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ENTERPRISE AND INDUSTRY DIRECTORATE-GENERAL

Technical support relating to performance of antennas of mobile phones

Final report

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1. Scope

This *Final report* relates to a *Technical support relating to performance of antennas of mobile phones*, ordered by the European Commission, Enterprise and Industry Directorate-General (“the Commission”), to Eurexcem. This second edition supersedes the first edition dated 5 January 2014.

The technical references appear in “§ 9. Technical References”. In the text of this report, characters between square brackets, such as [T2], indicate one of the technical references listed in § 9.

2. Executive summary

This report is about mobile phones, a mobile phone being defined as a portable cellular phone comprising one or more integral antennas, which is intended to be held by the user during wireless communication, and which bears the CE conformity marking defined in Annex VII of the R&TTE directive. The observed radio performance of a mobile phone, that is to say its performance as regards reception of radio signals or emission of radio signals, as it is experienced by a user, depends on the characteristics of its antenna(s). Because of poor antenna performance, the observed radio performance of a mobile phone is not always satisfactory in places where the signal from the base station is weak. This report investigates whether the technical requirements of harmonized standards are adequate to avoid this problem, and analyses the need for and the feasibility of the introduction of additional requirements.

Measuring the relevant characteristics of the antenna(s) of a mobile phone is always very difficult, and it requires a modification of the mobile phone which is likely to alter these characteristics significantly. Moreover, the measurements would be of unrealistic complexity for mobile phone designs implementing an adaptive antenna tuning. The best approach to guarantee a satisfactory observed radio performance of a mobile phone in places where the signal from the base station is weak consists in defining limits for suitable radiated radio performance tests applicable to the mobile phone regarded as a system comprising the antenna(s), because the corresponding measurements are simpler.

A review of the adequacy of existing performance requirements on emission and reception, as regards the observed radio performance of mobile phones, allows us to maintain that:

- the compliance of a mobile phone with the harmonized standards currently covering the essential requirements of article 3.2 of the R&TTE directive, as they are actually implemented, does not ensure a satisfactory observed radio performance in places where the signal from the base station is weak;
- additional requirements applicable to radiated radio performance tests, meeting seven criteria discussed in the report, could be sufficient to guarantee a satisfactory observed radio performance in places where the signal from the base station is weak;
- test specifications of radiated radio performance tests meeting at least four of these criteria are already available in some published test specifications, and it is possible to define additional or modified test specifications, so as to meet all criteria.

Concerns have been raised on the compatibility between a good observed radio performance in places where the signal from the base station is weak, and a low user’s exposure to electromagnetic fields. It may be shown that there is no conflict so that a mobile phone can provide both characteristics.

The possibility of promoting an improved observed radio performance can be addressed from two perspectives: the technical feasibility of an improved observed radio performance; and the technical feasibility of new technical requirements or new labeling requirements. We reach the following conclusions:

- many techniques exist to improve the observed radio performance in places where the signal from the base station is weak;
- new systematic and consistent technical requirements for placing a mobile phone on the market in the European Union, which would guarantee that the mobile phone should provide a satisfactory observed radio performance in places where the signal from the base station is weak, are technically feasible;
- such new technical requirements might duplicate some of the requirements of current voluntary certification programs;
- new labeling requirements for placing a mobile phone on the market in the European Union, which would ensure that consumers are informed of the observed radio performance to be expected of a mobile phone in places where the signal from the base station is weak, are technically feasible and could use at least 3 performance levels.

3. Introduction

3.1 Motivation

The Commission recently received a question from a Member of the European Parliament (MEP) [T59] mentioning investigations on the connection quality of mobile telephony in Denmark [T56] [T58] which have shown that:

- the coverage of cellular wireless networks is very nonuniform over this country, in terms of the ability to access the network (coverage) of a telecom operator, and of the achievable data rate;
- there are differences among telecom operators, as regards coverage and achievable data rate;
- there are differences in the sensitivity of mobile telephones, determined as the minimum electric field strength providing a specified downlink performance, in the presence of a human phantom head and hand.

The MEP considers that the antennas of popular mobile phones “are often unable to capture weaker signals” and asks the Commission if it agrees “that consumers should be better informed through an EU labeling system on antenna strength” and if the Commission will “reconsider introducing requirements for a new minimum standard for mobile antennae in the European market”.

Furthermore, concerns have been raised on the relation between performance of antennas and reduction of measured Specific Absorption Rate (SAR). Some stakeholders have alleged possibly contradictory objectives. According to them, a good user experience and the effective use of the spectrum are facilitated by higher antenna gains, whereas the pressure from consumer associations and authorities to have low SAR values may bring some manufacturers to opt for lower antenna gains.

Therefore the Commission has considered appropriate to have a deeper factual analysis of the current situation, and of the feasibility of the introduction of additional requirements and/or a labeling system before taking action in this area [T60]. This is the purpose of the contract *Technical support relating to performance of antennas of mobile phones* of Eurexcem with the Commission, which led to the present report.

3.2 This document

This report is about the observed radio performance of a mobile phone in places where the signal from the base station is weak, how it is covered by regulations and standards, whether it can be improved, and the availability of related information to users. The definitions of a *mobile phone*, of the *observed radio performance*, and of other important concepts used throughout the report are provided in § 4.

The observed radio performance of a mobile phone depends on the characteristics of its antenna(s). As pointed out in § 3.1, the observed radio performance of a mobile phone is not always satisfactory in places where the signal from the base station is weak. In § 5, we present the main parameters influencing the observed radio performance of a mobile phone in places where the signal from the base station is weak, from the perspectives of wireless communication theory and of electromagnetic theory. We also use the § 5 to address some electronic engineering and compliance engineering aspects of the question. A reader who is not interested in technical details can skip § 5.

In § 6, we review the adequacy of existing performance requirements on emission and reception as regards the observed radio performance of mobile phones, and we define some requirements meeting the actual technical needs. In § 7, we discuss the possibility of combining a good observed radio performance in places where the signal from the base station is weak, with a low user's exposure to electromagnetic fields.

In § 8, we address the possibility of promoting an improved observed radio performance, from two perspectives: the technical feasibility of an improved observed radio performance; and the technical feasibility of new technical requirements or new labeling requirements

4. Vocabulary

The following definitions apply to the present document. They are listed in a logical order instead of an alphabetical order.

R&TTE directive
Directive 1999/5/EC of the European Parliament and of the Council [T1].
Note: we do not take into account the current revision process and the proposed radio equipment directive [T3].

harmonized standard
A standard meeting the definition given in article 2 of the R&TTE directive, and referred to as in § 5.1 of the R&TTE directive.

radio performance test
A test of a wireless device, the result of which is representative of the performance of the wireless device as regards reception of radio signals or emission of radio signals.

conducted radio performance test
A radio performance test during which the power used for radio transmission is transferred via one or more conductors (based on the definition 161-03-27, conducted disturbance, of IEV [T5]).
Note 1: A conducted performance test may relate to emission and/or reception by the wireless device.
Note 2: A conducted performance test is typically performed using an antenna connector of the wireless device, as a part of a link between a wireless device under test and one or more measuring instruments.

radiated radio performance test
A radio performance test during which the power used for radio transmission is transferred through space in the form of electromagnetic fields propagated in space without artificial guide (based on the definition 161-03-28, radiated disturbance, of IEV [T5], and Article 2 of the R&TTE directive [T1]).
Note 1: A radiated radio performance test may relate to emission and/or reception by the wireless device.
Note 2: A radiated radio performance test is only applicable to a wireless device comprising an antenna, for instance a wireless device comprising an integral antenna.
Note 3: A radiated radio performance test is sometimes referred to as over-the-air (OTA) test.

mobile phone
A portable cellular phone comprising one or more integral antennas, which is intended to be held by the user during wireless communication, and which bears the CE conformity marking defined in Annex VII of the R&TTE directive.

GSM mobile phone
A mobile phone intended to be able to operate as a mobile station (MS) of a GSM network. This also covers the possible GPRS or EDGE capabilities.
Note: a GSM mobile phone may also be a UMTS mobile phone and/or an LTE mobile phone.

UMTS mobile phone
A mobile phone intended to be able to operate as a user equipment (UE) of a UMTS network or its upgrades which, like UMTS, uses CDMA as multi-access technique. This covers possible HSPA or HSPA+ capabilities, even though they use TDMA as primary multi-access technique.
Note: a UMTS mobile phone may also be a GSM mobile phone and/or an LTE mobile phone.

