th><th colspan="3">High</th></tr>
<tr><td>802.11n</td><td>2.4</td><td>20</td><td>17</td><td>1
2412
(0.88)</td><td>12
2467
(0.99)</td><td>12
2467
(0.98)</td><td>12
2467
(0.88)</td></tr>
<tr><td>802.11n</td><td>2.4</td><td>40</td><td>17</td><td>1
2412
(0.83)</td><td>12
2467
(0.98)</td><td>12
2467
(0.96)</td><td>12
2467
(0.83)</td></tr>
<tr><td>802.11n</td><td>5</td><td>20</td><td>20</td><td>36
5180
(0.88)</td><td>-</td><td>-</td><td>140
5700
(0.88)</td></tr>
<tr><td>802.11n</td><td>5</td><td>40</td><td>20</td><td>36
5180
(0.83)</td><td>-</td><td>-</td><td>136
5680
(0.83)</td></tr>
<tr><td>802.11ac</td><td>5</td><td>80</td><td>20</td><td>36
5180
(0.79)</td><td>-</td><td>-</td><td>136
5680
(0.79)</td></tr>
<tr><td></td><td></td><td></td><td></td><td>64-QAM</td><td>BPSK
(NSS = 1)</td><td>BPSK</td><td>64-QAM</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="4">Modulation</td></tr>
</table>

Table 11: Test modes for the WAP. NSS = 2 unless otherwise specified.

5.3 Test Procedures

Before the SAR measurements were performed, the system was verified according to IEC 62209-2 [10] the measured values were confirmed to lie within the $\kappa = 1$ measurement uncertainty of 12.4 % (see Section 5.4) compared to calibrated target.

5.3.1 Tablet

In a first step, the worst-case positions were determined by measuring all orientations: the four edges, the front (screen), and the back (cover), as shown in Figure 3 a. These measurements were concucted at 2.4 GHz, IEEE 802.11n, 20 MHz bandwidth, BPSK Modulation and are shown in Table 13. The worst-case position found is the front screen (Figure 3 c), followed by the top edge (Figure 3 b). In all subsequent measurements, only these two positions were measured. Similarly, previous measurements for comparable cases that showed significantly reduced SAR were omitted. For instance, the lower frequency channels were typically much lower in SAR, as was (to a lesser extent) 64-QAM compared to BPSK, which is why these measurements were skipped in some cases (Table 10). Since the location of the antennas is the same for operation in the 2.4 GHz and 5 GHz bands, the worst-case position was validated only in the 2.4 GHz band.

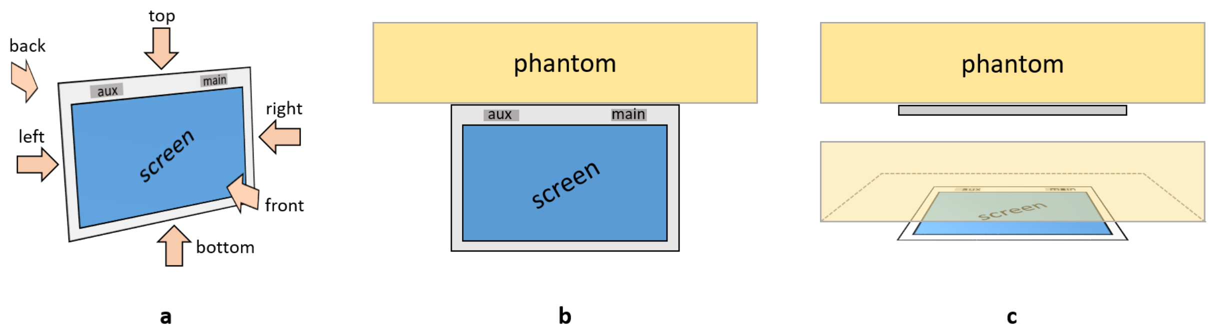

Figure 3: The geometry and positions of the tablet (showing the main and auxiliary (aux) antennas at the top of the screen), and the measured orientations, indicated by arrows, are shown in a. The two worst-case positions – the top edge and the front screen – are shown in detail in b and c, respectively.

