MOBILE HANDSET TESTING

A REPORT FOR OFCOM, THE UK COMMUNICATION REGULATOR

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Document information

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Executive Summary

Ofcom commissioned this study as part of its work on mobile coverage and in support of its 2015/16 priorities, including the promotion of better coverage of fixed and mobile services for residential and business consumers. The main purposes of the study were to:

1. Develop a better understanding of the sensitivity performance of handsets available on the retail mass market and how these relate to the assumptions made for the performance of handsets by mobile operators.
2. Inform, where possible, the development of interactive coverage maps by Ofcom.

The study involved measuring the sensitivity[i] of a range of handsets in a controlled anechoic environment. In particular:

- The measurements were made using standard RF facilities, conformant with the specifications set out by the Cellular Telephone Industries Association (CTIA);
- The tested handsets were acquired *off-the-shelf* from the UK's consumer retail market; and
- The measurements were made in the appropriate frequency bands used by 2G, 3G and 4G services in the UK.

The handsets tested, were chosen to representative of those currently available in the UK market. In particular, handsets were selected on the basis of their: type (smart or non-smart), market (popularity), cost (high, medium and low), support for the different mobile standards (2G, 3G and 4G) and frequencies used in the UK, and support for different services (voice and data).

The measurement campaign used consisted of three phases:

- Phase 1 involved measuring the free space sensitivity of 10 different types of mobile handset.
- Phase 2 involved measuring for 5 of the handsets types tested in phase 1, the variations in manufacturing performance across 3 samples of each handset.
- Phase 3 involved measuring for 5 of the handsets types tested in phase 1, the variations in performance when used with a phantom hand-and-head.

In this report, we compare the results of our measurements with recently published recommendations by the GSM Association[ii], which provide guidelines for the target performance for mobile devices.

The following key observations can be drawn from the results of this study and their comparison with the GSMA recommended levels:

[i] The sensitivity of a handset is understood to be the smallest amount of external power delivered to the handset antenna such that the handset can maintain reliable communication.

[ii] The GSMA is an association of mobile operators and related companies supports the standardising, deployment and promotion of mobile cellular networks. It represents the interests of mobile operators worldwide and the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and Internet companies (http://www.gsma.com).

- When tested in free space, the majority of devices performed close to or better than the GSMA recommendations across all technologies and frequency bands.
- The introduction of a phantom hand-and-head in the sensitivity tests caused wide variations in performance degradation across different handsets, technologies and frequencies. In particular:
  - 2G sensitivity reduced on average by 12dB from -104dB, and the performance of different handsets ranged from -84 to -102dB.
  - 3G sensitivity reduced on average by 10dB from -107dB, and the performance of different handsets ranged from -87 to -104dB.
  - 4G sensitivity reduced on average by 6dB from -93dB, and the performance of different handsets ranged from -81 to -90dB.
- No single device systematically outperformed the others across all frequency bands and technologies.
- For 2G, when used with a phantom hand-and-head, the average smart phone performance was 7dB worse than the non-smart phones. Some of the smart phones tested required over 10x (10dB) more power than the best performing non-smart phone.
- A significant variation in performance (up to 9dB) was observed for some devices depending on whether it was held in the left or right hand.
- For 3G, whilst the average handset performance was within 2dB of the GSMA recommendations. However, the worst performance was 9dB below the GSMA recommendations.
- For 4G, whilst the average handset performance was within 5dB of the GSMA recommendations. However, the worst performance was 7dB below the GSMA recommendations.

The above observations have implications for link budget calculations, network planning and the extent of mobile coverage experienced by users of these phones.

The measurement results are presented in an anonymised format. There are a number of reasons for this:

- The number of phones tested of each type was insufficient to enable statistically significant comparisons to be made between different manufacturers' handsets.
- No handset outperformed the others across different frequency bands and technologies. Hence, none anonymised results are unlikely to provide additional useful information for consumers.
- Some common consumer usage scenarios were not measured such as the use of earpieces and handset accessories, which may have yielded different results.
- It was not possible to test all of the factors which can affect real world handset performance such as cell handover and the use of handset antenna diversity.

Abbreviations

3GPP	3rd Generation Partnership Project
8PSK	Eight Phase Shift Keying
AICH	Acquisition Indicator Channel
AMR	Adaptive Multi-Rate
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BER	Bit Error Rate
BHHL	Beside Head and Hand Left Side
BHHR	Beside Head and Hand Right Side
BLER	Block Error Rate
BS	Base Station
CC	Component Carriers
CCCH	Common Control Channel
CRC	Cyclic Redundancy Check
CS	Circuit Switched
CTIA	Cellular Telephone Industries Association
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DFT	Discrete Fourier Transform
DL	Downlink
DPCH	Dedicated Physical Channel
DTCH	Dedicated Traffic Channel
EDGE	Enhanced Data rates for GSM Evolution
EIS	Equivalent Isotropic Sensitivity
EPRE	Energy Per Resource Element
E-UTRA	Evolved UMTS Terrestrial Radio Access
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FS	Free Space
GMM	GPRS Mobility Management
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GSMA	Groupe Speciale Mobile Association
HARQ	Hybrid ARQ
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MM	Mobility Management
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OTA	Over-The-Air
PBCH	Physical Broadcast Channel
PCC	Primary Component Carrier

PCCH	Paging Control Channel
P-CCPCH	Primary Common Control Physical Channel
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit
PHICH	Physical Hybrid ARQ Indicator Channel
PICH	Paging Indicator Channel
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PS	Packet Switched
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RB	Resource Blocks
RE	Resource Element
REFSENS	Reference Sensitivity power level
RF	Radio Frequency
RLC	Radio Link Control
RMC	Reference Measurement Channel
RNTI	Radio Network Temporary Identifier
RRC	Radio Resource Control
RS	Reference Signal
RSRP	Reference Signal Received Power
SAR	Specific Absorption Rate
S-CCPCH	Secondary Common Control Physical Channel
TC	Test Control
TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power
TS	Technical Specification
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VoLTE	Voice over LTE
WCDMA	Wideband Code Division Multiple Access

1. Introduction

To support Ofcom's initiatives on enabling better mobile coverage, Ofcom commissioned this study to develop a better understanding of modern mobile handset sensitivity performance and whether it is consistent with that typically assumed in mobile network coverage planning assumptions. Mobile coverage is dependent on the location and number of mobile stations and also handset sensitivity performance.

1.1 Factors impacting handset performance

There are a range of factors that can affect handset sensitivity performance, including but not limited to:

- *The consumer use scenario:* whether mobile handsets are used in the hand away from the body, with an earpiece or close to the head can affect antenna performance and hence handset sensitivity performance.
- *Antenna design:* whether an internal or external antenna is used and its size can affect the gain of the handset antenna and hence handset sensitivity performance.
- *Handset design:* different handset materials can have different absorption effects on mobile signals and hence affect handset sensitivity performance.
- *RF receiver design:* noise and nonlinearity introduced by the handset receiver circuitry can affect handset sensitivity performance[iii].
- *The number of frequency bands supported:* as more frequency bands are added the handset antenna and receiver design becomes more complex, which can make it more difficult to achieve good sensitivity performance.

In this study, we tested the sensitivity performance of a range of handsets that are representative of those available in the consumer market under both in free space and typical head and hand usage scenario.

1.2 Figure of merit

There are number of different methods and figures of merit that can be used to evaluate and describe handset sensitivity. The choice of what metric to use is dependent upon the application envisaged.

In this report, we have taken handset sensitivity to mean the smallest amount of external received power that handset antenna must receive such that the handset can maintain reliable communication. To measure this, we have adopted the Total Isotropic Sensitivity (TIS) as the figure of merit. The TIS has become increasingly important metric for handset sensitivity, as it can quantify the "over-the-air" (OTA) performance of mobile handset with integrated antennas. It is also the industry standard by which handset sensitivity is quantified, see below.

[iii] In addition, noise generated within the receiver itself can, depending on its design, be picked up by the handset antenna.

1.3 Approach

The general approach taken by this study was to measure the receiver TIS sensitivity for a range of handsets available from the retail market. A comparison is also made of the measured handset performance with those typically used in mobile coverage link budget calculations.

To this end, the testing of different mobile phones using radiated signals was conducted in a controlled anechoic chamber. The measurements were made in the appropriate frequency bands used by 2G, 3G and 4G services in the UK.

The radiated measurements covered two aspects:

1) Free space measurements.
2) Phantom hand-and-head: this takes into account the use case in which a consumer is holding the handset to their head with their hand while making a voice call.