LTE mobile phone
A mobile phone intended to be able to operate as a user equipment (UE) of an LTE network and its upgrades which, like LTE, uses OFDMA as downlink multi-access technique and SC-FDMA as uplink multi-access technique. This covers possible LTE-Advanced (LTE-A) capabilities.
Note: an LTE mobile phone may also be a UMTS mobile phone and/or a GSM mobile phone.

user effects
The effects, on a wireless link comprising a mobile phone, of the coupling between the user of the mobile phone and one or more integral antennas of the mobile phone. These effects comprise:

- a variation in the impedance of the antenna (in the case of a single integral antenna), or in the impedance matrix of the antennas (in the case of a plurality of integral antennas);
- a variation in the radiation efficiency of the system formed by the mobile phone and the user;
- a variation in the directivity of the system formed by the mobile phone and the user.

anthropomorphic phantom
A physical model of a human body or of one or more parts of a human body, intended to be used in some radiated radio performance tests, or in tests relating to human exposure to electromagnetic fields.

anthropomorphic phantom effects
The effects, during a radiated radio performance test relating to a mobile phone, of the coupling between an anthropomorphic phantom and one or more integral antennas of the mobile phone.
Note: anthropomorphic phantom effects are intended to accurately emulate user effects, but this goal is difficult to achieve, because of the variability of human bodies, postures and movements.

observed radio performance
The performance of a wireless device as regards reception of radio signals or emission of radio signals, as it is experienced by a user.

MIMO
MIMO stands for multiple-input and multiple-output. MIMO systems are studied in signal processing theory, communication theory and circuit theory. In the field of wireless transmission, spatial diversity and spatial multiplexing, which involve multiple antennas for emission and/or reception, are often collectively referred to as MIMO techniques (even though MIMO should only refer to spatial multiplexing).

5. Preliminary technical discussion

5.1 Some wireless communication engineering aspects

In downlink transmission, a mobile phone receives a signal from a base station. Here, the signal strength at the terminals of an antenna of the mobile phone depends on the instantaneous path loss between the antenna of the mobile phone and the one or more antennas used, in the base station, to cover the place where the mobile phone operates. The inverse of the path loss is a path gain. At a place where the signal from the base station is weak, the average path gain (discussed below in § 5.2.3) is low. This typically occurs at the boundary of a cell. The instantaneous path loss and average path gain applicable to uplink transmission, where a mobile phone emits a signal intended for the base station, are the same as the one applicable to downlink transmission.

The instantaneous path loss experienced by a mobile phone varies with time, a phenomenon referred as fading. We may distinguish three cases as regards fading: negligible fading, which may for instance occur in the case where a stable line-of-sight path is much stronger than all reflected and scattered paths; slow fading, which may for instance occur when the mobile phone and the reflecting objects surrounding it move at a zero or low enough speed with respect to the base station; and fast fading, which may for instance occur when the mobile phone move at a high enough speed with respect to the base station. Different performance measures of a downlink or uplink channel are applicable to the three fading scenarios [T36, ch. 5]:

- in the cases of negligible fading and fast fading, it is possible to define a *capacity* of the channel, that is to say the maximum data rate for which an arbitrary small error probability can be achieved;
- in the case of slow fading, it is possible to define an *outage probability* of the channel as the probability of not being able to decode a given data rate with an arbitrary small error probability, and an *ε-outage capacity* of the channel, as the maximum data rate for which the outage probability is less than ε.

At places where the average path gain is low, the input-referred signal-to-noise ratio (SNR) experienced by the receiver is low. In this context, the capacity and the ε-outage capacity are proportional to the input-referred signal-to-interference plus noise ratio (SINR) experienced by the receiver, the SINR being low because it is less than or equal to the SNR. This is in contrast with the context of high SINR, where the effect of SINR on capacity and ε-outage capacity is less pronounced. The effect of SINR on the outage probability is more complex, and depends on the statistical properties of the channel. However, an increased SINR obviously reduces the outage probability. It can be shown that MIMO techniques (see § 4 above) using multiple antennas in a mobile phone, to obtain spatial diversity or spatial multiplexing, are very effective to reduce the outage probability [T27, Sec. 9, Par. 7] [T36, ch. 5]. We note that the diversity versus multiplexing tradeoff is a complex subject [T36, ch.9] [T50, § 5.6]. In a GSM mobile phone, downlink MIMO using two antennas in the mobile phone, providing spatial diversity only, is possible using a recent addition to the standards called Mobile Station Receive Diversity (MSRD) [T25, § 14.19] [T51, § 19.2]. In a UMTS mobile phone, downlink MIMO using two antennas in the user equipment can provide spatial diversity or spatial multiplexing, as from 3GPP release 7 [T12, § 5] [T19, § 9] [T50, § 1.2.4] [T51, § 19.1]. In a LTE mobile phone, spatial diversity or spatial multiplexing may be obtained in downlink MIMO using up to 8 antennas in the user equipment, and in uplink MIMO using up to 4 antennas in the user equipment, as from 3GPP release 10 [T21, § 5 and § 6] [T26] [T51, § 11.3] [T67, § 14.1]. However, these capabilities are currently only partially implemented in mobile phones.

If the average path gain discussed above is low, the SINR at the input of the mobile phone receiver and the SINR at the input of the base station receiver are low. The mobile phone has no access to the network if the SINR at the input of the mobile phone receiver is so low that the mobile phone cannot synchronize with a cell of the cellular network and acquire the information needed to communicate with the cell; or if the SINR at the input of the base station receiver is so low that the base station cannot acquire the information needed to communicate with the mobile phone. If the mobile phone has access to the network, a range of data rates, coding schemes and modulations are available to take advantage of the channel condition at a given time. This range depends on the types of cellular wireless transmission system (e.g., GSM, UMTS, LTE) that the mobile phone and the base station can use. However, the capacities or ε-outage capacities (as applicable) of the downlink and uplink channels set upper bounds on the achievable data rates, and they are, as explained above, proportional to SINR in places where the average path gain is low.

The coverage of a cellular wireless network is the geographical area where some quality of service requirements are met. A common requirement is a minimum throughput at the 5% point in the cumulative distribution function (CDF), for the downlink and the uplink [T10]. A throughput at the 5% point in the CDF corresponds to the maximum data rate for which a specified mobile phone can communicate with a cell, with a probability of at least 95%, divided by the overall cell bandwidth. The throughput at the 5% point in the CDF is bounded by the 5%-outage capacity. One may argue that different throughput at the 5% point in the CDF should be defined for GSM, UMTS and LTE, because the expected performance is higher for UMTS than for GSM, and higher for LTE than for UMTS. It is important to note that the throughput expected at the cell edge (where the average path gain is low) is much lower than the peak throughput [T15]. Since the coverage is not a property of a mobile phone, it will not be discussed in this report. However, it has a lot to do with the satisfaction of a mobile phone user.

Up to now, we have emphasized the importance of SINR at the input of the receiver, and diversity techniques to improve the performance in places where the average path gain is low. The SINR is a ratio, whose denominator is the sum of the power of interfering signals and the input-referred noise power of the receiver. The relative importances of noise and interference are likely to be different for GSM, UMTS and LTE, because they use different multiple access techniques and different frequency reuse schemes between adjacent cells.

5.2 Some electromagnetic engineering aspects

5.2.1 Antenna gain, radiation efficiency and directivity

The *absolute gain* of an antenna, in a given direction, is the product of the *radiation efficiency* and the *directivity* in the given direction [T31, § 2.7]. The radiation efficiency is a positive real number less than or equal to 1, independent of the direction. It is equal to 1 for an ideal antenna. The average directivity over solid angles corresponding to all directions is one, that is to say

$$\frac{1}{4\pi}\oint\!\!\oint_{\Omega} D\,d\Omega = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} D\sin\theta \; d\theta \; d\varphi = 1 \qquad (1)$$

where D denotes the directivity; Ω denotes the solid angle of a sphere, that is 4π steradians; and θ and φ denotes the angles of spherical coordinates, for which the element of solid angle is $\mathrm{d}\Omega = \sin\theta \; d\theta \; \mathrm{d}\varphi$. A directivity pattern of an antenna is a plot of its directivity as a function of θ or φ. A directivity pattern is said to be directional if it has one major lobe with a directivity much greater than one and a directivity much less than one elsewhere. Conversely, an omnidirectional directivity pattern corresponds to a low maximum directivity, for instance a directivity less than 3, keeping in mind that the smallest possible maximum directivity is 1.

In the case of a mobile phone, the current flowing in the antenna or antennas during reception or emission is associated with a current flowing in other parts of the mobile phone with a significant current density. Typically, the current flowing in the antenna(s) and the current flowing in said other parts of the mobile phone interact strongly. Consequently, the absolute gain and the radiation efficiency of an antenna of the mobile phone are in fact the absolute gain and the radiation efficiency of the system formed by the antenna and the other parts of the mobile phone. They are defined in an hypothetical configuration where the mobile phone would operate at a sufficient distance from other items (including persons).

