Mobile Phone Antenna Performance 2023

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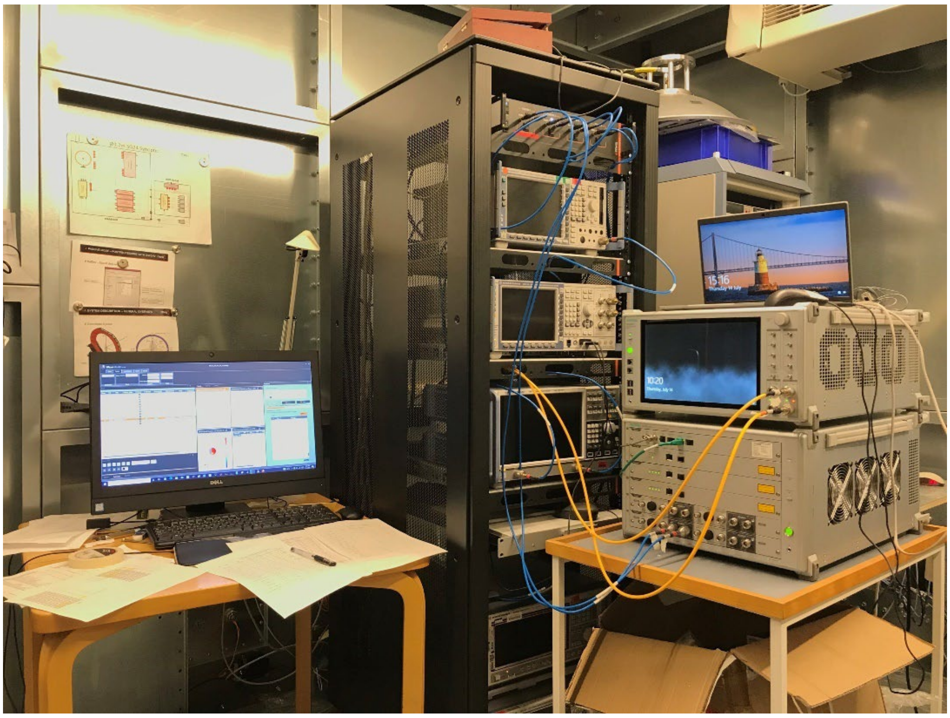

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Conclusions

The communication performance of a mobile phone is crucial to how well it functions in the network, such as whether or not the phone can be used in areas with limited network coverage. Based on standardized measurements, the current report studies the performance of the 18 most popular new phones in Denmark in 2022.

For voice mode, the low frequency band (LTE700) is considered the most important for ensuring the user good network coverage, e.g., for emergency calls. In this band the variation among the phones is 5-6 dB, which is smaller than in the previous studies. However, it has earlier been demonstrated that a 7 dB variation in phone performance can result in a largely reduced coverage [Erst12], so the variation observed in the current study is still important. Generally, a very large variation in the communication performance was found among the tested mobile phones in the different bands. Up to 14 dB variation was seen (Table 3) which is similar to that found in previous studies [Ped12, Ped13, Ped16, Ped18].

It is also noteworthy that for several phones, the voice mode performance depends strongly on which side of the head the phone is used. Up to 7 dB variation in the LTE bands (Samsung Galaxy S22+) and up to 10 dB for the NR band (Xiaomi Redmi Note 11 Pro) was measured.

For data mode, the variation among the phones is 4-6 dB, depending on the band and which hand is used, and thus a smaller variation than for voice mode. It is also smaller than what was found in the earlier study [Ped18] where up to 10 dB difference was observed.

Although the performance of the phones depends on the usage, a few phones stands out. For voice mode the Sony Xperia 5 III phone is the best ranking in 3 of the 4 LTE bands and within 1.6 dB of the best phone in the last band. For data mode use, OnePlus 10 Pro is the best in 2 of the 4 LTE bands and within 2.5 dB of the best in the remaining 2 LTE bands. In the bottom of the ranking the Samsung Galaxy S22+ has overall worse performance for voice and the iPhone14 has the overall worse performance for data service.