1.4 CTIA Standard, 3GPP Standards and GSMA Recommendations

The Over the Air (OTA) performance of mobile devices is of fundamental importance to their actual real world performance, in particular in low signal strength areas. Mobiles devices often use small embedded antennas and their performance has an important direct impact on their sensitivity. Furthermore, the extents to which these antennas are affected by their local environment such as their proximity to a human head or hand also become equally important. These developments have necessitated the need for a common testing approach of OTA handset sensitivity.

The Cellular Telephone Industries Association (CTIA) has defined a common a set of industry-standard test procedures called OTA performance measurements, in which the overall radiation pattern performance and sensitivity of mobiles devices is evaluated. The CTIA is an international industry trade group representing the wireless communications sectors including cellular and its test procedures are widely used and accepted by the mobile communications industry.

Table 1 provides for reference purposes a summary of the expected TIS handset sensitivity (using the CTIA test procedure) for different mobile technologies and frequency bands as provided by 3GPP and GSMA[iv].

[iv] The GSMA is an association of mobile operators and related companies which supports the standardising, deployment and promotion of mobile cellular networks. It represents the interests of mobile operators worldwide and the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and Internet companies (http://www.gsma.com).

Table 1: Standards used in the measurement process and corresponding frequency bands.

3GPP Standard	Target Technology	Bands (MHz)	Expected Sensitivity		
			3GPP (FS)	GSMA (FS)	GSMA (BHH)
TS 05.05 TS 51.010-1	GSM/GPRS/EDGE 900	900	-104	-103	-95
	GSM/GPRS/EDGE1800	1800	-102	-104	-99
TS 25.101	UMTS Band I	2100	-117	-106	-101
	UMTS Band VIII	900	-114	-104	-96
TS 36.521-1	E-UTRA Band 3	1800	-94	-94	-89
	E-UTRA Band 7	2600	-92	-94	-89
	E-UTRA Band 20	800	-94	-93.5	-85

1.5 High-level handset test methodology

Each of the handsets tested was placed in a controlled anechoic chamber. A base station emulator is used to transmit a typical mobile signal with known transmit power and arriving at the handset from a pre-set direction. The transmit signal power is reduced until the handset stops working. The point at which the handset stops working is recorded as the sensitivity of the device in the given signal direction. This was repeated for 2G, 3G and 4G; different signal directions and different frequency bands.

Note that

- The bands addressed in this study are given in Table 1.
- A more detailed description of the measurement methodology is given in appendix A.
- The UL measurement environment is described in detail in appendix B.

All the measurements conducted in this report were carried out at UL's measurements laboratory which is conformant to the CTIA test plans[v].

1.6 Breakdown of the report

The content of this report is structured as follows:

- Section 2 describes the measurements made including the choice of handsets. This section also refers to the appropriate appendices where the detailed results from the measurements are provided.
- Section 3 provides a summary of the report conclusions.

Additional supporting material is provided in the appendices on the details of the test approach and the test equipment used.

[v] CATL Lab Code 20111025-00

2. Test Methodology and Measurement Results

In this section, we describe the test methodology used for this study, including the handset selection criteria and the TIS anechoic chamber measurements.

In order to limit the large amount of testing time required to make TIS measurements across different frequency bands and technologies, only 10 different handset models were selected. The basis for selecting these handsets is described in section 2.1 through section 2.4. The remainder of this section then describes the TIS tests made on these handsets.

2.1 Choice of Handsets

A wide diverse range of mobile handsets are currently on sale in the UK's retail market. Ten different handsets were selected for this study and their selection was based on the three factors below:

- Type: We ensured that both *smart* and *non-smart phones* were selected.
- Market share: We ensured that handsets from a range of different manufactures with a significant share of today's UK handset retail market were selected.
- Cost: We ensured that high, medium and low cost handsets were selected.

2.2 Mobile Technologies and Bands

Table 2 provides a list of the mobile technologies and frequency bands used for the handset sensitivity measurements in this study.

Table 2: Mobile technologies and band addressed in the measurement campaign.

	Band Name	Mid Frequency (MHz)	Channel Frequency (MHz)		
			Low	Mid	High
2G	900	942.6	925.2	942.6	959.8
	1800	1842.6	1805.2	1842.6	1879.8
2.5G	900	942.6	925.2	942.6	959.8
	1800	1842.6	1805.2	1842.6	1879.8
2.75G	900	942.6	925.2	942.6	959.8
	1800	1842.6	1805.2	1842.6	1879.8
3G	Band 1	2140	2112.4	2140	2167.6
	Band 8	942.6	927.4	942.6	957.6
4G	Band 3	1842.5	1810	1842.5	1875
	Band 7	2655	2630	2655	2680
	Band 20	806	796	806	816

2.3 Measurement campaign

The measurement campaign used consisted of three phases:

- Phase 1 involved measuring the free space sensitivity of 10 different types of mobile handset.
- Phase 2 involved measuring for 5 of the handsets types tested in phase 1, the variations in manufacturing performance across 3 samples of each handset.

- Phase 3 involved measuring for 5 of the handsets types tested in phase 1, the variations in performance when used with a phantom hand-and-head.

2.4 Identified Handsets and their Properties

Table 3 lists the mobile properties of the handsets based on the factors described in section 2.1.

Table 3: The mobile handsets, the bands supported by each handset and their properties used in the measurement campaign.

			Device 1	Device 2	Device 3	Device 4	Device 5	Device 6	Device 7	Device 8	Device 9	Device 10
Type			Smart	Smart	Smart	Smart	Non-Smart	Smart	Smart	Smart	Non-Smart	Non-Smart
Market Share			High	High	High	Mid	Low	Mid	Mid	Mid	Low	Low
Cost			High	High	Mid	Low	Low	High	High	Mid	Low	Low
	Band Name	**Mid Freq (MHz)**										
2G	900	942.6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	1800	1842.6										
2.5G	900	942.6					No 2G Data					
	1800	1842.6										
2.75G	900	942.6										
	1800	1842.6										
3G	Band 1	2140	Yes	Yes	Yes	Yes	No 3G	Yes	Yes	Yes	No 3G	No 3G
	Band 8	942.6										
4G	Band 3	1842.6	Yes	Yes	Yes	No 4G	No 4G	Yes	Yes	No 4G	No 4G	No 4G
	Band 7	2655										
	Band 20	806										

Phase 1: Measurement of Sensitivity Variation in Free Space

The first phase of the study was to perform TIS measurements on 10 different handsets in a free space environment (labelled “Device *n*, Sample #1”). The TIS measurements were performed using the 2G, 3G and 4G frequency bands used in the UK where they were supported by the handset. Furthermore, three different channels were tested across each of these frequency bands.

The result of this measurement can be found under appendix D.1.

Following the completion of the free space testing, further testing was conducted in order to determine the selection of handsets for Phase 2. This additional testing was performed with the handset placed on hand next to a head phantom (BHHR) in GSM900 band.

The result of this measurement can be found under appendix D.2.

2.5 Phase 2: Measurement of Sensitivity Variation with a Given Brand / Model in Free Space

Based on test data from Phase 1, 5 handsets were selected for further investigation. The 5 handsets were chosen to maintain representation of the original 10 handsets in terms of type, cost and market popularity. The 5 handsets were placed in 5 groups, and two additional identical samples were added to each group. This results in 5 groups of 3 identical handsets in each.

free space measurements were performed on the newly added handsets to further investigate the variation of the TIS values of different samples across a given brand / model of handset.

The results of these measurements can be found in appendix E.

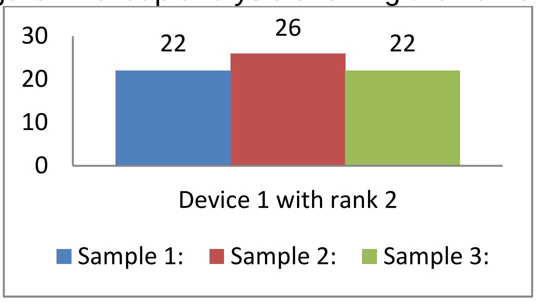
<u>Choosing one sample from each group to take forward to Phase 3</u>

Next, one sample was selected from each group to take forward to the detailed testing of phase 3. The following selection method was used in order to identify a middle performing handset from each of group of three samples:

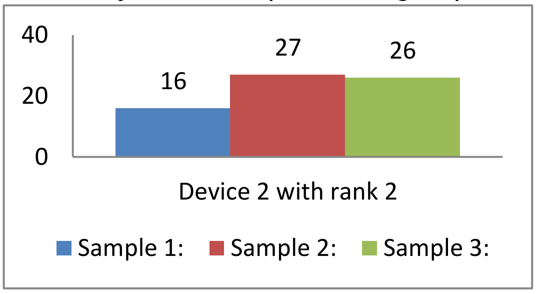
1. The three samples in each group were analysed and compared against each other for each tested band.
2. A ranking between 1 and 3 was given to each device. A score of 1, 2 or 3 were awarded to a given device if its sensitivity was highest, middle or lowest amongst the sample of 3 in the group, respectively.
3. The sample that scores the most number of 2's was selected for Phase 3 measurement.