5.3.2 Wireless Access Point

Due to the complex geometry of the WAP (three external, direction-adjustable antennas for the 5 GHz range and three internal antennas for the 2.4 GHz range), a fast SAR system (cSAR3D QUAD) was used to determine the worst-case positions (see Figure 4). These were found to be the top face (Figure 4 b) at 2.4 GHz and, at 5 GHz, in touch with the external antennas angled at 90° (Figure 4 d). In addition, the cSAR3D QUAD system was used to confirm that the highest SAR is observed during operation with multiple antennas enabled, where the highest output power is achieved.

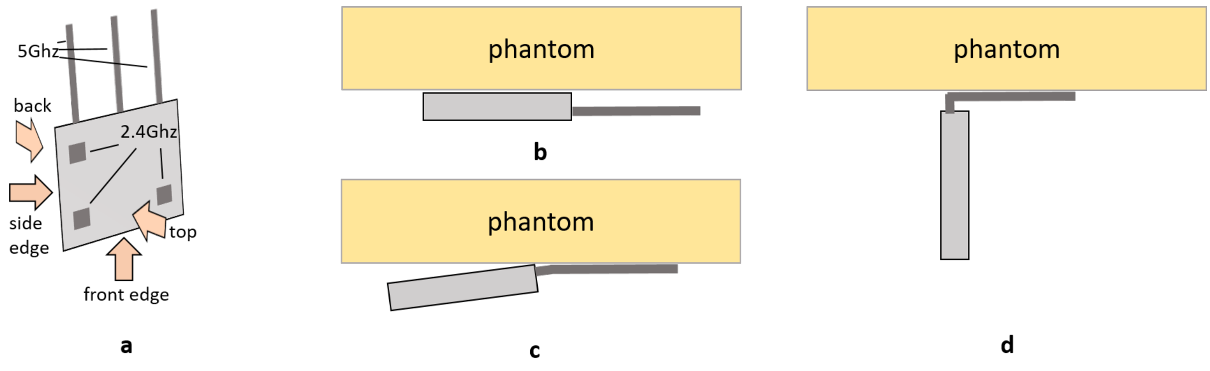

Figure 4: The geometry of the WAP (showing three internal antennas for 2.4 GHz operation and three external antennas for 5 GHz) and the measured orientations at 2.4 GHz depicted with arrows, are shown in a. The worst-case position at 2.4 GHz is shown in b. At 5 GHz, two positions with the external antennas in contact with the phantom were measured: one with the antenna flush against the phantom shown in c, and the other with the antenna angled at 90°, which is the worst case, depicted in d.

5.4 Measurement Uncertainty

The uncertainty budgets for 1 g and 10 g peak spatial average SAR (Table 12) were determined for the DASY6 measurement system according to clause 7 of IEC 62209-2 Ed.1. The expanded uncertainty ($\kappa = 2$) assessed for 10 g average SAR was ± 0.97 dB.