Compared to the 2018 study [Ped18], the present study introduces measurements for 5G mobile phones. The performance in this system varies among the phones similarly to what was found for the LTE bands.

Given the large variation in performance it is recommended that the manufacturers make the test results for each phone publicly available to guide the consumers when buying mobile phones.

Introduction

This study investigates the antenna performance of some of the most widely used mobile phones in Denmark in 2022. The communication performance varies for each kind of mobile phone, and the antenna performance of a phone is vital for its ability to ensure radio coverage in low signal situations. The study is based on the mobile systems in Denmark and on both voice and data services including both 4G Long Term Evolution (LTE) and 5G New Radio (NR). The selected phone models are the most popular new phones at the time of this study. Although it was not yet available when the main study took place, a limited study of the iPhone 14 is also included in the final report.

The radio coverage for a phone depends on the available signal from the antenna mast and on the phone's ability to collect this signal. This ability is strongly influenced by the antenna in the phone and by the way the user holds the phone close to the head during a voice call [Pel09] or away from the head in browsing mode. If the phone is not handheld but is instead in a hands-free installation or connected to a headset, the phone itself may for example be placed in so-called free-space mode, where no objects are near the phone. In such case the ability to collect a radio signal is typically very different and generally better than for the handheld case.

The present study is a follow-up on similar studies conducted in 2012, 2013, 2016 and 2018 on phone models common in the market at that time [Ped12, Ped13, Ped16, Ped18]. The aim of the earlier studies was to establish the field strength calculations for mobile telephony and to set the minimum field strength needed to ensure coverage, see appendix II. Besides, the earlier studies also measure the phones' ability to transmit (for voice mode) and receive (for data mode) in 4G service and below. The new study described in this report investigates 5G mobile phones in the market, and also considers the position of the phone with respect to the head in voice mode and to the hand in data mode. The phones are measured in the 4G bands LTE700, LTE900, LTE1800, LTE2100 and the 5G NR TD3500 band.

In order to ensure a connection between the mobile phone and the base station, a sufficiently strong link is needed both from the phone to the base station (the phone is transmitting and the base station is receiving) and from the base station to the mobile phone (the base station is transmitting and the mobile phone is receiving). The weakest link determines the quality of the connection/service. For voice services, the weakest link is typically the one from the mobile phone to the base station, called "uplink" by mobile network operators, see Figure 1. The mobile phone has less resources than the base station and will be the limiting factor, e.g. in areas relatively far away from the nearest base station. Therefore, the antenna performance is crucial in such areas. For data services, the weakest link is typically the one from the base station to the mobile phone, called "downlink" by mobile network operators. A weak downlink can often be compensated for by the base station sending a stronger signal. However, this is an undesirable solution from the network point of view and ultimately also for the individual user. For the reasons mentioned, the current study focuses on the *transmitter* performance for voice services and the *receiver* performance for data services, as these are the crucial links in weak radio signal conditions.

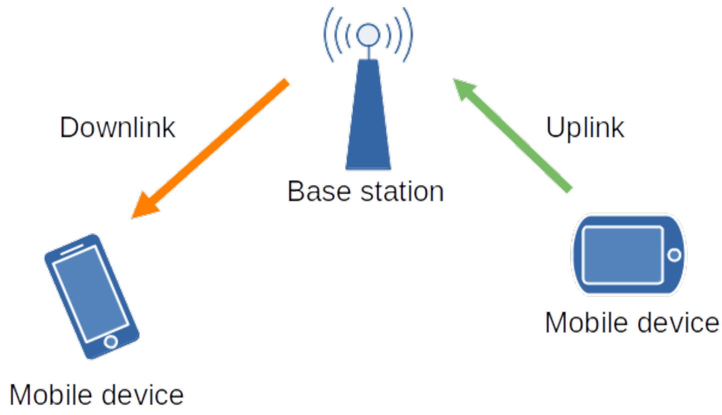

Figure 1. Uplink and downlink transmission in the mobile network.