The results for the 5 groups are depicted in Figure 1.

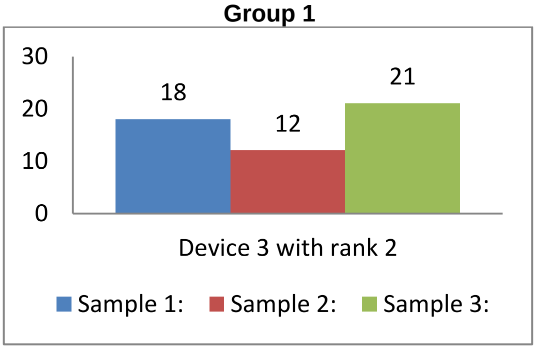
Figure 1: Group analysis showing the number of 2's scored by each sample in the group.



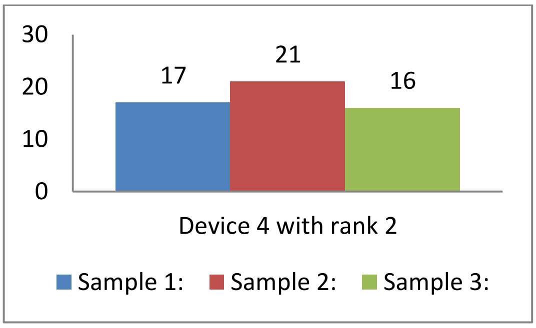
Group 1



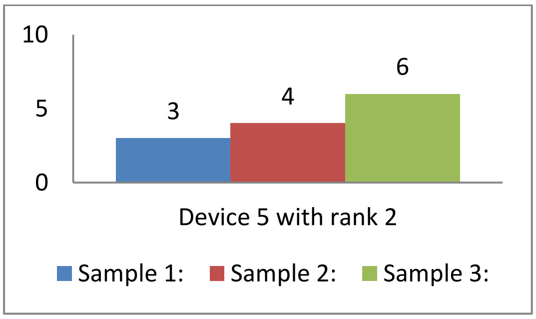
Group 2



Group 3



Group 4



Group 5

2.6 Phase 3: Measurement of Sensitivity Variations with Phantom Hands-and-Head

Based on test data from Phase Two, one sample from each group was selected to take forward to Phase 3 as presented in Table 4.

The sensitivity test was executed again on a model human head and hand (phantom hand-and-head) as specified in the CTIA OTA test plan [R1]. As different mobile handset positioning may result in different measurement results, both left and rights ears for the phantom hand-and-head test were performed.

Table 4: A sample of 5 handsets and the measurements made using hand and head phantoms.

	Group 1 of 3 x Device 1	**Group 2 of 3 x Device 2**	**Group 3 of 3 x Device 3**	**Group 4 of 3 x Device 4**	**Group 5 of 3 x Device 5**
Selected samples	Sample #1 **Sample #2** Sample #3	Sample #1 **Sample #2** Sample #3	Sample #1 Sample #2 **Sample #3**	Sample #1 **Sample #2** Sample #3	Sample #1 Sample #2 **Sample #3**

The result of these measurements can be found in appendix F.

3. Outcome from the measurement results

The results of the measurements described in section 2, are summarised in the table below.

Table 5: Outcome from analysis of the results.

Band	Freq (MHz)	Ofcom Measured Handset Sensitivity in Free-Space (FS) (dBm)			GSMA Recommendations (dBm)	Ofcom Measured Handset Sensitivity with HH (dBm)			GSMA Recommendations (dBm)
		Min	Ave	Max		Min	Ave	Max	
GSM 900	900	-99	-104	-107	-103	-85(R)	-90	-98(L)	-95
GSM 1800	1800	-102	-105	-110	-104	-87(L)	-95	-102(R)	-99
3G Band 1	2100	-105	-106	-110	-106	-99(R)	-102	-104(R)	-101
3G Band 8	900	-102	-105	-107	-104	-87(L)	-94	-98(L)	-96
4G Band 3	1800	-93	-96	-97	-94	-83(R)	-87	-90(L)	-89
4G Band 7	2600	-87	-90	-91	-94	-82L	-84	-88R	-89
4G Band 20	800	-88	-92	-95	-93.5	-80(R)	-84	-86(R)	-85

We have drawn the following high level conclusions from these results:

- When tested in free space, the majority of devices performed close to or better than the GSMA recommendations across all technologies and frequency bands.
- The introduction of a phantom hand-and-head in the sensitivity tests caused wide variations in performance degradation across different handsets, technologies and frequencies. In particular:
    - 2G sensitivity reduced on average by 12dB from -104dB, and the performance of different handsets ranged from -84 to -102dB.
    - 3G sensitivity reduced on average by 10dB from -107dB, and the performance of different handsets ranged from -87 to -104dB.
    - 4G sensitivity reduced on average by 6dB from -93dB, and the performance of different handsets ranged from -81 to -90dB.
- No single device systematically outperformed the others across all frequency bands and technologies.
- For 2G, when used with a phantom hand-and-head, the average smart phone performance was 7dB worse than the non-smart phones. Some of the smart phones tested required over 10x (10dB) more power than the best performing non-smart phone.
- A significant variation in performance (up to 9dB) was observed for some devices depending on whether it was held in the left or right hand.
- For 3G, whilst the average handset performance was within 2dB of the GSMA recommendations. However, the worst performance was 9dB below the GSMA recommendations.
- For 4G, whilst the average handset performance was within 5dB of the GSMA recommendations. However, the worst performance was 7dB below the GSMA recommendations.

4. References

[R1] CTIA: "Test Plan for Wireless Devices Over-the-Air Performance".

[R2] 3GPP TS 36.521-1: ""Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) conformance specification Radio transmission and reception; Part 1: Conformance Testing;"

[R3] 3GPP TS 34.109: "Terminal logical test interface; Special conformance testing functions"

[R4] 3GPP TS 51.010-1 V12.6.0 (2015-06): "Technical Specification Group, GSM/EDGE Radio Access Network, Digital cellular telecommunications system (Phase 2+); Mobile Station (MS) conformance specification"

[R5] MD Foegelle "Antenna Pattern Measurement: Concepts and Techniques", Compliance Engineering, Annual Reference Guide 2002.

[R6] Operator Acceptance Values for Device Antenna Performance, Version 3.0, 2014, http://www.gsma.com/newsroom/all-documents/ts-24-v-3-0/.

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A. <u>Handset Sensitivity: Characterisation and Measurement</u>

In this section, the basic characterisation of a mobile handset antenna is explored. To this end, the concept of mobile handset receiver sensitivity with respect to radiated power is presented. The measurement method of the sensitivity is also outlined. This section finally discusses the standards that were implemented in order to conform to the receiver measurement sensitivity for 2G, 3G and 4G.

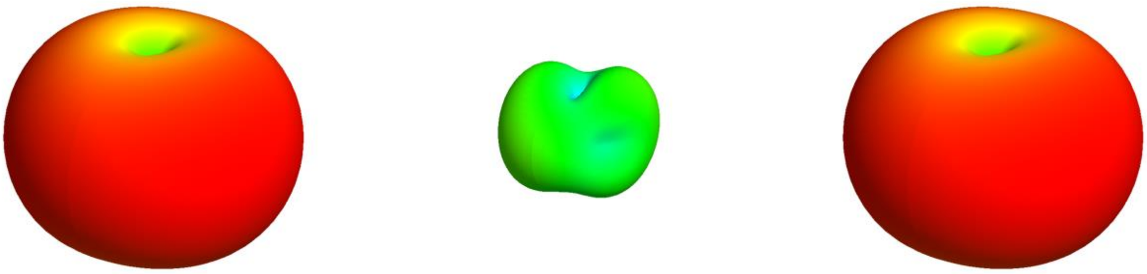
A.1 Characterisation

An antenna is a physical device that receives and/or radiates energy, almost always with some directional dependence. The energy being received or radiated by a given an antenna is also polarised: the electric field is in a particular orientation.

Mobile handsets inherit these properties from their integrated antenna so that their ability to receive is also affected by their direction of signal reception with respect to the handset frame of reference, as well as the signal polarisation.