DASY6 Uncertainty Budget
According to IEC 62209-2 Ed.1 [10]
0.03 – 6 GHz range

Error Description	Uncertainty Value	Prob. Dist.	Div.	(c_i) 1 g	(c_i) 10 g	Std. Unc. (1 g)	Std. Unc. (10 g)	(v_i) v_{eff}
Measurement System								
Probe Calibration	± 6.55%	N	1	1	1	± 6.55%	± 6.55%	∞
Axial Isotropy	± 4.7%	R	$\sqrt{3}$	0.7	0.7	± 1.9%	± 1.9%	∞
Hemispherical Isotropy	± 9.6%	R	$\sqrt{3}$	0.7	0.7	± 3.9%	± 3.9%	∞
Boundary Effects	± 1.0%	R	$\sqrt{3}$	1	1	± 0.6%	± 0.6%	∞
Linearity	± 4.7%	R	$\sqrt{3}$	1	1	± 2.7%	± 2.7%	∞
System Detection Limits	± 1.0%	R	$\sqrt{3}$	1	1	± 0.6%	± 0.6%	∞
Modulation Response	± 2.4%	R	$\sqrt{3}$	1	1	± 1.4%	± 1.4%	∞
Readout Electronics	± 0.3%	N	1	1	1	± 0.3%	± 0.3%	∞
Response Time	± 0.8%	R	$\sqrt{3}$	1	1	± 0.5%	± 0.5%	∞
Integration Time	± 2.6%	R	$\sqrt{3}$	1	1	± 1.5%	± 1.5%	∞
RF Ambient Conditions	± 3.0%	R	$\sqrt{3}$	1	1	± 1.7%	± 1.7%	∞
RF Ambient Reflections	± 3.0%	R	$\sqrt{3}$	1	1	± 1.7%	± 1.7%	∞
Probe Positioner Mech. Restr.	± 0.02%	R	$\sqrt{3}$	1	1	± 0.0%	± 0.0%	∞
Probe Positioning	± 0.4%	R	$\sqrt{3}$	1	1	± 0.2%	± 0.2%	∞
Spatial x-y Resolution	± 10.0%	R	$\sqrt{3}$	1	1	± 5.8%	± 5.8%	∞
Fast SAR z-Approximation	± 7.0%	R	$\sqrt{3}$	1	1	± 4.0%	± 4.0%	∞
Test Sample Related								
Test Sample Positioning	± 2.9%	N	1	1	1	± 2.9%	± 2.9%	145
Device Holder Uncertainty	± 3.6%	N	1	1	1	± 3.6%	± 3.6%	5
Drift of Output Power	± 5.0%	R	$\sqrt{3}$	1	1	± 2.9%	± 2.9%	∞
Power Scaling	± 0%	R	$\sqrt{3}$	0	0			
Phantom and Setup								
Phantom Uncertainty	± 6.1%	R	$\sqrt{3}$	1	1	± 3.5%	± 3.5%	∞
SAR correction	± 1.9%	R	$\sqrt{3}$	1	0.84	± 1.1%	± 0.9%	∞
Liquid Conductivity (meas.)	± 2.5%	N	1	0.78	0.71	± 1.1%	± 1.0%	∞
Liquid Permittivity (meas.)	± 2.5%	N	1	0.23	0.26	± 0.3%	± 0.4%	∞
Temp. Unc.-Conductivity	± 3.4%	R	$\sqrt{3}$	0.78	0.71	± 1.5%	± 1.4%	∞
Temp. Unc.-Permittivity	± 0.4%	R	$\sqrt{3}$	0.23	0.26	± 0.1%	± 0.1%	∞
Combined Std. Uncertainty						± 12.5%	± 12.4%	748
Expanded Uncertainty ($\kappa = 2$)						**± 24.9%**	**± 24.9%**	
						± 0.97 dB	**± 0.97 dB**	

Table 12: Uncertainty budget for DASY6, assessed according to IEC 62209-2 Ed.1

6 SAR Test Results

6.1 Tablet

Table 13 shows the SAR values for different positions of the tablet. Based on these results, the positions at the front screen and top edge were chosen for the subsequent measurements. The top edge showed consistently lower SAR values than the front screen. For simplicity, only results of the front screen position are reported below. The SAR measurements corresponding to the test modes (see Table 10) are shown in Table 14. To make a comparison between the transmission modes without the bias due to the different DCs, an up-scaled SAR value was calculated, corresponding to 100 % DC (shown in brackets). In practice, such high DCs do however not occur, due to the frame structure of IEEE 802.11 (very large frame sizes would be required for some transmission modes to approach 99% DC). The worst-case scenarios, remeasured for the three configurations of the antennas (with only the main antenna active, only the auxiliary antenna active, or both active), are listed in Table 15. The mode with both antennas active resulted in the highest SAR, for which an example SAR distribution is shown in Figure 5.

Standard IEEE	Band (GHz)	BW (MHz)	CH	Modulation	Position	SAR 10 g (W/Kg)
802.11n	5	20	165	BPSK	front screen	0.565
					back cover	0.151
					top edge	0.233
					bottom edge	0.008
					left edge	0.024
					right edge	0.059

Table 13: The SAR measurements of the tablet used determine the worst-case positions.