The present study is focused on the antenna test, even though the test includes more than the antenna itself. The transmitter and receiver electronics is also involved in the tests, but the electronics must fulfil mandatory limits during manufacturing, e.g., for the transmitted power, as given by e.g. the 4G LTE and 5G NR specifications [ETSI-1]. Therefore, the differences in the design of the antennas are the reason for the significant performance variation among phones.

As 5G matures, now is the time for its large-scale deployments and commercialization. The 5G new radio (NR) system is now implemented in so-called non-standalone mode. There are two types of 5G, i.e. non-standalone (NSA) and standalone (SA). The main difference between NSA and SA is that NSA anchors the control signalling of 5G radio networks to the 4G core, while the SA scheme connects the 5G radio directly to the 5G core network, and the control signalling does not depend on the 4G network at all. As the name suggests, the NSA is a 5G service that does not "stand alone" but is built over an existing 4G network. Therefore, an NSA architecture enables the mobile network operators to leverage their existing network investments in transport and mobile core — rather than deploy a completely new end-to-end standalone 5G network.

Test Procedure

The receiver performance is evaluated in terms of the so-called Total Isotropic Sensitivity (TIS) for each frequency band. The lower the value of the TIS, the smaller the signal required by the phone for operation, i.e. phones with lower TIS are more able to receive in weaker signal areas. For the transmitter performance, the evaluation is in terms of the so-called Total Transmitted Power (TRP). The higher the TRP, the stronger signal at the base station is delivered by the phone, and the better the connection. The tests conducted in the study are based on the agreed standard test procedures for mobile phones, created by the Cellular Telecommunications Industry Association (CTIA) [CTIA18] with a few exceptions [Ped18].

To limit the number of tests on each phone, only the frequency bands used in Denmark (and generally in Europe) are measured and only the centre channel is studied, as a representative of the band. Further, the following usage scenarios are investigated:

- Voice mode with phone next to the left-hand side of the head phantom placed in a left-hand phantom, see Figure 2 (beside head hand left – BHHL).
- Voice mode with the phone next to the right-hand side of the head phantom placed in the right-hand phantom, see Figure 3 (beside head hand right – BHHR).
- Data mode with phone placed in the right-hand phantom (RH), see Figure 4.
- Data mode with phone placed in the left-hand phantom (LH), see Figure 5.
- Voice and data mode with phone placed in free space (FS), for both receive and transmit directions. Free space is the case with no phantom hand or head present, see Figure 6.

All phantoms are as specified in the CTIA test plan [CTIA18] and made by Speag AG.

By comparing the results obtained with and without the phantom hand/head, the robustness of the antenna to the user's influence can be seen. The difference in the performance with the phantom hand/head present and in free space is often called the body loss.

The test procedure for 4G LTE measurements is the same as the earlier study in 2018 [Ped18]. First a connection is established, and a request is made for the phone to transmit with maximum power for TRP or, for a TIS measurement, a signal is sent with gradually reduced power (iterative process) until a certain level of error is reached.

The test on the iPhone14 was only made at 4G bands as the iPhone14 was not launched at the time of the main measurement were the 5G test equipment were available.

The test procedure for 5G NR measurements is different and new. Two extra pieces of communication equipment (see appendix I) and one more antenna probe are used to perform the measurements. First an LTE connection is established followed by a switch to the NR band. In our 5G measurement, the NSA mode is deployed due to the lack of an end-to-end standalone 5G network. As a 5G test is not standardized by CTIA currently, the results for 5G are provided as informative data.

Figure 2: Voice mode with phone next to the left-hand side of the head phantom placed in A left-hand phantom (beside head hand left – BHHL).

Figure 3: Voice mode with the phone next to the right-hand side of the head phantom placed in the right-hand phantom (beside head hand right – BHHR).

Figure 4: Data mode with phone placed in the right-hand phantom (RH).

Figure 5: Data mode with phone placed in the left-hand phantom (LH).