The propagation characteristics of a given antenna are often described using 3D plots, see Figure 2. For example, a 3D plot of sensitivity gives a measure of the minimum required power impinging on the handset in a given direction (expressed in θ and φ, respectively) and polarisation to achieve a particular frame error rate. This is termed effective isotropic sensitivity and is denoted by EIS(θ, φ).

Figure 2: 3D Sensitivity Plots (sensitivity due to vertical polarisation is greater than horizontal).



Vertical polarisation | Horizontal polarisation | Vertical + Horizontal polarisation

A.2 TIS as a metric for handset sensitivity

The TIS is a parameter that is often used to represent a three-dimensional characterisation of a receiver performance. The receiver performance is measured by utilising the specified error criteria to evaluate effective radiated receiver sensitivity at each spatial measurement location. Data points taken every 30 degrees in Theta and Phi axes and all of the measured sensitivity values for each test conditions will be integrated to give a single figure of merit referred to as TIS.

The TIS is a measure of the average sensitivity of a receiver-antenna system, when averaged over the entire 3-dimensional sphere. The result will be strongly related to the antenna's radiation pattern.

For a complete sphere measured with *N* Theta intervals and *M* Phi intervals, both with even angular spacing, the TIS is calculated as follow:

$$TIS \cong \frac{2NM}{\pi \sum_{i=1}^{N-1} \sum_{j=0}^{M-1} \left[\frac{1}{EIS_{\theta}(\theta_i, \phi_j)} + \frac{1}{EIS_{\phi}(\theta_i, \phi_j)} \right] \sin(\theta_i)} \qquad \text{Equation 1}$$

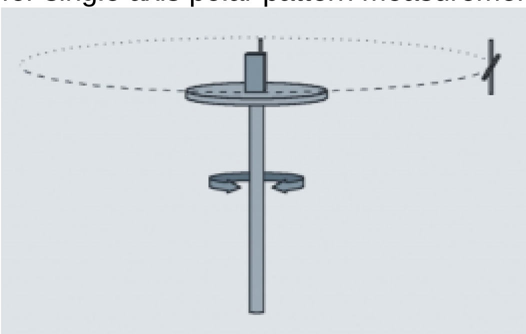
Here, EIS is the radiated effective isotropic sensitivity measured at each direction and polarisation.

A.3 Measurement methodology

Here, an overview of the measurement methodology is given. More details are available in [R1][R5].

Figure 3 shows a typical polar pattern test setup. The mobile handset is placed on a rotating turntable, and a dual polarised antenna is placed surrounding the arch of the handset a fixed distance away. The turntable is rotated 180°, and the response between the antennas is measured as a function of angle. This measurement is performed in a fully anechoic (simulated free space) environment.

Figure 3: Typical test setup for single axis polar pattern measurement.



In order to generate a full spherical-pattern measurement, it is necessary to change the relationship between the mobile handset and the measuring antenna and repeat the previous polar test for each new orientation. The changes in orientation must be perpendicular to the plane of the measurement to completely cover a spherical surface. In simpler terms, the second axis of rotation must be perpendicular to and intersect the first axis of rotation. The two axes correspond to the θ and Φ angles of the spherical coordinate system and are typically referred to as elevation and azimuth. Just as in the spherical coordinate system, only one axis needs to be rotated through 360°, whereas the other is rotated through 180°.

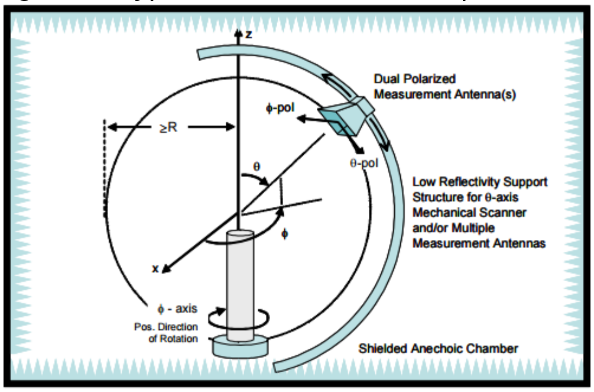
There are two acceptable methods proposed by CTIA for performing 3D antenna measurements, see Figure 4, namely:

1. The “conical” cut method, whereby the mobile handset rotates on its long axis and the measurement antenna is moved (either mechanically or in the case of this study, electrically, as the system uses multiple measurement antennas) to several locations both above and below the mobile handset for each rotation.

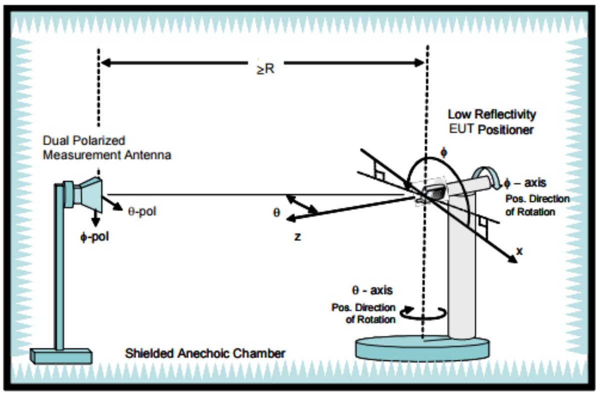
2. The "great circle" cut method, whereby the measurement antenna remains fixed and the mobile handset is rotated about two axes in sequential order.

Both methods are equally valid providing Equation 1 is correct applied.

Figure 4: Typical measurement setup.



Distributed system



Combined system

For devices that support receiver diversity, the CTIA test plan states that each receiver shall be tested separately by enabling the wanted receiver and disabling the other receiver. However, the process of enabling and disabling the diversity can only be accomplished in a test mode configuration provided by the manufacturer. As all the handsets in this study were acquired off-the-shelf, the receiver sensitivity measurements were performed with all receivers remaining active simultaneously.

A.4 Relevant standards

The CTIA test plan for Wireless Device Over-the-Air Performance requires measurements against the standards given in Table 6.

Table 6: Set of standards used in the measurement process.

3GPP Standard	Target Technology	Expected Sensitivity			Target Criteria	Details
		3GPP	GSMA (FS)	GSMA (BHH)		
TS 05.05	GSM/GPRS/EDGE 900	-104	-103	-95	BER 2.439% (Voice); BLER 10% (Data)	See below for details
	GSM/GPRS/EDGE 1800	-102	-104	-99		
TS 51.010-1	GSM/GPRS/EDGE 900	-104	-103	-95		
	GSM/GPRS/EDGE 1800	-102	-104	-99		
TS 25.101	UMTS Band I	-117	-106	-101	BER ≤1.2%	
	UMTS Band VIII	-114	-104	-96		
TS 36.521-1	E-UTRA Band 3	-94	-94	-89	BLER ≤5%	
	E-UTRA Band 7	-92	-94	-89		
	E-UTRA Band 20	-94	-93.5	-85		

Next we describe how the measurements relate to the respective mobile technologies.

A.5 2G

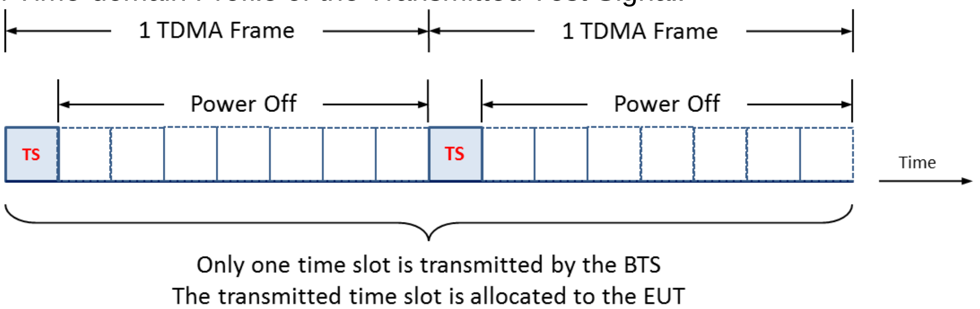
GSM modes use a constant envelope modulation known as Gaussian Minimum Shift Keying (GMSK) that encodes one bit per symbol. The signal is divided into 8 timeslots of approximately 0.577ms with 148 symbols per slot. Single timeslot measurements are used for the GSM mode.

As highlighted in Table 6 the two relevant standards, namely 3GPP TS 05.05 and 51.010, recommend that the Access Burst (which occupies a single timeslot) is used when meeting the specified bit error rate. The Access Burst was selected for measurement since this type of burst is shorter than Normal Bursts and hence less likely to collide with subsequent timeslots whilst the base station re-determines the required timing advance. Furthermore, this burst type is sufficiently robust to perform well and is computationally efficient without sacrificing performance.