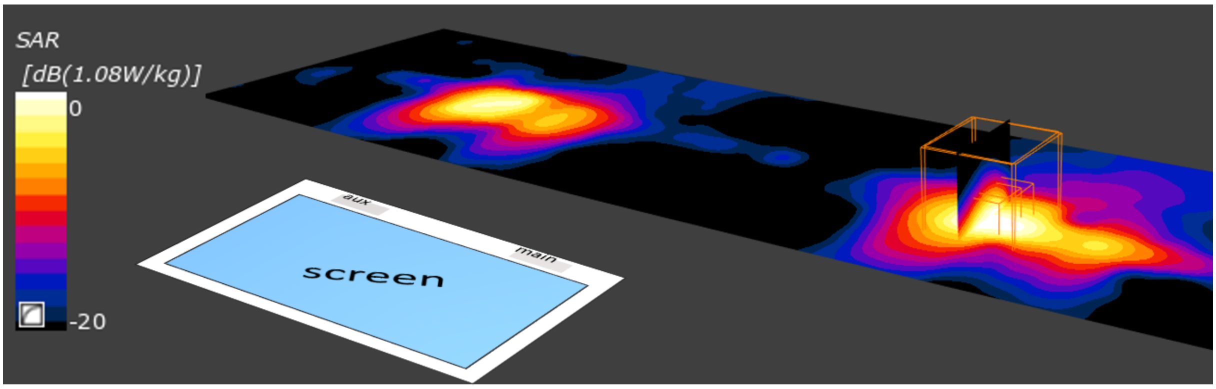

Figure 5: The SAR plot of the tablet, with both antennas active, front screen position. The SAR in the horizontal plane closest to the device is shown. A small sketch of the device is included, showing its orientation with respect to the plot. The nested outlined cubes represent the 1 g and 10 g averaging volumes. Also shown is the SAR on a vertical cut through the cube.

Standard IEEE	Band (GHz)	BW (MHz)	Channels: Low		Mid		High		
			BPSK	64-QAM	BPSK	64-QAM	BPSK	64-QAM	
802.11n	2.4	20	0.312 (0.315)	-	0.336 (0.339)	-	0.343 (0.346)	0.332 (0.361)	SAR 10 g (W/Kg)
802.11n	2.4	40	-	-	-	-	0.344 (0.351)	0.307 (0.349)	SAR 10 g (W/Kg)
802.11n	5	20	0.217 (0.219)	-	0.403 (0.407)	0.396 (0.430)	0.565 (0.570)	0.566 (0.615)	SAR 10 g (W/Kg)
802.11n	5	40	-	-	0.470 (0.480)	0.409 (0.465)	0.540 (0.551)	0.488 (0.555)	SAR 10 g (W/Kg)
802.11ac	5	80	0.260 (0.271)	-	0.442 (0.460)	-	0.454 (0.473)	0.374 (0.468)	SAR 10 g (W/Kg)
			Modulation						

Table 14: The SAR measurements of the tablet for the front screen position. The value in brackets is the SAR scaled to 100% DC.

Standard IEEE	Band (GHz)	BW (MHz)	CH	Modulation	DC	SAR 10 g (W/Kg)		
802.11n	2.4	20	13	BPSK	0.99	0.253 (0.256)	0.365 (0.369)	0.398 (0.402)
802.11n	2.4	40	11	BPSK	0.98	0.264 (0.269)	0.344 (0.351)	0.347 (0.354)
802.11n	5	20	165	BPSK	0.99	0.502 (0.507)	0.643 (0.649)	0.697 (0.704)
802.11n	5	40	159	BPSK	0.98	0.465 (0.474)	0.58 (0.592)	0.598 (0.610)
802.11ac	5	80	155	BPSK	0.96	0.411 (0.428)	0.497 (0.518)	0.511 (0.532)
						aux	main	both
						Antennas		

Table 15: The SAR measurements for worst-case configurations of the tablet (see Table 10), including the auxiliary antenna, front screen position. The value in brackets is the SAR scaled to 100% DC.

6.2 Wireless Access Point

The SAR measurements for different positions of the WAP are shown in Table 16. The worst-case positions are in contact with the top face at 2.4 GHz and in contact with the external antennas, angled at 90°), at 5 GHz. The SAR measurements for various antenna configurations are shown in Table 17. Note that a ‘1’ in the antenna setting does not guarantee that the antenna is indeed transmitting. Rather, this indicates that the driver is free to use this antenna. At 2.4 GHz, for instance, typically all available antennas (i.e., those set to ‘1’) were transmitting. At 5 GHz, in contrast, only two antennas were actually transmitting in most cases, even when all three were available. Examples of plots of the SAR distribution that illustrate the case are shown in Figure 6. Note also that the number of transmitting antennas may be different from the number of spatial streams (NSS) used for MIMO. (A typical case is the use of all three antennas for transmission, even when the WAP was configured in single-input single-output (SISO) mode, with NSS = 1, whereby all antennas transmit the same signal.)
Although the SISO case (NSS = 1) at antenna setting (1,1,1) was slightly higher in SAR compared to the MIMO case (NSS = 2), the (unrestricted) MIMO case was used in further measurements. This choice is due to limitations in the WAP driver, which does not allow configuration of the NSS in all operation modes. Table 18 shows the SAR measurements according to the test modes in Table 11. The measurements were carried out in the corresponding worst-case position and with no restriction on the antenna setting. As for the tablet, an up-scaled SAR value (shown in brackets), corresponding to 100 % DC, is calculated.