Figure 6: Voice and data mode with phone placed in free space (FS).

Mobile phones tested

The phone models tested are listed in Table 1. The list was provided by the Danish Agency for Data Supply and Infrastructure based on lists from Teleindustrien and the newsletter website MereMobil.dk.

Device	Phone model
1	iPhone SE
2	iPhone 12
3	iPhone 12 mini
4	iPhone 12 pro
5	iPhone 13
6	iPhone 13 mini
7	iPhone 13 Pro

8	iPhone 13 Pro Max
9	Samsung Galaxy S22
10	Samsung Galaxy S22+
11	Samsung Galaxy S22 Ultra
12	Motorola Edge 30 Pro
13	Nokia G50
14	Sony Xperia 5 III
15	Xiaomi 12
16	OnePlus 10 Pro
17	Xiaomi Redmi Note 11 Pro
18	iPhone 14

Table 1: List of all tested phones. The list is provided by the Agency for Data Supply and Infrastructure.

Results for Handheld Case

All the values of measured receiver sensitivities (TIS) and transmitter powers (TRP) are listed in Table 2-5. The values are averages over all directions and both polarisations, as defined for the so-called Total Isotropic Sensitivity (TIS) for receivers and Total Radiated Powers (TRP) for transmitters, defined in, e.g., the CTIA test plan [CTIA18]. The values are in logarithmic scale, as customary for these measurements, and given in dBm values (dB above 1 mW).

Low values are desirable for the TIS and the best phones have the most negative value in dB. A low TIS value means that only a weak received signal is necessary at the mobile for a successful connection.

High values are desirable for the TRP and the best phones have the most positive value in dB. A high TRP value indicates a strong signal delivered at the base station.

For data services TIS is measured, and a bandwidth of 10 MHz is used for LTE700, LTE900, LTE1800 and LTE2100, and a bandwidth of 100 MHz is used for TD3500.

In all the tables each row presents the results for a single phone, where the rows have been sorted according to the LTE700 results, so that the best performing phones in this respect are at the top and the worst at the bottom. Among the considered frequency bands, LTE700 is the lowest and generally allows for the largest distances between the mobile phone and a serving base station. Therefore, the LTE700 band is considered the most critical for successful network access in areas where network coverage might be limited, e.g., in areas where the nearest base station is far away. In other areas or for other uses the remaining bands may be more important. To ease reading of the tables, the best result is marked with green color and the worst result with orange color, for each band / column.

Voice mode: TRP values (dBm), BHHR						
Rank	**Phone model**	**LTE700**	**LTE900**	**LTE180**	**LTE210**	**TD3500**

				0	0	
1	OnePlus 10 Pro	**11.97**	8.89	11.10	11.24	**6.44**
2	iPhone 13 Pro	11.56	9.15	5.67	10.17	14.26
3	iPhone 12 mini	11.11	8.47	5.77	4.81	12.35
4	iPhone 13	11.11	7.88	5.58	7.01	16.09
5	Sony Xperia 5 III	10.34	**11.13**	**13.59**	**12.50**	9.12
6	iPhone 12 pro	10.20	7.19	**1.94**	**2.22**	12.44
7	Xiaomi Redmi Note 11 Pro	9.69	8.89	6.45	2.28	13.77
8	iPhone 13 mini	9.60	6.35	6.75	5.16	7.95
9	iPhone SE	9.58	9.04	9.39	9.59	10.36
10	iPhone 12	9.54	7.39	4.23	2.61	16.04
11	Samsung Galaxy S22 Ultra	9.10	8.27	5.54	5.15	14.87
12	Xiaomi 12	9.06	9.92	9.79	7.24	7.44
13	iPhone 14	7.64	8.83	2.47	4.38	-
14	iPhone 13 Pro Max	7.58	9.23	9.72	9.75	12.55
15	Nokia G50	6.92	6.31	13.27	10.72	16.85
16	Samsung Galaxy S22	6.50	7.68	8.88	6.66	12.45
17	Motorola Edge 30 Pro	5.90	6.06	7.94	7.42	**17.22**
18	Samsung Galaxy S22+	**5.57**	**5.25**	11.98	11.61	14.70

Table 2. Measured BHHR performance of all phones sorted from the best performing (phone rank 1) to the worst performing (phone rank 17) according to LTE700 results. Measurements according to the CTIA specifications for voice mode in right hand, labelled as BHHR [CTIA18].