During lab testing, the base station emulator is configured to transmit Access Bursts in a continuous manner to the handset whilst listening to the handset reporting of the recorded BER. Each handset is allocated all 1 downlink slots and the BER measurement is conducted over 135 TDMA frames. No other types of bursts were transmitted alongside the Access Burst. Figure 5 depicts the transmitted test signal.

The base station transmitted RF signal power, which is carrying the Access Bursts, was recorded. This signal has the bandwidth of 200 kHz. For voice, the handset sensitivity shall be equivalent to the recorded minimum RF power level that results in a maximum BER of 2.439%.

Figure 5: GSM Time-domain Profile of the Transmitted Test Signal.



In 2G, RxLev is a measure of the *conducted* received signal power[vi], ie post the analogue front-end of the handset. The radiated and conducted power are related by the following

$$\text{RxLev (full)} = \beta \text{ (Radiated power)} + \Delta \text{ (dB)} \qquad \text{Equation 2}$$

where β and Δ is a measure of the combined gain/loss of the handset receiver chain from the antenna through to where RxLev is being measured. Different handsets will have different β and Δ values. Equation 2 suggests that the relationship between the radiated power and RxLev is linear in theory. In practice, this may not be the case, especially in the sensitive region of the handset receiver.

[vi] Need a reference to an appropriate book that talks about RxLev and defines it

A.6 2.5G (GPRS)

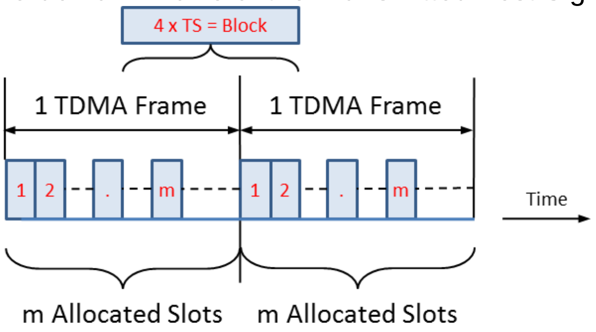
As in the case of GSM, the GPRS mode also uses GMSK that encodes one bit per symbol. Again, the signal is divided into 8 timeslots of approximately 0.577 ms with 148 symbols per slot. Multi-slot measurements are used for this mode.

As highlighted in in Table 6 for GPRS, the two relevant standards, namely 3GPP TS 05.05 and 51.010, specify the use of Block Error Rate (BLER) rather than BER. The standards also specify that Access Bursts (which occupies a single timeslot) are used when meeting the specified BLER and in a similar fashion to GSM. A single radio block consists of four Access Bursts.

The number of data bits in a block depends on the channel-coding scheme that is in use. The coding scheme (CS) used in this study is CS-1 as defined in CTIA Test Plan. This coding scheme provides the most robust channel coding that maintains the data loopback session.

During lab testing, the base station emulator is configured to transmit Access Bursts in a continuous manner to the handset whilst listening to the handset reporting of the recorded BLER. The handset is allocated m downlink slots, see Figure 6, and the BLER measurement is conducted over 2000 blocks. No other types of bursts were transmitted alongside the Access Burst. The number of time slots allocated to the devices is given in Table 7.

Figure 6: GPRS/EDGE Time-domain Profile of the Transmitted Test Signal.



The base station transmitted RF signal power, which is carrying the Access Bursts, was recorded. This signal has the bandwidth of 200 kHz. For data, the handset sensitivity shall be equivalent to the recorded minimum RF power level that results in BLER of 10%.

Table 7: Time Slots Allocated per Device during GPRS/EDGE Testing.

Device	Multislot class	Number of Allocated Time Slots (m)	Comment
1	12	4	Max supported by handset class
2	12	4	Max supported by handset class
3	33	5	Max supported by handset class
4	12	4	Max supported by handset class
5	N/A	N/A	No GPRS/EDGE support by the device
6	12	4	Max supported by handset class
7	12	4	Max supported by handset class
8	33	5	Max supported by handset class
9	N/A	N/A	No GPRS/EDGE support by the device
10	N/A	N/A	No GPRS/EDGE support by the device

A.6 2.75G (EDGE)

EGPRS (EDGE) Packet Switched modes use a non-constant envelope signalling known as 8-Phase Shift Keying (8-PSK) modulation that encodes three data bits per symbol. As in the case of GSM and GPRS, the signal is divided into 8 timeslots of approximately 0.577ms with 148 symbols per slot. Multi-slot measurements are used for EDGE mode.

As highlighted in Table 6 for EDGE, the two relevant standards, namely 3GPP TS 05.05 and 51.010, specify the use of Block Error Rate (BLER). The standards also specify that Access Bursts (which occupies a single timeslot) are used when meeting the specified BLER and in a similar fashion to GSM and GPRS. A single radio block consists of four Access Bursts.

The number of data bits in a block depends on the channel-coding scheme that is in use. There are nine different modulation and coding schemes (MCS-1 through MCS-9) using different modulation combined with varying levels of error protection. The coding scheme used for EDGE is MCS-5. This coding scheme provides the most robust channel coding to maintain the data loopback session. Whilst in principle, the reference sensitivity for mobiles varies depending on the coding scheme that is in use; here the sensitivity will be measured with respect to MCS-5.

During lab testing, the base station emulator is configured to transmit Access Bursts in a continuous manner to the handset whilst listening to the handset reporting of the recorded BLER. The handset is allocated m downlink timeslots; see Figure 6, and the BLER measurement is conducted over 2000 blocks. No other types of bursts were transmitted alongside the Access Burst. The number of time slots allocated to the devices is given in see Table 7.

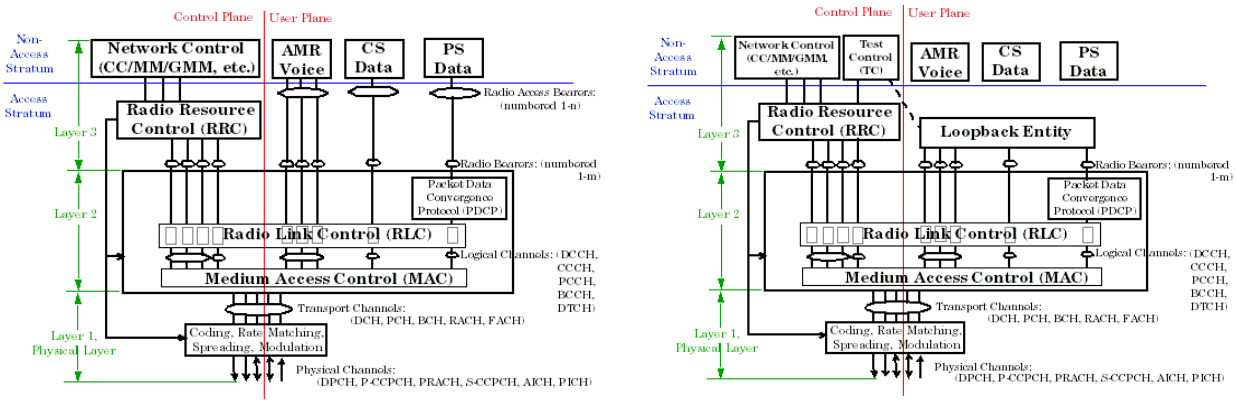
The base station transmitted RF signal power, which is carrying the Access Bursts, was recorded. This signal has the bandwidth of 200 kHz. For data, the handset sensitivity shall be equivalent to the recorded minimum RF power level that results in BLER of 10%.

A.7 3G

3G is based on Wideband CDMA (WCDMA) which is based on digital spread spectrum technology. The WCDMA structure is divided vertically into an "Access Stratum" and a "Non-Access Stratum", see Figure 7. Protocol Layers 1 and 2 are in the Access Stratum. Protocol Layer three is divided between the Access and Non-Access strata. The base station manages power control dynamically by sending binary “up” or “down” signals to maintain the received power at an optimal level.

Radio Bearer Test Mode is a special mode of operation defined by the 3G WCDMA specifications [R3] which includes a suite of uplink (UL) and downlink (DL) reference measurement channels (RMCs) to use for mobile transmitter and receiver conformance test. Its purpose is to provide for efficient manufacturing testing of a WCDMA device (in this case a mobile handset) by offering a simplified mode of operation wherein the Test Set has complete control of the necessary mobile functions. The typical use of the Radio Bearer Test Mode is to set up the special test configuration known as “Reference Measurement Channels”. The reference measurement channels are a defined set of configurations of layer 1 and 2 that provide stable, predictable behaviour for radio testing. A Radio Bearer Test Mode connection to the mobile is done via a special Test Control (TC) protocol entity and any User Plane radio bearers are terminated in a layer-3 loopback entity, see Figure 7, rather than being connected through to a real service. In radio Bearer Test Mode the protocol structure appears as shown in 3G frame structure in Radio Bearer Test Mode. All aspects of these layers are explicitly defined by the definition of the Reference Measurement Channels given in the WCDMA system specifications [R3].