Standard IEEE	Band (GHz)	BW (MHz)	CH	Power (dBm)	Position	SAR 10g (W/Kg)
802.11n	2.4	20	1	17	top face	0.129
					bottom face	0.036
					side edge	0.061
					front edge	0.037
802.11n	5	20	36	20	flat	0.074
					90°	0.081
802.11ac	5	80	36	20	flat	0.057
					90°	0.061

Table 16: Preliminary fast SAR measurements of the WAP to determine the worst-case position, with modulation 64-QAM in all cases.

Standard IEEE	Band (GHz)	BW (MHz)	CH	Position	Power (dBm)	NSS	Antenna Setting	SAR 10 g (W/Kg)
802.11n	2.4	20	1	top face	12	1	0, 0, 1	0.12
					15	1	0, 1, 1	0.121
					17	1	1, 1, 1	0.193
					17	2	1, 1, 1	0.182
802.11n	5	20	36	90°	20	1	0, 0, 1	0.069
					20	1	0, 1, 1	0.081
					20	2	1, 1, 1	0.081

Table 17: Preliminary fast SAR measurement of the WAP to determine the worst-case antenna setting, with modulation 64-QAM in all cases. The antenna setting determines which antennas are available for transmission (1) and which are switched off (0). There is no guarantee, however, that the specific antenna is indeed transmitting.

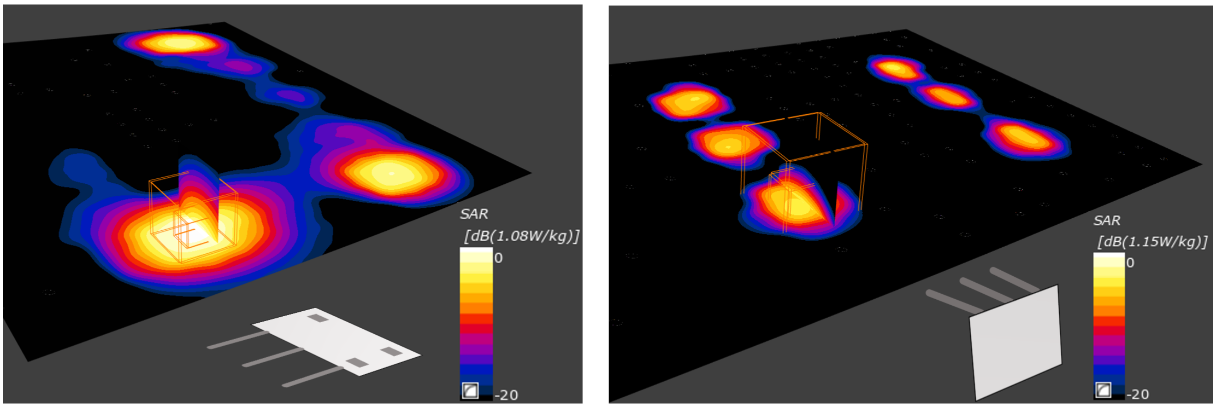

Figure 6: The SAR plots of the WAP, showing the SAR in the horizontal plane closest to the device. A small sketch of the device is included, showing its orientation with respect to the plot. The outlined cubes represent the 1 g and 10 g averaging volumes. Also shown is the SAR on a vertical cut through the cube. Left panel: the 2.4 GHz range, where three internal antennas are active. Right panel: the 5 GHz range, where the two external antennas are active.

Standard IEEE	Band (GHz)	BW (MHz)	Power (dBm)	Channels: Low	Channels: High			
				SAR 10 g (W/Kg)				
802.11n	2.4	20	17	0.242 (0.275)	0.248 (0.251)	0.236 (0.241)	0.251 (0.285)	
802.11n	2.4	40	17	0.223 (0.269)	0.256 (0.261)	0.254 (0.265)	0.241 (0.290)	
802.11n	5	20	20	0.068 (0.077)	-	-	0.095 (0.108)	
802.11n	5	40	20	0.060 (0.072)	-	-	0.096 (0.116)	
802.11ac	5	80	20	0.067 (0.085)	-	-	0.070 (0.089)	
			Modulation	64-QAM	BPSK (NSS=1)	BPSK	64-QAM	

Table 18: The SAR measurements of the WAP for the worst-case position, according to the test modes in Table 11. NSS = 2 if not otherwise specified. The value in parentheses is the SAR scaled to 100% DC.