Voice mode: TRP values (dBm), BHHL						
Rank	**Phone model**	**LTE700**	**LTE900**	**LTE180**	**LTE210**	**TD3500**
1	Sony Xperia 5 III	**11.12**	**11.38**	**14.15**	13.33	10.79
2	Samsung Galaxy S22	8.94	7.84	9.62	7.19	15.22
3	OnePlus 10 Pro	8.19	5.00	10.84	11.07	6.95
4	iPhone 13 Pro Max	8.06	9.20	13.15	13.27	13.92
5	iPhone 12 pro	7.69	7.67	5.66	4.90	10.89
6	Motorola Edge 30 Pro	7.52	6.34	11.35	10.90	**17.88**
7	iPhone 12 mini	7.43	6.86	6.30	**4.10**	8.59
8	iPhone 14	7.43	9.34	9.62	10.67	-
9	iPhone SE	7.33	**4.75**	12.77	**13.98**	11.02
10	iPhone 13 Pro	7.33	8.16	13.25	12.88	10.98
11	iPhone 12	7.28	8.02	**4.70**	4.19	12.07
12	Xiaomi 12	7.19	8.18	10.85	9.44	11.13
13	Nokia G50	6.92	7.94	5.86	6.92	16.99
14	Samsung Galaxy S22 Ultra	6.67	7.88	9.16	7.13	14.40
15	Samsung Galaxy S22+	6.62	6.16	4.88	4.69	14.27
16	iPhone 13	6.1	8.28	8.00	8.00	12.29
17	Xiaomi Redmi Note 11 Pro	6.01	9.27	6.54	5.51	**4.12**
18	iPhone 13 mini	**5.82**	6.45	11.99	11.63	15.03

Table 3. Measured BHHL performance of all phones sorted from the best performing (rank 1) to the worst performing (rank 17) according to LTE700 results. Measurements according to the CTIA specifications for voice mode in left hand, labelled as BHHL [CTIA18].

Data mode: TIS values (dBm), Right Hand (RH)						
Rank	**Phone model**	**LTE700**	**LTE900**	**LTE180**	**LTE210**	**TD3500**
1	iPhone 13	**-91.32**	-90.80	-93.42	-92.24	-82.99
2	iPhone 13 Pro	-90.76	-90.27	-93.67	-93.37	-82.19
3	Motorola Edge 30 Pro	-90.53	-90.30	-93.93	-94.49	-84.61
4	OnePlus 10 Pro	-90.53	-89.45	**-96.42**	**-95.52**	**-84.98**
5	iPhone SE	-90.42	-91.07	-92.47	-91.56	-79.85
6	Samsung Galaxy S22 Ultra	-90.36	-91.85	-93.71	-92.51	-83.09
7	Sony Xperia 5 III	-90.25	-90.26	-92.00	-92.29	**-79.17**
8	Samsung Galaxy S22	-89.95	**-91.98**	-94.02	-94.20	-82.86
9	Xiaomi 12	-89.88	-91.74	-95.27	-93.78	-81.89
10	iPhone 12 mini	-89.68	-88.13	-92.09	-93.04	-80.97
11	Samsung Galaxy S22+	-89.12	-91.19	-94.40	-95.14	-84.26
12	iPhone 12 pro	-88.86	-88.89	-93.41	-92.36	-81.81
13	iPhone 12	-88.63	-89.22	-93.66	-92.49	-82.50
14	iPhone 13 mini	-88.48	-87.39	-93.51	-92.72	-81.93
15	iPhone 14	-87.38	-88.07	**-91.62**	**-91.49**	-
16	iPhone 13 Pro Max	-86.41	**-87.37**	-92.80	-92.66	-83.34
17	Nokia G50	-86.24	-89.75	-95.43	-92.62	-81.40
18	Xiaomi Redmi Note 11 Pro	**-86.20**	-88.14	-93.71	-92.64	-83.69

Table 4. Measured RH performance of all phones sorted from the best performing (rank 1) to the worst performing (rank 17) according to LTE700 results. Measurements according to the CTIA specifications for data mode in right hand, labelled as RH [CTIA18].