Figure 7: 3G Protocol Stack.



Normal Radio Bearer *Radio Bearer Test Mode*

When the test set measures loopback BER, it sends a known data pattern (DL DTCH Data) on the downlink dedicated traffic channel (DTCH) to a mobile handsets that is configured in loopback mode 1, as all TS 34.121 tests utilising the BER measurement require loopback mode 1. The handset decodes the data and re-transmits it on the uplink DTCH. The test set analyses the uplink data to see how closely it matches the data bits originally sent on the downlink. The test set compares the downlink and uplink data one transport block at a time and reports the BER.

For RMCs with a downlink rate of 12.2 kbps, the test set sends a block every 20 ms.

During lab testing, the base station simulator is set up in accordance to 3GPP TS 25.101 and 3GPP TS 34.121, where it is configured to transmit burst frame continuously to the handset whilst listening to the handset reporting the frame errors. This number of frame is monitored and the number of frames observed shall be no more than 20,000 bits (82 frames). No other types of frames were transmitted alongside the packet burst. The transmitted signal power carrying the access burst frame was recorded. This signal has a bandwidth of 5MHz. The recorded sensitivity level is equivalent to the minimum RF power level that results in an error rate of 1.2% or less.

In 3G, the Received Signal Code Power (RSCP) is used as an indication of signal strength, as the basis for handover criterion, in downlink power control and to calculate path loss. RSCP is a measure of the *conducted* received signal power, i.e. post the analogue front-end of the handset. The radiated and conducted power are related by the following

$$\text{RSCP} = \beta\ (\text{Radiated power}) + \Delta\ (\text{dB}) \qquad \text{Equation 3}$$

where β and Δ is a measure of the combined gain/loss of the handset receiver chain from the antenna through to where RSCP is being measured. Different handsets will have different β and Δ values. Equation 3 suggests that the relationship between the radiated power and RSCP is linear in theory. In practice, this may not be the case, especially in the sensitive region of the handset receiver.

A.6 4G

The OFDM technology is based on using multiple narrow band sub-carriers spread over a wide channel bandwidth. The sub-carriers are mutually orthogonal in the frequency domain. The downlink physical layer of LTE is based on OFDMA, to multiplex traffic by allocating specific patterns of sub-carriers in the time-frequency space to different users. Control channels and reference symbols are also transmitted alongside user data traffic. The transmission can be scheduled by Resource Blocks (RB) each of which consists of 12 consecutive sub-carriers, or 180 kHz, for the duration of one slot (0.5 ms).

The sensitivity level of a 4G handset is the level where a device is able to receive data at a given average throughput for a low, mid and high channels. The correct bandwidth, frequency, Reference Measurement Channel (RMC) and network signalling values along with the details of the resource block (RB) allocations are defined in CTIA Test Plan and TS 36.521-1 – these are set on the base station simulator at the beginning of the test, see Table 8. The purpose of the test is to verify QPSK modulation and full RB allocation in the downlink[vii].

Table 8: The number of RBs allocated during the testing.

E-UTRA Band	Channel Bandwidth	UL RB Allocation	DL RB Allocation
3	10	50 RB with RBstart=0	50 RB with RBstart=0
7	20	75 RB with RBstart=25	100 RB with RBstart=0
20	10	20 RB with RBstart=0	50 RB with RBstart=0

During lab testing, the throughput that is achieved under these conditions is measured. In an example shown below, the throughput is 7884 kbps, which represents 100 % of the scheduled throughput according to the RMC settings. The throughput shall be ≥ 95 % of the reference measurement channels' maximum throughput. The maximum throughput for FDD is defined in TS 36.521-1, Annex A.2.2 and Table A.3.2 (see Table 9 and Table 10).

Table 9: Reference Channels for QPSK with full RB Allocation [R2].

Parameter	**Unit**	**Value**					
Channel bandwidth	MHz	**1.4**	**3**	**5**	**10**	**15**	**20**
Allocated resource blocks		6	15	25	50	75	100
DFT-OFDM Symbols per Sub-Frame		12	12	12	12	12	12
Modulation		QPSK	QPSK	QPSK	QPSK	QPSK	QPSK
Target Coding rate		1/3	1/3	1/3	1/3	1/5	1/6
Payload size	Bits	600	1544	2216	5160	4392	4584
Transport block CRC	Bits	24	24	24	24	24	24
Number of code blocks per Sub-Frame (Note 1)		1	1	1	1	1	1
Total number of bits per Sub-Frame (Note 1)	Bits	1728	4320	7200	14400	21600	28800
Total symbols per Sub-Frame		864	2160	3600	7200	10800	14400
UE Category		≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1
Note 1: If more than one Code Block is present, an additional CRC sequence of L = 24 Bits is attached to each Code Block (otherwise L = 0 Bit)							

[vii] The allocation includes both data and signalling RBs.

Table 10: Fixed Reference Channel for Receiver Requirements (FDD) .

Parameter	Unit	Value					
Channel bandwidth	MHz	**1.4**	**3**	**5**	**10**	**15**	**20**
Allocated resource blocks		6	15	25	50	75	100
Subcarriers per resource block		12	12	12	12	12	12
Allocated subframes per Radio Frame		9	9	9	9	9	9
Modulation		QPSK	QPSK	QPSK	QPSK	QPSK	QPSK
Target Coding Rate		1/3	1/3	1/3	1/3	1/3	1/3
Number of HARQ Processes	Processes	8	8	8	8	8	8
Maximum number of HARQ transmissions		1	1	1	1	1	1
Information Bit Payload per Sub-Frame							
For Sub-Frames 1,2,3,4,6,7,8,9	Bits	408	1320	2216	4392	6712	8760
For Sub-Frame 5	Bits	n/a	n/a	n/a	n/a	n/a	n/a
For Sub-Frame 0	Bits	152	872	1800	4392	6712	8760
Transport block CRC	Bits	24	24	24	24	24	24
Number of Code Blocks per Sub-Frame (Note 3)							
For Sub-Frames 1,2,3,4,6,7,8,9	Bits	1	1	1	1	2	2
For Sub-Frame 5	Bits	n/a	n/a	n/a	n/a	n/a	n/a
For Sub-Frame 0	Bits	1	1	1	1	2	2
Binary Channel Bits Per Sub-Frame							
For Sub-Frames 1,2,3,4,6,7,8,9	Bits	1368	3780	6300	13800	20700	27600
For Sub-Frame 5	Bits	n/a	n/a	n/a	n/a	n/a	n/a
For Sub-Frame 0	Bits	528	2940	5460	12960	19860	26760
Max. Throughput averaged over 1 frame	kbps	341.6	1143.2	1952.8	3952.8	6040.8	7884
UE Category		≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1
Note 1: 2 symbols allocated to PDCCH for 20 MHz, 15 MHz and 10MHz channel BW. 3 symbols allocated to PDCCH for 5 MHz and 3 MHz. 4 symbols allocated to PDCCH for 1.4 MHz Note 2: Reference signal, Synchronization signals and PBCH allocated as per TS 36.211 [8] Note 3: If more than one Code Block is present, an additional CRC sequence of L = 24 Bits is attached to each Code Block (otherwise L = 0 Bit)							

In 4G, the Reference Symbol Received Signal Power (RSRP) is used as an indication of the received signal strength. RSRP is a measure of the *conducted* received signal power, ie post the analogue front-end of the handset. The radiated and conducted power are related by the following

$$\text{RSRP} = \beta\,(\text{Radiated power}) + \Delta\ (\text{dB}) \qquad \text{Equation 4}$$

where β and Δ is a measure of the combined gain/loss of the handset receiver chain from the antenna through to where RSCP is being measured. Different handsets will have different β and Δ values. Equation 4 suggests that the relationship between the radiated power and RSRP is linear in theory. In practice, this may not be the case, especially in the sensitive region of the handset receiver.