5.2.2 About the path loss

In the context of fixed microwave links (which are point-to-point radio services in which neither station is mobile) and of microwave links between earth and spacecrafts, high gain antennas are used for the station built on earth, so that a single-path and line-of-sight propagation takes place. In this context, the path loss between an antenna A used for emission and an antenna B used for reception, is sometimes defined by [T28, ch. 34] [T41, ch. 5]

$$L_1 = G_A G_B \frac{P_T}{P_R} \tag{2}$$

where P_T is the power delivered to the antenna A for transmitting a signal; P_R is the power delivered by the antenna B for this signal; G_A is the absolute gain of the antenna A in the direction of the antenna B; G_B is the absolute gain of the antenna B in the direction of the antenna A; and L_1 is the path loss defined by (2). In this definition, we see that any polarization mismatch of the antenna B with the incident field, and/or any impedance mismatch between the antenna B and the load seen by the antenna B will modify P_R so that L_1 depend on the effect of such mismatches. To avoid this problem, another definition of path loss is

$$L_2 = G_A G_B \frac{P_T}{P_{AVA} L_P} \tag{3}$$

where P_{AVA} is the available power at the terminals of the antenna B for the signal sent by the antenna A; L_P is a *polarization loss* defined as the inverse of the polarization mismatch factor, as in (A2) of Appendix A; and L_2 is the path loss defined by (3). If there is no mismatch between the antenna B and the load seen by the antenna B, and no polarization mismatch of the antenna B with the incident field, then $L_2 = L_1$. The beauty of this definition resides in that, in the context defined above, L_2 is completely independent from the characteristics of the transmitter, the receiver and the antenna B, and from the gain of the antenna A. In the context of single-path and line-of-sight propagation, we have

$$L_2 = \left(\frac{4\pi\, d}{\lambda} \right)^2 L_A \tag{4}$$

where λ is the wavelength; d is the distance between the antennas; and L_A is the atmospheric attenuation (which would be equal to one in the case of a lossless atmosphere).

In the context of a cellular wireless network, a lot of scattering is expected to occur in the vicinity of the mobile station (MS) or user equipment (UE), so that multiple paths are involved in the link. Consequently, the antenna gain applicable to the MS or UE antenna(s) is not defined. Moreover, multipath propagation and undetermined orientation of the MS or UE imply an undetermined polarization loss. Additionally, the direction from the base station to the MS or UE is not known, so that the antenna gain applicable to the base station is not accurately known. Thus, the definitions (2) and (3) cannot be used. A radical solution to this problem is another definition of path loss which is similar to the definition of § 2.1 of the COST 231 Final Report [T33]:

$$L_3 = \frac{P_T}{P_R} \tag{5}$$

where L_3 is an instantaneous path loss subject to fluctuations. Another advantage of this definition is that it is valid in the presence of the user effects. Unfortunately, L_3 depends on the characteristics of the antenna A, of the antenna B, of the load connected to the antenna B. Also, like L_1, L_3 is influenced by any polarization or impedance mismatch between the antenna B and the load seen by the antenna B.

To establish a link budget between a base station and a mobile phone, engineers commonly use another approach [T32, § 6.4.4] [T44, § 9.5]: they formally use (3), with the following modifications: they set the antenna gain of the mobile phone antenna(s) to 0 dBi; they use a nominal gain of the base station antenna(s) instead of the actual gain in the direction from the base station to the mobile phone; they introduce a separate factor accounting for the user effects. If we assume a single antenna in the base station and a single antenna in the mobile phone, the resulting formula is

$$L_4 = G_{BSN} \frac{P_T}{P_R \, L_{BOD4}} \tag{6}$$

where G_{BSN} is the nominal absolute gain of the base station antenna, which is independent of the direction; L_{BOD4} is a body loss accounting for the user effects, defined more accurately below; and where L_4 is an instantaneous path loss subject to fluctuations. Since link budgets are established to determine worst-case scenarios where the mobile phone is at the cell boundary, since the base station antenna is normally intended to have a maximum directivity toward the cell boundary, and since little scattering is expected to occur near the base station antenna, it is legitimate to use their nominal gain G_{BSN} in (6).

In (6), L_{BOD4} describes all effects, on P_R, of the coupling between the user of the mobile phone and the integral antenna of the mobile phone, so that $P_R \, L_{BOD4}$ is the power which would be delivered by the antenna B for the signal applied to the antenna A, if the user was not present. We note that L_{BOD4} comprises the effects, on P_R, of the radiation efficiency of the system formed by the mobile phone and the user, of the directivity of the system formed by the mobile phone and the user, and of the impedance of the mobile phone antenna.

A first problem in (6) is that L_4 and L_{BOD4}, like L_1 and L_3, are influenced by any impedance mismatch between the antenna B and the load seen by the antenna B. We must note that a good impedance match is difficult to achieve at every frequency used by a mobile phone for reception [T42, § 5.3.1], and that, in addition, the impedance of each antenna may be significantly influenced by the user effects [T42, § 7.6.2]. Consequently this first problem is significant for the downlink link budget. A second problem in (6) is that, in the context of strong scattering close to the mobile phone antenna, an averaging of the gain over the solid angle of a sphere is legitimate, but, according to (1), the result of this averaging is the radiation efficiency of the mobile phone antenna, instead of 1 or 0 dB. Consequently, L_4 depends on this radiation efficiency! A third problem in (6) is that, in this context of a scattering-rich environment, an averaging of $1/L_P$ over all possible polarizations is legitimate, but, as explained in Appendix A, the result of this averaging is 1/2, instead of 1 or 0 dB. For these reasons, we introduce another definition of the path loss,

$$L_5 = \frac{e_{MP}}{2} G_{BSN} \frac{P_T}{P_{AVA} L_{BOD5}} \tag{7}$$

where e_{MP} is the radiation efficiency of the mobile phone antenna (which, as explained in § 5.2.1 is in fact a property of the whole mobile phone) in a configuration where the user is not present; L_{BOD5} is a body loss accounting for the user effects, defined more accurately below; and where L_5 is an instantaneous path loss subject to fluctuations.

In (7), L_{BOD5} describes all effects, on P_{AVA}, of the coupling between the user of the mobile phone and the integral antenna(s) of the mobile phone, so that $P_{AVA} \, L_{BOD5}$ is the power which would be available from the antenna B for the signal applied to the antenna A, if the user was not present. We note that L_{BOD5} comprises the effects, on P_{AVA}, of the radiation efficiency of the system formed by the mobile phone and the user, and of the directivity of the system formed by the mobile phone and the user. We note that L_{BOD5} is in general different from L_{BOD4}.

L_5 and L_{BOD5}, like L_2, are not influenced by an impedance mismatch between the antenna B and the load seen by the antenna B. Moreover, L_5 is independent of the radiation efficiency of the mobile phone antenna.

Based on the previous discussion, we can say that, among the definitions that we have considered, (7) is the most suitable for the discussion of link budgets, because L_5 has the smallest dependence on the characteristics of the transmitter, the antenna A, the receiver and the antenna B. We note that L_5 is more relevant at the cell boundary, where the average signal from the base station is expected to be the weakest.

Up to now, we have discussed the concept of path loss in the context of a single transmitting antenna (antenna A) and a single receiving antenna (antenna B). In the case where multi-antenna techniques are used in the base station and/or in the mobile phone, (7) can nevertheless be used to define the path loss, for the following reasons:

- the definitions of P_T and P_{AVA} are applicable to a multiport antenna array, so that L_{BOD5} is also defined;
- the different antennas used, in the base station, to communicate with the mobile phone typically have a sufficient spacing to allow us to use (7) with each of these antennas, each having its own G_{BSN} ;
- the different antennas used, in the mobile phone, to communicate with the base station typically do not have a sufficient spacing to allow us to ignore the non-diagonal entries of their impedance matrix, but we can use the definition of e_{MP} given by (B11) in Appendix B, which takes these entries into account.

5.2.3 Link budget and the effect of the directivity of a mobile phone antenna

Based on (7), the following formula can be used to establish an instantaneous link budget:

$$P_{AVA\,dBm} = P_{T\,dBm} + G_{BSN\,dB} + 10\log(e_{MP}) - 3\,\mathrm{dB} - L_{5dB} - L_{BOD5dB} \tag{8}$$

where $P_{AVA\,dBm}$ is the available power, in dBm, at the terminals of the receiving antenna(s), for the signal sent by the transmitting antenna(s); $P_{T\,dBm}$ is the power delivered to the transmitting antenna(s), in dBm; G_{BSNdB} is the nominal absolute gain of the base station antenna(s), in dB; $L_{5\,dB}$ is the instantaneous path loss defined by (7), in dB; and $L_{BOD5\,dB}$ is the body loss accounting for the user effects, defined above, in dB.

Some experimental results on the user effects indicate the combined effects of $L_{BOD5\,dB}$ and of the variation of the impedance of a mobile phone antenna on the power received by a measuring receiver. The results are different for the different categories of mobile phone shapes, commonly referred to as “candybar”, “clamshell” and “slider”. This combined effects, for a head and a hand, typically range, for a “candybar” mobile phone from 7 dB to 12 dB in the 800 MHz to 900 MHz band and from 3 dB to 9 dB in the 1.8 GHz to 2.1 GHz band [T40] [T42, § 5.2.5] [T54] [T57, § 4.2].