Data mode: TIS values (dBm), Left Hand (LH)						
Rank	**Phone model**	**LTE700**	**LTE900**	**LTE180**	**LTE210**	**TD3500**
1	iPhone SE	**-90.89**	-91.02	-93.22	-92.16	**-79.22**
2	Motorola Edge 30 Pro	-90.53	-90.89	-94.18	-94.20	**-84.01**
3	Sony Xperia 5 III	-90.53	-90.75	-91.98	-92.95	-80.14
4	Samsung Galaxy S22	-89.46	-90.90	-93.16	-93.26	-83.02
5	Xiaomi 12	-89.36	-91.10	-95.08	-93.60	-83.50
6	Samsung Galaxy S22+	-89.13	-90.80	-93.86	-93.58	-81.92
7	Samsung Galaxy S22 Ultra	-89.04	**-91.72**	-93.82	-92.82	-82.65
8	iPhone 13 Pro Max	-88.85	-88.97	-92.63	-92.51	-82.83
9	OnePlus 10 Pro	-88.60	-89.19	**-95.53**	**-95.17**	-83.66
10	iPhone 13 Pro	-88.59	-88.36	-92.30	-91.81	-82.13
11	iPhone 12	-88.32	-89.63	-92.99	-92.19	-81.85
12	iPhone 13	-88.22	-89.06	-92.28	-92.28	-82.82
13	iPhone 12 pro	-88.06	-89.01	-92.34	-91.15	-80.99

14	iPhone 14	-87.37	-89.58	-91.53	**-90.72**	-
15	iPhone 13 mini	-87.07	-88.09	-92.45	-92.02	-82.82
16	Nokia G50	-86.63	-89.53	-94.89	-92.70	-81.35
17	iPhone 12 mini	-86.55	**-86.87**	**-90.70**	-92.32	-81.44
18	Xiaomi Redmi Note 11 Pro	**-86.35**	-88.94	-93.96	-93.01	-81.88

Table 5. Measured LH performance of all phones sorted from the best performing (rank 1) to the worst performing (rank 17) according to LTE700 results. Measurements according to the CTIA specifications for data mode in left hand, labelled as LH [CTIA18].

Results for Free Space Case

All phones are also measured with no hand or head present as a reference case. This represent the situation where the phone is placed free standing in e.g. a handsfree-kit or the alike and a wired or wireless connection is used between the user and the phone. The best performance is often obtained in this case.

Voice mode: TRP values (dBm), Free Space (FS)						
Rank	**Phone model**	**LTE700**	**LTE900**	**LTE180**	**LTE210**	**TD3500**
1	Motorola Edge 30 Pro	**16.83**	15.72	18.24	17.66	18.55
2	iPhone 14	16.70	15.89	11.75	17.04	-
3	Sony Xperia 5 III	16.51	**16.50**	18.10	**18.02**	14.74
4	Samsung Galaxy S22	16.42	14.55	18.12	16.53	17.09
5	Samsung Galaxy S22 Ultra	15.86	14.99	17.23	16.68	16.11
6	Samsung Galaxy S22+	15.5	15.09	17.13	13.22	16.63
7	Nokia G50	14.7	15.42	**18.96**	16.80	**18.63**
8	Xiaomi 12	14.66	15.23	18.75	17.98	16.33
9	iPhone 13	14.58	13.77	13.09	11.98	17.21
10	iPhone 13 Pro Max	13.82	12.99	11.04	14.73	16.43
11	iPhone 12 mini	13.78	13.46	15.38	12.06	12.56
12	iPhone 12	13.62	12.74	**8.78**	9.14	17.16
13	iPhone SE	13.5	15.54	15.77	16.08	12.80
14	iPhone 12 pro	13.4	11.94	9.30	**8.83**	15.37
15	Xiaomi Redmi Note 11 Pro	13.24	13.75	11.52	14.78	16.82
16	iPhone 13 Pro	11.89	13.90	11.45	12.02	15.29
17	iPhone 13 mini	11.88	12.07	13.27	11.74	16.63
18	OnePlus 10 Pro	**11.25**	**9.88**	15.44	15.39	**9.53**