B. Measurement Environment

Test equipment list:

Hardware/Firmware Description	Manufacturer	Model/Type	Serial Number	Calibration Due Date
OTA Test System	Satimo	SG24 version E	P209	12/12/2015
Satimo SAM Software	Satimo	2.24.0	N/A	N/A
Satimo SatEnv Software	Satimo	2.0.1.4	N/A	N/A
Satimo SMM Software	Satimo	1.6	N/A	N/A
Universal Radio Communication Tester	Keysight	E5515C	GB43344892	03/12/2016
Amplification Unit	Satimo	P208	MODU-020-A-0005	12/12/2015
Active Switching Unit	Satimo	P209	MODU-009-A-0071	12/12/2015

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C. Measurement Uncertainty

The expanded measurement uncertainties for Total Isotropic Sensitivity are reported in the table below. These uncertainties refer to a coverage factor of 2, corresponding to 95% confidence level.

Uncertainty Values Applicable for full sphere measurements:

TIS Measurement Uncertainty		
Band	**Free Space**	**SAM Head and Hand Phantom**
LTE700	1.92	2.18
Cellular	1.94	2.20
PCS	1.88	2.15
AWS-1 Rx	1.93	2.19
LTE/WLAN 2300-2800 MHz	1.89	2.16

D. Results from Phase 1

D.1 – Determining the range of sensitivity across a long list of 10 handsets in free space

RAT / Band	Channel	TIS (dBm) in Free Space									
		Device 1 (Sample #1)	Device 2 (Sample #1)	Device 3 (Sample #1)	Device 4 (Sample #1)	Device 5 (Sample #1)	Device 6 (Sample #1)	Device 7 (Sample #1)	Device 8 (Sample #1)	Device 9 (Sample #1)	Device 10 (Sample #1)
GSM 900	Low	-103.6	-103.6	-101.3	-105.7	-107.6	-103.8	-106.2	-105.1	-106.6	-104.1
	Mid	-103.3	-103.1	-101.5	-104.9	-106.6	-104.5	-105.9	-104.7	-106.2	-103.5
	High	-101.7	-102.2	-98.9	-103.7	-106.7	-103.9	-103.9	-104.1	-104.8	-101.6
GSM 1800	Low	-105.0	-106.0	-105.5	-103.7		-103.6	-106.4	-104.1	-104.7	-105.2
	Mid	-104.7	-106.2	-104.9	-104.0		-104.7	-107.0	-104.2	-104.5	-103.7
	High	-104.3	-105.5	-104.6	-102.9		-104.0	-106.3	-104.2	-103.2	-103.6
GPRS 900	Low	-107.2	-107.4	-105.2	-109.6		-108.3	-106.0	-107.1		
	Mid	-107.1	-107.4	-105.9	-109.1		-108.5	-105.8	-107.0		
	High	-105.4	-106.1	-103.1	-107.5		-107.1	-103.8	-106.2		
GPRS 1800	Low	-108.0	-109.6	-109.5	-107.5		-106.7	-108.0	-107.2		
	Mid	-107.4	-109.5	-108.7	-108.0		-108.0	-107.3	-107.2		
	High	-106.9	-108.4	-108.2	-107.0		-107.1	-107.3	-106.4		
EGPRS 900	Low	-98.9	-98.5	-96.6	-100.1		-100.1	-97.1	-99.5		
	Mid	-98.7	-98.3	-97.0	-100.3		-100.4	-96.9	-99.3		
	High	-97.0	-97.1	-94.1	-99.1		-99.7	-95.2	-98.6		
EGPRS 1800	Low	-100.7	-100.3	-101.1	-98.8		-99.3	-99.8	-98.6		
	Mid	-100.0	-100.2	-100.3	-98.8		-100.6	-100.4	-98.8		
	High	-99.6	-99.2	-99.9	-97.8		-99.9	-98.4	-98.8		
WCDMA Band I	Low	-107.3	-110.1	-108.4	-106.5		-107.7	-107.9	-105.9		
	Mid	-108.9	-109.6	-107.7	-106.6		-107.7	-105.9	-105.4		
	High	-107.1	-109.6	-107.4	-106.5		-106.8	-107.9	-105.3		
WCDMA Band VIII	Low	-107.9	-107.7	-104.7	-107.8		-105.3	-106.9	-106.7		
	Mid	-107.2	-106.5	-105.6	-107.6		-105.1	-105.7	-107.3		
	High	-106.0	-105.0	-103.4	-105.2		-104.4	-104.4	-106.5		
LTE Band 3	Low	-95.6	-96.3	-95.4			-96.3	-94.7			
	Mid	-96.8	-97.4	-96.9			-96.0	-94.5			
	High	-95.2	-96.7	-95.9			-95.7	-93.6			
LTE Band 7	Low	-88.8	-91.5	-89.8			-88.3	-89.9			
	Mid	-88.7	-91.3	-90.8			-88.9	-90.1			
	High	-87.7	-90.7	-89.9			-89.1	-90.2			
LTE Band 20	Low	-94.3	-95.1	-89.9			-91.4	-91.8			
	Mid	-94.4	-94.1	-90.2			-88.6	-90.8			
	High	-93.5	-94.1	-91.9			-89.9	-89.8			

D.2 – Determining the range of sensitivity across a long list of 10 handsets with hand-head phantoms in GSM900 only

RAT / Band	Channel	TIS (dBm) with BHHR									
		Device 1 (Sample #1)	Device 2 (Sample #1)	Device 3 (Sample #1)	Device 4 (Sample #1)	Device 5 (Sample #1)	Device 6 (Sample #1)	Device 7 (Sample #1)	Device 8 (Sample #1)	Device 9 (Sample #1)	Device 10 (Sample #1)
GSM 900	Low	-93.7	-93.3	-91.8	-95.6	-97.8	-95.0	-95.2	-94.0	-96.0	-96.9
	Mid	-94.1	-93.2	-92.8	-94.8	-97.2	-95.0	-94.9	-93.8	-95.3	-97.2
	High	-92.2	-92.6	-91.4	-93.3	-97.0	-94.1	-93.0	-92.8	-93.8	-96.0

E. Results from Phase 2

RAT/ Band	Channel	TIS (dBm) in Free Space														
		Samples of Device 1			Samples of Device 2			Samples of Device 3			Samples of Device 4			Samples of Device 5		
		#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3
GSM 900	Low	-103.6	-104.0	-104.0	-103.6	-103.1	-104.0	-101.3	-96.3	-101.2	-105.7	-106.1	-105.9	-107.6	-108.2	-108.5
	Mid	-103.3	-104.0	-104.3	-103.1	-102.9	-103.2	-101.5	-96.2	-101.3	-104.9	-105.4	-106.2	-106.6	-107.1	-106.9
	High	-101.7	-103.0	-104.0	-102.2	-101.8	-102.4	-98.9	-96.4	-101.1	-103.7	-104.2	-105.3	-106.7	-106.7	-106.9
GSM 1800	Low	-105.0	-104.4	-105.9	-106.0	-105.7	-106.0	-105.5	-102.5	-105.6	-103.7	-104.2	-104.8	-110.0	-107.7	-108.0
	Mid	-104.7	-104.2	-105.0	-106.2	-106.5	-106.1	-104.9	-102.0	-104.8	-104.0	-104.7	-105.0	-108.7	-106.2	-107.2
	High	-104.3	-104.1	-104.5	-105.5	-106.2	-105.8	-104.6	-101.6	-104.4	-102.9	-103.3	-103.9	-107.0	-105.0	-106.1
GPRS 900	Low	-107.2	-107.9	-107.6	-107.4	-107.7	-106.5	-105.2	-104.4	-105.0	-109.6	-109.9	-109.4			
	Mid	-107.1	-108.2	-108.7	-107.4	-106.4	-106.9	-105.9	-104.5	-105.8	-109.1	-109.3	-109.4			
	High	-105.4	-106.3	-107.6	-106.1	-105.5	-105.5	-103.1	-102.5	-105.3	-107.5	-108.2	-107.9			
GPRS 1800	Low	-108.0	-109.1	-109.7	-109.6	-108.9	-109.7	-109.5	-106.6	-110.2	-107.5	-107.7	-108.0			
	Mid	-107.4	-108.7	-108.8	-109.5	-110.1	-110.0	-108.7	-106.3	-109.1	-108.0	-108.3	-108.9			
	High	-106.9	-107.7	-107.7	-108.4	-109.9	-110.1	-108.2	-106.3	-108.8	-107.0	-106.8	-107.7			
EGPRS 900	Low	-98.9	-99.2	-99.4	-98.5	-99.3	-99.5	-96.6	-95.4	-94.8	-100.1	-101.5	-100.9			
	Mid	-98.7	-99.9	-100.1	-98.3	-98.1	-98.9	-97.0	-97.1	-96.1	-100.3	-101.0	-100.9			
	High	-97.0	-98.5	-99.5	-97.1	-98.4	-97.5	-94.1	-93.8	-96.3	-99.1	-99.8	-99.1			
EGPRS 1800	Low	-100.7	-100.9	-98.5	-100.3	-101.2	-101.2	-101.1	-98.1	-101.4	-98.8	-99.4	-99.7			
	Mid	-100.0	-100.6	-102.3	-100.2	-101.7	-101.9	-100.3	-97.9	-100.9	-98.8	-100.1	-100.3			
	High	-99.6	-99.2	-100.4	-99.2	-101.9	-101.4	-99.9	-97.0	-100.3	-97.8	-99.0	-99.3			
WCDMA Band I	Low	-107.3	-107.2	-107.3	-110.1	-109.0	-109.0	-108.4	-104.9	-107.7	-106.5	-106.3	-106.4			
	Mid	-108.9	-106.9	-107.1	-109.6	-108.7	-108.7	-107.7	-104.6	-106.7	-106.6	-106.4	-107.3			
	High	-107.1	-106.9	-106.6	-109.6	-108.5	-108.2	-107.4	-105.5	-106.3	-106.5	-106.6	-106.6			
WCDMA Band VIII	Low	-107.9	-106.8	-107.5	-107.7	-106.2	-105.9	-104.7	-103.6	-103.2	-107.8	-108.7	-108.3			
	Mid	-107.2	-107.0	-107.3	-106.5	-105.3	-105.2	-105.6	-104.9	-102.5	-107.6	-107.8	-108.4			
	High	-106.0	-105.8	-105.8	-105.0	-103.5	-104.0	-103.4	-102.1	-100.2	-105.2	-106.6	-107.0			