Assuming the independence of the randomness of L_P, L_5 and L_{BOD5}, the following formula can be used to establish an average link budget at a given place, using a uniform probability density function for the orientations of the mobile phone:

$$< P_{AVA} >_{dBm} = P_{T\,dBm} + G_{BSN\,dB} + 10\log(e_{MP}) - 3\,\mathrm{dB} + < G_5 >_{dB} + < G_{BOD5} >_{dB} \tag{9}$$

where $< P_{AVA} >_{dBm}$ is the expectation of P_{AVA}, in dBm; $< G_5 >_{dB}$ is the expectation of the path gain $G_5 = 1/L_5$, in dB; and $<G_{BOD5}>_{dB}$ is the expectation of $G_{BOD5} = 1/L_{BOD5}$, in dB. Several models are available to estimate $< G_5 >_{dB}$ in a given environment, for instance the propagation prediction models of the COST 231 Final Report [T33, ch. 4] or other propagation prediction models [T42, ch. 3].

We observe that, as explained in § 5.2.2, (9) does not contain the gain of the mobile phone antenna(s). However, (9) contains e_{MP} which is either the radiation efficiency given by (B2) of Appendix B, in the case of a mobile phone using a single antenna to communicate with the base station, or an average value of the radiation efficiency for instance given by (B11) of Appendix B, in the case of a mobile phone using multiple antennas to communicate with the base station. In both cases, $e_{MP} \leq 1$, and $e_{MP} = 1$ is of course the most desirable value.

In spite of the averaging over the solid angle of a sphere and over all possible polarizations used to obtain e_{MP} in (7), the directivity of the mobile phone antennas and their polarization play a role in (7) and (8). For instance, if there is no or little scattering close to an hypothetical mobile phone using a single antenna having a directional directivity pattern, $L_{5\ dB}$ and $P_{AVA\ dBm}$ will both change a lot when the orientation of the mobile phone is varied over all possible directions. However, because of the averaging performed to obtain (9), $< G_5 >_{dB}$ and $< P_{AVA} >_{dBm}$ are independent of the orientation of the mobile phone. Consequently, the directivity of the mobile phone antennas and their polarization play no role in (9).

In a context where there is no or little scattering close to a mobile phone using a single antenna to communicate with the base station, an omnidirectional directivity pattern should provide the best user experience, because the user of a mobile phone is not expected to look for the orientation providing the lowest path loss. We must keep in mind that the directivity pattern of an antenna is significantly influenced by the user effects [T42, § 7.6.3].

5.2.4 Directivity and correlations for a mobile phone using a multiport antenna array

In the case of a mobile phone using simultaneously multiple antennas to communicate with the base station, these antennas form a multiport antenna array presenting a nondiagonal impedance matrix. As said in § 4, multiple antenna techniques are loosely referred to as MIMO technique. Here, the directivity of each antenna of the antenna array depends on the impedance matrix of the multiport circuit connected to the antenna array [T39, § 4]. It is also possible to define a cumulative directivity for all the antennas of the antenna array, which also depends on the impedance matrix of the multiport circuit connected to the antenna array.

In a context where there is no or little scattering close to a mobile phone using multiple antennas to communicate with the base station, an omnidirectional cumulative directivity pattern should provide the best user experience.

It was said in § 5.1 that MIMO techniques using multiple antennas in a mobile phone are very effective to reduce the outage probability. To obtain the benefits of such techniques using multiple antennas, it is necessary to use antenna having sufficiently small correlation coefficients for incident waves having given angular power probability density functions [T42, § 5.2.4]. In the base station, a low correlation can be easily obtained using a sufficient spacing between the antennas. In a mobile phone, a sufficient distance is not available in the lowest relevant frequency bands. We note that a low correlation can in theory be obtained using antennas having non-overlapping directivity patterns (this is difficult to achieve in the lowest relevant frequency bands); or cross-polarized antennas (in practice this is limited to 2 polarizations); or, in the case where multipath components arrive uniformly from all angles of arrival, a matching network providing bilateral Hermitian match [T34].

The directivity pattern of each antenna in an antenna array, and the correlation coefficients between its antennas are clearly influenced by the user effects [T42, § 7.7.4].

5.3 Some electronic engineering aspects

5.3.1 Conducted sensitivity

The sensitivity of a wireless receiver may be defined as the minimum level of electrical signals applied at the antenna inputs of the receiver, for which the output signal of the receiver meets a certain criterion, in a given test configuration. For instance, in the case of an analog receiver for single-side band (SSB) communication, the criterion may be an output signal having a signal-to-noise ratio of 12 dB, for a nominal receiver selectivity of 2.3 kHz. For instance, in the case where this analog receiver has a single antenna input which corresponds to an antenna connector with a nominal input impedance of 50 Ω, the given test configuration may use a signal generator having an internal impedance of 50 Ω, producing a continuous wave, having its output coupled to the antenna connector, and the signal level may be defined as the r.m.s. voltage delivered by the generator, if the antenna input of the receiver is replaced with a 50 Ω load. In the case of the receiver of a mobile phone, the situation is much more complex than in our simple example of an analog receiver. Complexity occurs because:

- the mobile phones defined in § 4 use digital wireless communication, for which the definition of the criterion and of the test configuration is more involved;
- the mobile phones may use different modulations and bandwidths;
- in the case where a time domain duplex (TDD) is not used, for instance in the case of a UMTS mobile phone or LTE mobile phone operating in frequency domain duplex (FDD), the transmitter and the receiver of the mobile phone operate simultaneously so that the transmitter may degrade the performance of the receiver, and this effect must be taken into account during the tests;
- as explained in § 5.1 and § 5.2.4, the receiver of a mobile phone may simultaneously use multiple antennas which are intended to receive different signals and interferences, so that the receiver has multiple antenna inputs and a more elaborate definition of the minimum signal level must be used;
- a mobile phone defined in § 4 being intended to use one or more integral antennas, a sensitivity defined as the level of applied electrical signals need not be very meaningful, for instance if the mobile phone must be modified to install one or more "temporary antenna connectors" for measuring purposes.

The sensitivity that we have discussed so far in this § 5.3 is a minimum level of electrical signals applied at the antenna inputs of the receiver. It can therefore be referred to as a *conducted sensitivity*, because a conducted radio performance test (as defined in § 4) is used to measure it. This sensitivity does not take into account the actual performance of the antennas used by the receiver. This sensitivity could be expressed as an r.m.s. voltage, for instance expressed in μV or in dB(μV), or as an average power, for instance expressed in pW or in dBm. In the following, we will assume that the signal level is defined as a total average power of electrical signals applied at the antenna inputs of the receiver, which can for instance be:

- a total power of the electrical signals received by the inputs of the receiver, denoted by P_{IR} ; or
- a total power of the electrical signals delivered by generators each having an internal impedance of 50 Ω, if each antenna input of the receiver is replaced with a 50 Ω load, denoted by $P_{50\,\Omega}$.

Choosing $P_{50\Omega}$ to define the conducted sensitivity is advantageous from the measurement standpoint, because $P_{50\Omega}$ corresponds to the sum of the output level reading of conventional high frequency generators having an internal impedance of 50 Ω, or to the sum of the incident power determined using a vector network analyzer having a reference impedance of 50 Ω. From the mobile phone design standpoint, this choice might be relevant in the cases where the antenna inputs are uncoupled and each have a nominal input impedance of 50 Ω, but it will not be relevant for a mobile phone which does not use this nominal input impedance. Choosing P_{IR} to define the conducted sensitivity is a little bit more complex from the measurement standpoint, but P_{IR} is easily derived from vector network analyzer measurements of incident and reflected waves. From the mobile phone design standpoint, this choice is relevant regardless of the impedance (matrix) presented by the antenna input(s) of the receiver.

However, from the link design standpoints, choosing $P_{50\,\Omega}$ or P_{IR} to define the conducted sensitivity does not lead to a result which can be combined with (7), (8) and (9). This is caused by the fact that, in a context where the impedance (matrix) presented by the antenna (array) of a mobile phone varies significantly over the frequency bands used for reception and/or is significantly influenced by the user effects, neither $P_{50\,\Omega}$ nor P_{RI} need to be equal to the available power P_{AVA} used in (7), (8) and (9). This means that, if the electrical signals received by the inputs of the receiver are produced by the antennas of a mobile phone held by a user, $P_{50\,\Omega}$ and P_{RI} are likely to be much lower than P_{AVA} so that the observed radio performance will be degraded.

A specified sensitivity, termed *reference sensitivity* and expressed as a power level applied to one or more antenna connectors, is defined for a GSM mobile phone in [T7, § 14.2], for an UMTS mobile phone in [T14, § 7.3], and for an LTE mobile phone in [T20, § 7.3]. The reference sensitivity is intended to be such that the measured sensitivity of an inexpensive mobile phone can without difficulty be better (i.e., corresponds to a lower power level) than the reference sensitivity. It is therefore determined based on assumptions on the technology used in the mobile phone. A computation of the reference sensitivity is for instance explained in [T44, § 11.8] for the case of an LTE mobile phone having a noise figure of 9 dB and using a QPSK modulation. The result is a table where a reference sensitivity is computed for each E-UTRA band and the different bandwidths which are possible in this band. The reference sensitivities found in this table correspond to the one defined in the Table 7.3.1-1 of [T20, § 7.3], so that we can say that an LTE mobile phone may comprise a receiver having a noise figure of 9 dB. It is clear that mobile phones may easily have a sensitivity significantly better (for instance 4 dB better) than the reference sensitivity, as said above.