Table 5. Measured performance of the phones' ability to transmit in free space (FS).

Data mode: TIS values (dBm), Free Space (FS)						
Rank	**Phone model**	**LTE700**	**LTE900**	**LTE180**	**LTE210**	**TD3500**
1	iPhone SE	**-96.50**	**-96.13**	-95.33	-94.48	-81.87
2	iPhone 13 Pro	-94.25	-91.71	-95.03	-95.15	-82.62
3	iPhone 12	-93.83	-92.42	-95.81	-94.89	-84.17

4	iPhone 12 pro	-93.68	-91.99	-95.63	**-94.42**	-83.16
5	iPhone 14	-93.62	-92.74	-95.74	-95.93	-
6	Motorola Edge 30 Pro	-93.46	-91.76	-95.71	-96.29	**-85.37**
7	Samsung Galaxy S22	-93.39	-93.62	-95.50	-94.48	-84.05
8	iPhone 13	-93.35	-92.26	-95.30	-94.69	-84.58
9	iPhone 12 mini	-93.16	-92.48	**-92.45**	-95.30	-83.10
10	iPhone 13 Pro Max	-93.10	-92.08	-95.83	-96.48	-84.76
11	Sony Xperia 5 III	-93.03	-91.75	-94.02	-94.92	**-81.60**
12	iPhone 13 mini	-92.70	-92.88	-95.91	-94.91	-84.53
13	Samsung Galaxy S22+	-92.17	-92.11	-96.42	-95.80	-84.71
14	Samsung Galaxy S22 Ultra	-92.07	-92.73	-96.03	-94.94	-84.88
15	Xiaomi Redmi Note 11 Pro	-91.70	-92.01	-96.40	-94.80	-84.63
16	OnePlus 10 Pro	-90.90	-92.09	**-98.69**	**-98.09**	-85.08
17	Xiaomi 12	-90.65	-92.36	-96.57	-94.85	-84.35
18	Nokia G50	**-89.51**	**-91.50**	-97.03	-95.18	-83.17

Table 6. Measured performance of the phones' ability to receive in free space (FS).

Discussion

The results clearly show that the performance of the different models vary. The variation in the case of voice mode (TRP) is higher than that in the case of data mode (TIS). The TRP maximum difference between the worst and best phone among all studied bands is 12 dB for BHHR, 14 dB for BHHL, and 10 dB for FS. The TIS maximum difference between the worst and best phone among all studied bands is 6 dB for RH, 5 dB for LH, and 7 dB for FS.

The TRP maximum difference between FS and hand-head scenarios among all studied bands is 12 dB for BHHR, and 13 dB for BHHL. The TIS maximum difference between FS and hand-only scenarios among all studied bands is 7 dB for both RH and LH. The TRP performance variation between BHHR and BHHL scenarios is large (e.g. 10 dB maximum), while the TIS performance variation between RH and LH scenarios is small (e.g. 3 dB maximum).

It is noted that only a single sample of each mobile phone model is used in the measurements. Hence, any variations among different samples of the same model cannot be accounted for in this study, though they are expected to be low.