7 Discussion

7.1 Tablet

Regarding the position of the tablet, the highest SAR is observed when the antennas are closest to the phantom. The front screen position produced the highest SAR, followed by the top edge position, the SAR of which was about half as high (Table 13). The SAR due to the main antenna is higher compared to that of the auxiliary antenna, whether only one antenna is active or both antennas are simultaneously active (Table 15). Interestingly, the highest SAR is achieved when both antennas are transmitting, although there is no significant spatial overlap between the SAR patterns of the two antennas (Figure 5). A probable explanation is that higher power is allowed by the tablet's wireless driver for this case.
Further, there is a trend for higher SAR with increasing frequency within the same band (Table 14), which may be explained by the frequency dependent absorption of the material. In the 5 GHz band, this trend is more clearly visible, since the frequency range is much larger than in the 2.4 GHz band. The channel bandwidth also impacts the SAR, showing a lower SAR with increasing bandwidth in most cases. In contrast, the modulation has little influence on the SAR. The SAR for BPSK modulation is typically somewhat higher than for 64-QAM, however, this trend is weak and also dependent on the DC. The SAR scaled to 100% DC shows the opposite behavior, such that no clear conclusion can be drawn regarding the influence of the modulation.

7.2 Wireless Access Point

For the tablet, the positions with the highest SAR are those where the distance between phantom and antennas is minimized. Since the antennas for the 2.4 GHz and 5 GHz bands are in different locations, the worst-case positions (Figure 4) are different for the two bands (Table 16). The SAR pattern also depends on the antenna type: the external 5 GHz antennas exhibit three maxima per antenna, compared to only one peak per internal 2.4 GHz antenna (Figure 6). The SAR in the 5 GHz bands is less than half of the values in the 2.4 GHz bands, which can probably be largely attributed to the different geometrical configurations and antenna types. As in the case of the tablet, operation with all antennas active generates the highest SAR (Table 17) (despite negligible spatial overlap between the SAR patterns of the different antennas), which seems to be due to internal power management of the wireless driver.
The trend toward higher SAR values with increased frequency within each band is confirmed also for the WAP (Table 18). The modulation has again little influence on the SAR, although, note that the SAR scaled to 100% DC, shows higher values for 64-QAM compared to BPSK. However, only a small number of cases, for which the different modulations could be directly compared, were measured. The same is true for the case of different NSS, where no definite conclusion can be drawn.

8 Conclusions

The maximum measured SAR values for both devices – the tablet and the WAP – and for each band are shown in Table 19. The main factors that influence SAR values in these devices were found to be the following: the geometrical configuration (i.e., the distance between the phantom and the antenna), the number of antennas selected, and, to a lesser extent, the frequency, as well as the channel bandwidth. It should be noted that WLAN-capable devices can implement IEEE 802.11 communication in widely different ways, e.g., the limitations on output power per band, bandwidth, and modulation may be different. Thus, the measurement results cannot be generalized to other devices. The tablet exhibited the higher SAR values, despite lower output power, due to the small distance between the antenna and the phantom. In summary, the maximum SAR values from the IEEE 802.11n/ac devices measured in this study are in the same range as those found in [1, 2] for older generations of the IEEE 802.11 standard.

Band (GHz)	BW (MHz)	Channel Freq. (MHz)	Mod. (DC)	Power (dBm)	Position	Antennas Transmitting	SAR 10 g (W/Kg)
Tablet							
2.4	20	13 2472	BPSK (0.99)	14.5	Front screen	main, aux	0.398
5	20	165 5825	BPSK (0.99)	14.5	Front screen	main, aux	0.697
Wireless Access Point							
2.4	40	12 2467	BPSK (0.98)	17	Top face	3 out of 3 (NSS=1)	0.256
5	40	136 5680	64-QAM (0.83)	20	90°	2 out of 3 (NSS=2)	0.096

Table 19: Maximum measured SAR for both devices in each band. For all cases, IEEE 802.11n applies, and all antennas were configured as active.

Sven Kühn , 14 December 2017

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