5.3.2 Optimal impedance of an antenna and related techniques

Let us use Z_{IR} to denote the impedance presented by the antenna input of a wireless receiver having a single antenna input, and Z_{SANT} to denote the impedance presented by an antenna with its feeder to the receiver. Conjugate matching corresponds to the circumstance where $Z_{IR} = \overline{Z_{SANT}}$, where $\overline{Z_{SANT}}$ is the complex conjugate of Z_{SANT}. In this case, maximum power transfer occurs between the antenna and the receiver, because we have $P_{AVA} = P_{IR}$. We could assume that the receiver is designed in such a way that the noise figure of the receiver, which depends on the impedance seen by the antenna input of the receiver, reaches a minimum when this impedance is equal to Z_{SANT}, so that conjugate matching would correspond to the best performance of the receiver. However, we do not need this assumption on the receiver design to state that, for a given Z_{IR}, there exists an optimal value of Z_{SANT} for reception.

A mobile phone having a single antenna input may use an adaptively controlled tunable integral antenna [T35] [T42, § 5.3.4.1]. The adaptively controlled tunable integral antenna can be used to automatically modify Z_{SANT} so as to improve the observed radio performance of the mobile phone as regards reception. Alternatively, a mobile phone using a single antenna may comprise an adaptive single-antenna-port antenna tuner [T42, § 5.3.3.1] [T43] [T52] [T53]. The adaptive single-antenna-port antenna tuner can be used to automatically modify Z_{IR}, and consequently the optimal value of Z_{SANT} for reception, so as to improve the observed radio performance of the mobile phone as regards reception. For instance, an adaptively controlled tunable integral antenna or an adaptive single-antenna-port antenna tuner could (ideally) ensure that Z_{SANT} is always equal to the optimal value of Z_{SANT} for reception, in spite of the fact that Z_{SANT} varies significantly over the frequency bands used for reception and is significantly influenced by the user effects.

An adaptively controlled tunable integral antenna or an adaptive single-antenna-port antenna tuner can also be used to improve the observed radio performance of the mobile phone as regards emission, by ensuring that Z_{SANT} is always close enough to an optimal value of Z_{SANT} for emission.

We note that both mobile phone improvement techniques considered in this § 5.3.2, namely adaptively controlled tunable integral antenna and adaptive single-antenna-port antenna tuner, do not seem to be widely used today in mobile phones, in spite of the facts that the technology is available and that these techniques are common in some other types of wireless communication systems. This might be related to the incompatibility between these techniques and conducted radio performance tests defined in many specifications of 3GPP and in the harmonized standards covering the essential requirements of article 3.2 of the R&TTE directive (see § 6.1 below).

5.3.3 Optimal impedance matrix of an antenna array and related techniques

Let us use $\mathbf{Z}_{IR}$ to denote the impedance matrix presented by the antenna inputs of a wireless receiver having several antenna inputs, and $\mathbf{Z}_{SANT}$ to denote the impedance matrix presented by antennas with their feeders to the receiver. Hermitian matching corresponds to the circumstance where $\mathbf{Z}_{IR} = \mathbf{Z}_{SANT}{}^*$, where $\mathbf{Z}_{SANT}{}^*$ is the hermitian adjoint of $\mathbf{Z}_{SANT}$, that is to say a matrix equal to the matrix transpose of the matrix complex conjugate of $\mathbf{Z}_{SANT}$. In this case, maximum power transfer occurs because we have $P_{AVA} = P_{IR}$. Moreover, in the case where multipath components arrive uniformly from all angles of arrival, hermitian matching may for some receiver designs correspond to a perfect decorrelation of received signals, which implies that all benefits of MIMO techniques can be obtained [T34]. However, we do not need this assumption on the receiver design and on the statistics of multipath components to state that, for a given $\mathbf{Z}_{IR}$, there exists an optimal value of $\mathbf{Z}_{SANT}$ for reception.

In the case of a mobile phone using simultaneously multiple antennas to communicate with the base station, $\mathbf{Z}_{SANT}$ is typically a non-diagonal impedance matrix because of the interactions between the antennas. The receiver of such a mobile phone may comprise a multiple-input and multiple-output low noise amplifier, designed to obtain a non-diagonal $\mathbf{Z}_{IR}$ corresponding to a non-diagonal optimal value of $\mathbf{Z}_{SANT}$ for reception, so as to improve the observed radio performance of the mobile phone as regards reception [T34] [T39] [T48].

A mobile phone having multiple antenna inputs may use an adaptively controlled array of tunable integral antennas [T38]. The adaptively controlled array of tunable integral antennas can be used to automatically modify $\mathbf{Z}_{SANT}$ so as to improve the observed radio performance of the mobile phone as regards reception. Alternatively, a mobile phone using a single antenna may comprise an adaptive multiple-antenna-port antenna tuner [T37] [T47] [T54] [T65]. The adaptive multiple-antenna-port antenna tuner can be used to automatically modify $\mathbf{Z}_{IR}$ so as to improve the observed radio performance of the mobile phone as regards reception. For instance, an adaptively controlled tunable integral antenna or an adaptive single-antenna-port antenna tuner could (ideally) ensure that $\mathbf{Z}_{SANT}$ is always equal to the optimal value of $\mathbf{Z}_{SANT}$ for reception, in spite of the fact that $\mathbf{Z}_{SANT}$ varies significantly over the frequency bands used for reception and is significantly influenced by the user effects.

We note that the three mobile phone improvement techniques considered in this § 5.3.3, namely multiple-input and multiple-output low noise amplifier, adaptively controlled array of tunable integral antennas and adaptive multiple-antenna-port antenna tuner, do not seem to be used today in mobile phones. This might be related to the incompatibility between these techniques and conducted radio performance tests defined in many specifications of 3GPP and in the harmonized standards covering the essential requirements of article 3.2 of the R&TTE directive (see § 6.1 below).

5.4 Some compliance engineering aspects

5.4.1 Desirable attributes of tests

Acceptance tests performed on various mobile phones, for the purpose of establishing their compliance with a given standard, should preferably be identically applicable to all mobile phones (universality) and be unbiased as regards the internal design of the mobile phones (neutrality).

Conducted radio performance tests, as defined in § 4, either require that a tested mobile phone comprises one or more antenna connectors, or a modification of the tested mobile phone to install such antenna connectors. Any modification of a tested mobile phone is of course undesirable, since the impact of modifications is always difficult to assess. In addition, conducted radio performance tests are usually simpler in the case where the nominal input impedance at each antenna connector is 50 Ω, since a typical conducted radio performance test configuration uses instruments presenting an internal impedance of

50 Ω. Thus, conducted radio performance tests are neither applicable to all mobile phones, nor unbiased. Other drawbacks of conducted radio performance tests are:

- they do not use the antennas of the mobile phone, so that the tests neither take the actual antenna characteristics nor the user effects into account;
- they are not compatible with some mobile phone designs (mentioned in § 5.3.2 and § 5.3.3), which are based on realistic antenna behaviors.

Radiated radio performance tests use the antenna of the mobile phone to transfer the power used for radio transmission instead of the connection used in conducted radio performance tests. They should in principle be always preferred to conducted radio performance. However, radiated radio performance tests are more expensive and are affected by higher measurement uncertainties than conducted radio performance tests. In the next § 5.4.2 and § 5.4.3, we shall define two parameters which may be measured during radiated radio performance tests, to characterize a mobile phone: the total radiated power (TRP) and the total radiated sensitivity (TRS).

5.4.2 Total radiated power

The concept of total radiated power of a mobile phone does not require much comments. The total radiated power is of course equal to the flux of the average power density produced by the mobile phone, through a surface containing the mobile phone. In the case where a TRP measurement is performed without user or anthropomorphic phantom, (1) entails

$$P_{TRP\,dBm} = P_{TMP\,dBm} + 10\log e_{MP} \tag{10}$$

where $P_{TRP\,dBm}$ is the TPR, in dBm; $P_{TMP\,dBm}$ is the power delivered by the mobile phone to its antenna(s), in dBm; and where e_{MP} is either the radiation efficiency given by (B2) of Appendix B, in the case of a mobile phone using a single antenna, or an average value of the radiation efficiency given by (B11) of Appendix B, in the case of a mobile phone using multiple antennas. From the link design standpoints, we note that $P_{TRP\,dBm}$ appears in (7), (8) and (9) applied to the uplink. We also note that the maximum value of the absolute gain of a mobile phone antenna is not one of the parameters which determine the TRP. The uncertainty of an accurate TRP measurement with a phantom head is about ± 1.9 dB [T24, Annexes D and E] [T45].