For some of the phones it is observed that after repeating the measurements without changing anything in the setup, the TRP varies with a few dB, but the radiation pattern is the same. For other phones a difference in the radiation pattern was observed when repeating the TRP measurements. It is likely that the phone uses antenna switching in these cases. In addition, Xiaomi phones present unexpected radiation patterns even after repeating the TRP measurements multiple times (to ensure that this is not a software issue) – it seems that there is something like constant antenna switching.

Acronyms

4G	4. Generation
5G	5. Generation
BHHL	Beside head hand left
BHHR	Beside head hand right
CTIA	Cellular Telecommunications Industry Association
FS	Free Space
LH	Left-hand phantom
LTE	Long-Term Evolution
NR	New Radio
NSA	Non-stand alone
RH	Right-hand phantom
SA	Stand alone
TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power

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[ETSI-1]	*ETSI - TS 138 521-1* *5G; NR; User Equipment (UE) conformance specification; Radio transmission and reception; Part 1: Range 1 standalone*

Appendix I: Measurement equipment used

Equipment	Serial number	Uncertainty on TIS
TIS test system StarGate 24	1102287-0010	< ± 1,6 dB
TRP test system StarGate 24	1102287-0010	< ± 1,5 dB
Communication tester R&S CMW 500	1201.000K50- 106102-W1	< ± 1,0 dB
Radio communication test station Anritsu MX8000A		
Radio communication analyzer Anritsu MT8821C		
Phantom hand incl. spacer + test cube Speag SHOV 2 RP Right PDA Hand	25382	
Phantom hand incl. spacer + test cube Speag SHOV 2 RC Right Clam Hand	15203	
Phantom hand incl. spacer + test cube Speag SHOV 2 LP Left PDA Hand	20258	
Phantom hand incl. spacer + test cube Speag SHOV 2 LC Left Clam Hand	11129	
Phantom head V 4.5 BS Speag SAM	3481	
Phantom hand incl. spacer + test cube Speag SHOV 2 RD Data Hand Right	35205	

The test equipment consists of a ring with test probes and some instruments to establish a phone call and receive the measured data from the phone under test. The antenna ring with the probes is from Satimo and called the StarGsate-24, the tester for communication with the phone is the CMW500 for LTE, and MT8000A + MT8821C for 5G FR1 NSA. Further a head-phantom is used; it is the so called SAM head as specified by the CTIA [CTIA18]. And the last part is the hands where 4 different hands are used to fit the different types of phones tested as specified by CTIA [CTIA18] for each side of the head.

Appendix II: Calculation of limits

The reported values are field strengths and the required minimum levels by the mobile phones are power values. The relation is:

$$P = \frac{|E|^2 \lambda^2 G_0}{4\pi\eta}$$

Where E is the RMS value of the Electric field strength, λ the free space wavelength, η is the free space impedance equal to120 π, and G_0 the maximum gain. Assuming that the incoming power to the mobile phone is arriving equally likely from all directions and in both polarisations, as is the common assumption made in mobile communication [Jak74], it is possible to use the term Total Isotropic Sensitivity (TIS) as agreed upon by 3GPP and CTIA [CTI18]. The TIS includes all the losses in the phone (like impedance matching losses, ohmic and dielectric losses) and can include the losses in the human user of the phone.
This gives the following relation between TIS and the Root Mean Square (RMS) value of the magnitude of the electric field strength:

$$|E| = \frac{\sqrt{4\pi\eta \cdot TIS}}{\lambda}$$

The wavelength is related to the frequency of operation and the medium of radio propagation. The medium is free air and the relation is simply

$$\lambda = \frac{c}{f}$$

Where *c* is the speed of light. The frequency is given by the table below. For the calculations the centre frequency is used.

Mobile System	Frequency Band	Downlink frequency [MHz]	Wavelength [meters]
LTE	700	729 – 746 MHz	0,41
LTE	900	925 – 960 MHz	0.32
LTE	1800	1805 – 1880 MHz	0.16
LTE	2100	2110 – 2170 MHz	0.14
NR	3500	3300 – 3800 MHz	0.08

Frequency of operation for the downlink in the mobile systems investigated and the free space wavelength at the centre of the downlink.