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LTE Band 3	Low	-95.6	-95.6	-96.3	-96.3	-95.6	-95.7	-95.4	-89.3	-93.6						
	Mid	-96.8	-96.3	-96.9	-97.4	-97.4	-96.8	-96.9	-92.1	-94.1						
	High	-95.2	-95.4	-95.6	-96.7	-96.4	-96.0	-95.9	-94.4	-94.7						
LTE Band 7	Low	-88.8	-88.7	-89.1	-91.5	-91.7	-91.9	-89.8	-88.2	-87.9						
	Mid	-88.7	-88.7	-89.8	-91.3	-92.0	-92.9	-90.8	-89.2	-87.9						
	High	-87.7	-87.3	-88.3	-90.7	-91.1	-92.6	-89.9	-90.2	-87.1						
LTE Band 20	Low	-94.3	-94.3	-94.4	-95.1	-94.6	-95.3	-89.9	-87.8	-87.8						
	Mid	-94.4	-95.0	-94.0	-94.1	-94.6	-94.9	-90.2	-86.0	-88.9						
	High	-93.5	-94.2	-93.9	-94.1	-94.4	-94.9	-91.9	-90.8	-90.4						

F. Results from Phase 3

RAT/ Band	Chan nel	TIS (dBm) with Hand and Head Phantoms														
		Device 1 (Sample #2)			Device 2 (Sample #2)			Device 3 (Sample #3)			Device 4 (Sample #2)			Device 5 (Sample #3)		
		Free Space	BHHL	BHHR	Free Space	BHHL	BHHR	Free Space	BHHL	BHHR	Free Space	BHHL	BHHR	Free Space	BHHL	BHHR
GSM 900	Low	-104.0	-84.8	-92.9	-103.1	-85.0	-92.2	-101.2	-89.3	-90.6	-106.1	-94.4	-95.0	-101.2	-97.8	-97.6
	Mid	-104.0	-85.8	-93.8	-102.9	-86.4	-91.9	-101.3	-89.8	-91.3	-105.4	-93.5	-94.4	-101.3	-95.5	-96.2
	High	-103.0	-84.6	-92.5	-101.8	-85.1	-91.4	-101.1	-89.3	-89.8	-104.2	-92.3	-92.8	-101.1	-95.9	-95.6
GSM 1800	Low	-104.4	-98.1	-88.0	-105.7	-99.3	-94.6	-105.6	-100.5	-99.5	-104.2	-98.2	-98.1	-105.6	-102.1	-100.1
	Mid	-104.2	-98.3	-87.3	-106.5	-100.0	-95.4	-104.8	-99.8	-99.2	-104.7	-98.9	-98.6	-104.8	-101.4	-99.3
	High	-104.1	-97.5	-88.0	-106.2	-99.5	-94.8	-104.4	-99.3	-98.5	-103.3	-98.6	-98.2	-104.4	-100.6	-98.7
GPRS 900	Low	-107.9	-89.0	-96.3	-107.7	-87.6	-95.8	-105.0	-91.9	-93.9	-109.9	-97.1	-97.1			
	Mid	-108.2	-88.1	-96.9	-106.4	-88.5	-96.9	-105.8	-94.7	-96.4	-109.3	-96.2	-97.0			
	High	-106.3	-87.5	-95.4	-105.5	-87.0	-95.7	-105.3	-92.9	-97.0	-108.2	-95.2	-95.1			
GPRS 1800	Low	-109.1	-100.5	-88.4	-108.9	-99.4	-98.6	-110.2	-104.0	-103.2	-107.7	-99.6	-97.1			
	Mid	-108.7	-100.7	-88.9	-110.1	-98.9	-100.0	-109.1	-104.2	-102.7	-108.3	-101.8	-101.1			
	High	-107.7	-100.1	-89.7	-109.9	-98.4	-99.8	-108.8	-103.3	-103.0	-106.8	-100.3	-100.0			
EGPRS 900	Low	-99.2	-88.6	-87.4	-99.3	-85.6	-89.2	-94.8	-83.4	-85.5	-101.5	-88.7	-90.2			
	Mid	-99.9	-89.1	-88.5	-98.1	-85.4	-88.9	-96.1	-83.7	-86.9	-101.0	-88.9	-89.7			
	High	-98.5	-88.3	-87.1	-98.4	-84.6	-87.9	-96.3	-82.8	-85.0	-99.8	-87.4	-88.7			
EGPRS 1800	Low	-100.9	-93.2	-82.7	-101.2	-92.2	-90.0	-101.4	-94.1	-98.1	-99.4	-91.6	-92.7			
	Mid	-100.6	-93.2	-82.3	-101.7	-92.8	-91.5	-100.9	-93.9	-95.3	-100.1	-93.6	-93.1			
	High	-99.2	-92.9	-83.3	-101.9	-91.9	-91.6	-100.3	-93.8	-94.1	-99.0	-92.7	-93.2			
WCDMA Band I	Low	-107.2	-99.4	-98.9	-109.0	-103.9	-103.6	-107.7	-102.2	-104.5	-106.3	-103.7	-101.9			
	Mid	-106.9	-98.7	-99.3	-108.7	-103.8	-104.1	-106.7	-101.2	-103.1	-106.4	-104.0	-102.2			
	High	-106.9	-99.9	-100.3	-108.5	-103.9	-104.1	-106.3	-100.2	-103.0	-106.6	-103.8	-102.4			
WCDMA Band VIII	Low	-106.8	-95.2	-97.1	-106.2	-97.6	-97.0	-103.2	-90.6	-93.2	-108.7	-96.1	-97.2			
	Mid	-107.0	-95.2	-97.1	-105.3	-96.7	-96.3	-102.5	-90.6	-93.4	-107.8	-95.6	-96.5			
	High	-105.8	-94.0	-96.2	-103.5	-94.7	-95.2	-100.2	-87.1	-91.5	-106.6	-93.9	-94.7			

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LTE Band 3	Low	-95.6	-87.0	-83.8	-95.6	-88.2	-86.9	-93.6	-86.4	-84.5						
	Mid	-96.3	-88.0	-84.4	-97.4	-89.7	-87.7	-94.1	-90.0	-88.9						
	High	-95.4	-86.7	-83.8	-96.4	-89.2	-87.6	-94.7	-89.6	-88.4						
LTE Band 7	Low	-88.7	-82.3	-82.9	-91.7	-86.0	-87.4	-87.9	-85.1	-86.3						
	Mid	-88.7	-82.4	-83.7	-92.0	-86.1	-88.5	-87.9	-83.6	-85.9						
	High	-87.3	-81.7	-83.0	-91.1	-85.1	-86.8	-87.1	-82.6	-85.8						
LTE Band 20	Low	-94.3	-85.9	-85.3	-94.6	-86.4	-86.9	-87.8	-82.4	-80.4						
	Mid	-95.0	-85.0	-85.2	-94.6	-86.1	-82.4	-88.9	-81.0	-81.9						
	High	-94.2	-84.7	-84.6	-94.4	-85.6	-83.0	-90.4	-82.7	-82.0						

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