5.4.3 Total radiated sensitivity

For a mobile phone using its integral antennas to receive radio signals, it is possible to define a *radiated sensitivity* as the minimum level of a plane electromagnetic wave impinging on the mobile phone from a given direction (θ, φ) with a given polarization, for which the output signal of the receiver meets a certain criterion, in a given test configuration. Here, the sensitivity could be expressed as an r.m.s. electric field intensity, for instance expressed in μV/m or in dB(μV/m), or as an average power density, for instance expressed in pW/m² or in dB(mW/m²). In the following, we will assume that the signal level is an average power density. For a given direction (θ, φ), this average power density is denoted by $W_{TH\,1}$ for a first polarization, and $W_{TH\,2}$ for a second polarization orthogonal to the first polarization.

For a given direction (θ, φ) and a polarization $p \in \{1, 2\}$, the radiated sensitivity $W_{TH\,p}$ may be used to define an effective isotropic sensitivity (EIS), denoted by $P_{EIS\,p}$, as

$$P_{EIS\,p} = \frac{\lambda^2}{4\pi} W_{TH\,p} \tag{11}$$

where λ is the free-space wavelength of the incident wave. The effective isotropic sensitivity $P_{EIS\,p}$ is the power which would be available from an ideal isotropic and polarization-matched antenna receiving the average power density $W_{TH\,p}$. We can now define the total radiated sensitivity (TRS), also referred to as total isotropic sensitivity (TIS), denoted by $P_{TRS\,p}$, as follows [T46, Appendix E]:

$$P_{TRS} = \frac{\lambda^2}{\oiint_{\Omega} \left(\frac{1}{W_{TH1}} + \frac{1}{W_{TH2}} \right) d\Omega} = \frac{4\pi}{\oiint_{\Omega} \left(\frac{1}{P_{EIS1}} + \frac{1}{P_{EIS2}} \right) d\Omega} \tag{12}$$

To clarify the relevance of this definition, we shall consider the case where the mobile phone has a single antenna which, for a given direction (θ, φ), has a gain $G_{MP} = G_{MP\,1} + G_{MP\,2}$, where for the polarization $p \in \{1, 2\}$, $G_{MP\,p}$ is the product of G_{MP} and the polarization loss factor defined in Appendix A. The output signal of the receiver of the mobile phone meets said certain criterion for an available power P_{AVTH} at the terminal of the mobile phone antenna. For $p \in \{1, 2\}$, we have:

$$P_{AVTH} = \frac{\lambda^2}{4\pi} G_{MP\,p}\, W_{TH\,p} \tag{13}$$

so that

$$P_{TRS} = \frac{P_{AVTH}}{\frac{1}{4\pi} \oiint_{\Omega} \left(G_{MP1} + G_{MP2} \right) d\Omega} = \frac{P_{AVTH}}{e_{MP}} \tag{14}$$

where we have used (1). We consequently have

$$P_{TRS\,dBm} = P_{AVTH\,dBm} - 10 \log e_{MP} \tag{15}$$

where $P_{TRS\,dBm}$ is the TRS, in dBm; $P_{AVTH\,dBm}$ is the available power P_{AVTH}, in dBm; and where e_{MP} is the radiation efficiency given by (B2) of Appendix B. From the link design standpoints, we note that $P_{TRS\,dBm}$ can be used in (7), (8) and (9) applied to the downlink. We also note that the maximum value of the absolute gain of a mobile phone antenna is not one of the parameters which determine the TRS.

We have up to now considered TRS measurement without anthropomorphic phantom, but they may also be performed with an anthropomorphic phantom, for instance representing a head or a hand. The uncertainty of an accurate TRS measurement with a phantom head is about ± 2.3 dB [T24, Annexes D and E] [T45].

In the case where a time domain duplex (TDD) is not used, for instance in the case of a UMTS mobile phone or LTE mobile phone operating in frequency domain duplex (FDD), the transmitter of the mobile phone should preferably be used at full power during TRS measurements, to take into account the self-blocking effect. Additionally, TRS measurement could also be performed in the presence of one or more interfering signals, for instance to test the mobile phone's blocking characteristics, spurious response and intermodulation characteristics.

6. Performance requirements on emission and reception

6.1 Existing requirements

6.1.1 Presentation of the requirements

Some radiated radio performance tests are necessary to guarantee that a mobile phone will provide a satisfactory observed radio performance. However, radio performance tests are more expensive and often less accurate than conducted radio performance tests, so that radiated radio performance tests are not common in current specifications. We have consequently reviewed existing specifications, to determine the relative weights of conducted radio performance tests and radiated radio performance tests.

Requirements applicable to mobile phones are found in three categories of specifications:

- harmonized standards covering the essential requirements of article 3.2 of the R&TTE directive, discussed below in § 6.1.2 to § 6.1.4, and in § 6.1.6 and § 6.1.7;
- specifications of 3GPP, discussed below in § 6.1.5;
- other specifications, discussed below in § 6.1.8.

The harmonized standards covering the essential requirements of article 3.2 of the R&TTE directive do not contain any requirement on the total radiated power (TRP) and the total radiated sensitivity (TRS, or TIS) defined in § 5.4. However these harmonized standards and other specifications of 3GPP require or allow some radiated radio performance tests depending on the presence of an integral antenna or of an antenna connector. More precisely, we can say that:

- some specifications define different requirements for a mobile station (MS) or user equipment (UE) having an antenna connector, and for a MS or UE with an integral antenna;
- other specifications assume the availability of an antenna connector.

In the case of a MS or UE which does not comprise an integral antenna, at least one antenna connector is necessarily present to allow the user to connect at least one external antenna. In the case of a mobile phone, which by definition comprises one or more integral antennas, the meaning of “antenna connector” is less clear. In early generations of mobile phones, a user-accessible antenna connector was common, mainly to allow the connection to an external car antenna through a phone cradle. Such antenna connectors have become increasingly uncommon. A survey of currently commercially available mobile phones [T66, § 4.2] has found no mobile phone comprising a connector allowing the user to connect an external antenna. Thus, an important aspect of tests for establishing compliance with a specification mentioning the use of one or more antenna connectors is the interpretation of “antenna connector”. This question is addressed in § 6.1.2 to § 6.1.4, and in § 6.1.6.

6.1.2 Harmonized standard applicable to a GSM mobile phone

According to [T4], the harmonized standard currently covering the essential requirements of article 3.2 of the R&TTE directive for a GSM mobile phone is [T8], [T8] being a version of EN 301 511. Each conformance requirement of [T8] is identical to a clause of the chapters 12, 13 or 14 of [T7], [T7] being a version of TS 151 010-1. To clarify the implementation of tests for establishing compliance with [T8], we have conducted a survey of the practices of manufacturers as regards GSM mobile phones which do not comprise a connector allowing the user to connect an external antenna [T66, § 4.3], so that the user can only use the integral antenna (such GSM mobile phones being apparently, as explained in § 6.1.1, the only one available on the market).

The survey found that, for the tests of [T8] involving the measurement of transmitter output power of a GSM mobile phone:

- manufacturers typically use the test method, described in the chapter 13 of [T7], where the integral antenna is disconnected from an internal connector, and this internal connector is used for the test as if it was a connector allowing the user to connect an external antenna;
- manufacturers sometimes apply this test method to a modified mobile phone equipped with a temporary antenna connector, used as if it was a connector allowing the user to connect an external antenna;
- manufacturers typically do not use the test method, described in the chapter 13 of [T7], where a modified mobile phone is equipped with a temporary antenna connector for which calibration factors are determined using a radiated radio performance test.

The survey found that, for the tests of [T8] involving the measurement of receiver blocking and spurious response of a GSM mobile phone:

■ manufacturers typically use the test method, which might (or not) be considered as suggested in the chapter 14 of [T7], where the integral antenna is disconnected from an internal connector, and this internal connector is used for the test as if it was a connector allowing the user to connect an external antenna;
■ manufacturers sometimes apply this test method to a modified mobile phone equipped with a temporary antenna connector, used as if it was a connector allowing the user to connect an external antenna;
■ manufacturers typically do not use the test method, described in the chapter 14 and Annex 1 of [T7], where a modified mobile phone is equipped with a temporary antenna connector for which coupling factors are determined using a radiated radio performance test.

6.1.3 Harmonized standards applicable to a UMTS mobile phone

According to [T4], the harmonized standards currently covering the essential requirements of article 3.2 of the R&TTE directive for a UMTS mobile phone are [T16], i.e. a version of EN 301 908-1, and [T18], i.e. a version of EN 301 908-2. The requirements of [T18] are based on, but not identical to, some requirements of the applicable technical specifications of ETSI/3GPP.

Regarding the definition of the conformance requirements, [T18] says: "*Unless otherwise stated, the transmitter and receiver characteristics are specified at the antenna connector(s) of the UE. For UE(s) with an integral antenna only, a reference antenna(s) with a gain of 0 dBi is assumed for each antenna port(s). A UE with an integral antenna(s) may be taken into account by converting these power levels into field strength requirements, assuming a 0 dBi gain antenna*". We note that, for a UMTS mobile phone,
■ in the previous sentence, "antenna connector" may refer to a connector allowing the user to connect an external antenna, if present; or to an internal connector from which the integral antenna is disconnected, if present; or to a temporary antenna connector;
■ the test definitions of § 5 of [T18] only describes conducted radio performance tests, so that radiated radio performance tests are not sufficiently described, in particular where the UMTS mobile phone uses multiple antennas techniques in the downlink;
■ such UMTS mobile phones using multiple antennas techniques in the downlink are currently commercially available.

To clarify the implementation of tests for establishing compliance with [T18], we have conducted a survey of the practices of manufacturers as regards UMTS mobile phones [T66, § 4.4]. The survey found that, for the tests of [T18] applied to a UMTS mobile phone:
■ manufacturers typically do not perform any radiated radio performance test;
■ manufacturers typically connect the system simulator (SS) to an internal connector from which the integral antenna is disconnected;
■ manufacturers sometimes use the test method where a modified mobile phone is equipped with a temporary antenna connector and the SS is connected to the temporary antenna connector.

6.1.4 Harmonized standards applicable to an LTE mobile phone

According to [T4], the harmonized standards currently covering the essential requirements of article 3.2 of the R&TTE directive for a LTE mobile phone are [T16], i.e. a version of EN 301 908-1, and [T17], i.e. a version of EN 301 908-13. The requirements of [T17] are based on, but not identical to, some requirements of the applicable technical specifications of ETSI/3GPP.

Regarding the definition of the conformance requirements, [T17] says nothing about UE with an integral antenna only, and the test definitions of § 5 of [T17] only describes conducted radio performance tests, so that radiated radio performance tests are not allowed. We note that the "antenna connectors" referred to as in the test definitions of § 5 of [T17] may refer to a connector allowing the user to connect an external antenna, if present; or to an internal connector from which the integral antenna is disconnected, if present; or to a temporary antenna connector.

To clarify the implementation of tests for establishing compliance with [T17], we have conducted a survey of the practices of manufacturers as regards LTE mobile phones [T66, § 4.5]. The survey found that, for the tests of [T17] applied to a LTE mobile phone:
- manufacturers typically connect the system simulator (SS) to an internal connector from which the integral antenna is disconnected;
- manufacturers sometimes use the test method where a modified mobile phone is equipped with a temporary antenna connector and the SS is connected to the temporary antenna connector.

6.1.5 Radiated radio performance tests in 3GPP specifications

The specifications of 3GPP allow (or require, according to the point of view) the use of radiated radio performance tests for demonstrating the compliance of a GSM mobile phone to the conformance specification, as for instance explained in § 13.3, § 13.7, § 13.16, § 13.17, § 14 and § A1.1 of [T7] for the release 4, or of [T25] for the release 10.

The specifications of 3GPP allow the use of radiated radio performance tests for demonstrating the compliance of a UMTS mobile phone to the conformance specification, as for instance indicated by:
- the statement "*Unless otherwise stated, the transmitter characteristics are specified at the antenna connector of the UE. For UE with integral antenna only, a reference antenna with a gain of 0 dBi is assumed.*" in § 6.1 of [T14] and of a similar statement in § 5.1 of [T11];
- the statement "*Unless otherwise stated, the receiver characteristics are specified at the antenna connector of the UE. For UE(s) with an integral antenna only, a reference antenna with a gain of 0 dBi is assumed. UE with an integral antenna may be taken into account by converting these power levels into field strength requirements, assuming a 0 dBi gain antenna.*" in § 7.1 of [T14] and in § 6.1 of [T11].

The specifications of 3GPP allow the use of radiated radio performance tests for demonstrating the compliance of an LTE mobile phone to the conformance specification, as for instance indicated by:
- the statement "*Unless otherwise stated, the transmitter characteristics are specified at the antenna connector of the UE with a single or multiple transmit antenna(s). For UE with integral antenna only, a reference antenna with a gain of 0 dBi is assumed.*" in § 6.1 of [T20] and of a similar statement in § 6.1 of [T22];
- the statement "*Unless otherwise stated, the receiver characteristics are specified at the antenna connector(s) of the UE. For UE(s) with an integral antenna only, a reference antenna(s) with a gain of 0 dBi is assumed for each antenna port(s). UE with an integral antenna(s) may be taken into account by converting these power levels into field strength requirements, assuming a 0 dBi gain antenna.*" in § 7.1 of [T20] and in § 7.1 of [T22].

Unfortunately, said statements allowing the use of radiated radio performance tests for demonstrating the compliance of a UMTS mobile phone or of an LTE mobile phone are not fully operational from the point of view of testing technique, especially in the case of a mobile phone using multiple antenna techniques. The § 4 of the technical report [T23] confirms this view.

Another specification of 3GPP is available for testing the "over-the-air (OTA) antenna performance" of a GSM mobile phone and of a UMTS mobile phone [T24]. In fact, instead of describing tests for the measurement of some parameters of the antenna(s), the specification describes radiated radio performance tests for the mobile phone. The measured parameters are a total radiated power (TRP) which characterizes the emission of the mobile phone, and a total radiated sensitivity (TRS) which characterizes the reception by the mobile phone. The TRP and the TRS are defined and discussed in § 5.4. The specification includes measurements in a free space configuration, that is without anthropomorphic phantom, and measurements with anthropomorphic phantom effects produced by an anthropomorphic phantom representing a head.

6.1.6 Harmonized standards compared to 3GPP specifications

As explained above in § 6.1.2 to § 6.1.4, the harmonized standards currently covering the essential requirements of article 3.2 of the R&TTE directive are:
- in the case of a GSM mobile phone [T8], a subset of the requirements of an old release of the technical specification of 3GPP for GSM, namely the release 4 [T7], whereas the current release is release 10 [T25];
- in the case of a UMTS mobile phone [T16] [T18], based on, but not identical to, some requirements of the applicable technical specifications of ETSI/3GPP;
- likewise, in the case of an LTE mobile phone [T16] [T17], based on, but not identical to, some requirements of the applicable technical specifications of ETSI/3GPP.

We note that the statement "*Unless otherwise stated, the transmitter and receiver characteristics are specified at the antenna connector(s) of the UE. For UE(s) with an integral antenna only, a reference antenna(s) with a gain of 0 dBi is assumed for each antenna port(s). A UE with an integral antenna(s) may be taken into account by converting these power levels into field strength requirements, assuming a 0 dBi gain antenna*", which appears in [T18] (applicable to a UMTS mobile phone), is not present in [T17] (applicable to an LTE mobile phone), even though the basis for this statement exists in the requirements of the technical specifications of ETSI/3GPP applicable to an LTE UE, for instance in § 6.1 and § 7.1 of [T20]. Consequently, we can say that, for an LTE mobile phone:
- only conducted radio performance tests are allowed to demonstrate the compliance with [T17];
- the presence of an "antenna connector" is required by [T17], even though "antenna connector" is not unambiguously defined!

6.1.7 Radiated radio performance tests used to assess compliance with harmonized standards

As regards the actual implementation of tests for establishing the compliance of a mobile phone with the harmonized standards currently covering the essential requirements of article 3.2 of the R&TTE directive, the survey referred to as in § 6.1.2 to § 6.1.4 found that the manufacturers typically connect the system simulator (SS) to an internal connector from which the integral antenna is disconnected. This agrees with the literature covering this question [T44, § 11.6.2.2] [T45]. Consequently, radiated radio performance tests are not typically used to establish compliance of a mobile phone with the harmonized standards.

6.1.8 Some other specifications

An organization called "CTIA - The Wireless Association" publishes test specifications which seem to be used as voluntary or contractual requirements.

The revision 3.1 of the test plan entitled "Test Plan for Mobile Station Over the Air performance" [T46] of "CTIA - The Wireless Association" describes radiated radio performance tests which can be applied to a GSM mobile phone or a UMTS mobile phone. Like the 3GPP specification for testing the "over-the-air (OTA) antenna performance" presented in § 6.1.5, the test plan is about the measurement of the total radiated power (TRP) and of the total radiated sensitivity (TRS) defined above in § 5.4. For TRS, the test plan uses the wording total isotropic sensitivity (TIS). The test plan includes measurements in a free space configuration, and measurements with anthropomorphic phantom effects produced by anthropomorphic phantoms representing a head and/or a hand. In November 2013, the web site of "CTIA - The Wireless Association" indicates that this test plan "shall be used for device certification". The revision 3.2.2 of the test plan entitled "Test Plan for Mobile Station Over the Air performance" [T63] of "CTIA - The Wireless Association" is also available, but it does not seem to be implemented yet. It describes radiated radio performance tests which can be applied to a GSM mobile phone, a UMTS mobile phone or an LTE mobile phone, for measuring the TRP and the TRS.

6.2 Actual technical needs

In the case of a radio system comprising a transceiver and a separate antenna, it is often possible to accurately derive the main characteristics of the system based on the characteristics of the antenna and the results of conducted radio performance tests performed on the transceiver. In the case of a mobile phone, this possibility does not exist because measuring accurately the characteristics of the mobile phone's integral antennas is always very difficult, requires a modification of the mobile phone which is likely to alter these characteristics significantly, and would be of unrealistic complexity for designs involving adaptive antenna tuning. Furthermore, these characteristics are complex and are modified in a complex manner by the user effects. Consequently, though the characteristics of the antenna(s) play an essential role in the observed radio performance of a mobile phone, it is not desirable to directly specify them.

The best approach to guarantee a satisfactory observed radio performance of a mobile phone in places where the signal from the base station is weak consists in defining limits for suitable radiated radio performance tests applicable to the mobile phone regarded as a system comprising the antenna(s). We maintain that suitable radiated radio performance tests must satisfy all following criteria:

- (a) delivering one or more parameters each representing the minimum power density of incident waves needed to obtain a good enough communication in the downlink;
- (b) delivering one or more parameters each representing the power radiated by the mobile phone in the uplink;
- (c) using an unaltered mobile phone for all measurements, because the results of radiated measurements are very sensitive to modifications;
- (d) being neutral as regards the internal design of the mobile phone;
- (e) satisfactorily representing the user effects in a sufficient set of realistic uses of the mobile phone.

A mobile phone capable of using multiple antennas technique can provide superior performance in places where the signal from the base station is weak, as explained in § 5.1. For such a mobile phone, it is desirable to include radiated radio performance tests which indicate how effectively multiple antenna techniques are used by the mobile phone to improve the link, in places where the signal from the base station is weak. Such tests are complex to design because they must correctly emulate a radiated MIMO fading channel [T50, § 5.6]. Consequently, additional radiated radio performance tests could satisfy (c), (d), (e) and one of or both following criteria:

- (f) for mobile phone supporting multiple antenna reception techniques (for instance receive diversity, or downlink single-user MIMO), delivering one or more parameters each representing a minimum downlink performance in one or more MIMO fading channels presenting a large path loss;
- (g) for mobile phone supporting multiple antenna emission techniques (for instance transmit diversity, or uplink single-user MIMO), delivering one or more parameters each representing a minimum uplink performance in one or more MIMO fading channels presenting a large path loss.

Though antennas contribute to the performance of a mobile phone, we observe that no suitable specification of radiated radio performance tests for mobile phones can use measurements performed on the antenna(s) of the mobile phone, because this approach violates the criteria (c) and (d): a modified mobile phone must be used to access the antenna(s), and the approach is not neutral because it is incompatible with adaptive antenna tuning techniques or other mobile phone improvement techniques considered in § 5.3.2 and § 5.3.3.

As regards the criterion (e), the following observations might be relevant. Radiated radio performance tests in a free space configuration, that is without anthropomorphic phantom, may be necessary to represent a realistic use of the mobile phone when a user is not present. Such tests will also be more reproducible than tests using an anthropomorphic phantom, because their results are not affected by the uncertainties on the characteristics of the anthropomorphic phantom and on positioning of the mobile phone with respect to the anthropomorphic phantom. Radiated radio performance tests emulating the user effects using an anthropomorphic phantom comprising a head and one hand may be necessary to represent a realistic use of the mobile phone for voice transmission. Radiated radio performance tests emulating the user effects using an anthropomorphic phantom comprising two hands may be necessary to represent a realistic use of the mobile phone for data transmission. However, the cost of testing may become very large if multiple anthropomorphic phantoms and/or multiple anthropomorphic phantom positions are used to emulate the variability of human bodies, postures and movements.

Concerning the criterion (g), we may observe that no currently commercially available mobile phone seems to offer multiple antenna emission techniques. However, this possibility exists for an LTE mobile phone in 3GPP Release 10 [T26], [T51, § 11.3], [T67, § 14.1].

We have just defined a set of seven criteria which define suitable radiated radio performance tests applicable to the mobile phone regarded as a system comprising the antenna(s). But we have not addressed the question of the limits which could be applied to the parameters referred to as in the criteria (a), (b), (f) and (g). A first reason is that the limits cannot be chosen before the parameters are accurately defined. A second reason is that setting the limits is not within the scope of the present report. A third reason is that the limits depend on their intended use (e.g., new mandatory technical requirements versus the definition of performance levels or classes for consumer's information). A fourth reason is also the main reason: setting the limits has a political dimension, since these limits might impact the interests of users, mobile phone manufacturers, wireless network operators and base station manufacturers. However, we note that, from a purely technical standpoint:

- suitable limits for minimum values of the TRP measured without anthropomorphic phantom could be based on (10) of § 5.4.2, using existing limits for the minimum output power (defined for conducted radio performance tests), an assumed value of the efficiency e_{MP} , and a relaxation taking measurement uncertainties into account;
- suitable limits for maximum values of the TRS measured without anthropomorphic phantom could be based on (15) of § 5.4.3, using the reference sensitivity mentioned in § 5.3.1 (defined for conducted radio performance tests), a correction recognizing that they are not very demanding, an assumed value of the efficiency e_{MP}, and a relaxation taking measurement uncertainties into account.

Some other aspects of this question will be addressed in § 6.3 and § 8.1.

6.3 Requirements meeting the actual technical needs

A comparison between § 6.1 and § 6.2 allows us to maintain that:

- the compliance of a mobile phone with the harmonized standards currently covering the essential requirements of article 3.2 of the R&TTE directive, as they are actually implemented, does not ensure a satisfactory observed radio performance in places where the signal from the base station is weak;
- additional requirements on the TRS and the TRP could be sufficient to guarantee a satisfactory observed radio performance in places where the signal from the base station is weak, because
    - — a TRS measurement satisfies the criteria (a), (c) and (d) of § 6.2;
    - — a TRP measurement satisfies the criteria (b), (c) and (d) of § 6.2;
    - — TRS and TRP measurements can use anthropomorphic phantoms to comply with the criterion (e) of § 6.2.

Test specifications for TRS and TRP measurements exist [T24], [T46], [T63] and have been introduced in § 6.1.5 and § 6.1.8 above. They are widely described and used in the literature [T40] [T42, § 5.2.5], [T55], [T56], [T68], and they can be applied to GSM mobile phones, UMTS mobile phones and LTE mobile phones. These test specifications of radiated radio performance tests meet the criteria (a), (b), (c) and (d) of § 6.2. It also seems that some manufacturers routinely submit their mobile phones to such tests, to demonstrate the compliance with voluntary or contractual requirements [T66, § 4.6]. A set of such contractual requirements is typically inserted by a wireless network operator in a mobile phone purchase contract [T62, § 2.4], because the wireless network operator has his own specifications which ensure that the mobile phones he purchases will work well in his wireless network. Thus, though TRS and TRP are not the only possible choices of parameters to characterize a mobile phone, they are today the best choice of parameters for a possible legislation. It is important to note that this report neither declares nor suggests that the limits for TRP and TRS set in [T24], [T46] and [T63] are suitable to ensure that the observed radio performance of a mobile phone is always satisfactory in places where the signal from the base station is weak.

It might be argued that technical requirements regarding the TRS and/or TRP could in the future be regarded as necessary to meet the essential requirements of article 3.2 of the R&TTE directive for a mobile phone. If a positive answer is given to this question, it might be possible to merge some tests to reduce the cost of testing. For instance, TRP measurements without anthropomorphic phantom could advantageously replace all conducted radio performance tests for the maximum output power, which are in fact not very meaningful for a mobile phone (moreover, simultaneously specifying a high enough minimum TRP without anthropomorphic phantom and a maximum output power for conducted radio performance tests is not very consistent). For instance, a measurement of the TRS, without anthropomorphic phantom, in the presence of a blocking signal, could also advantageously replace all conducted radio performance tests on the receiver blocking characteristics. Replacing some conducted radio performance tests with much more relevant radio performance tests would also cure a problem of the former: as said in § 5.4.1, conducted radio performance tests are not identically applicable to all mobile phones and are biased as regards their internal design.

As regards the ability of a mobile phone to effectively use multiple antenna techniques to improve the observed radio performance in places where the signal from the base station is weak, we observe that suitable radiated radio performance tests are not fully mature yet. As a consequence, the best choice of parameters to satisfy the criterion (f) and/or the criterion (g) of § 6.2, is not obvious at this time. However, there is no doubt that suitable radiated radio performance tests can be defined. We note that the definition of radiated radio performance tests applicable to a UMTS mobile phone or an LTE mobile phone using MIMO techniques in the downlink, is a topical subject addressed by RAN4 of 3GPP [T23] [T61]. Two types of techniques are being considered: direct measurement techniques such as the multiple probe antenna methods and reverberation chamber methods; and indirect measurement techniques such as the two-stage and decomposition methods. In practice, only direct OTA measurement techniques can meet the criteria (c) and (d).

7. Observed radio performance and human exposure

To meet the essential requirements of article 3.1(a) of the R&TTE directive, a mobile phone must comply with basic restrictions related to human exposure to electromagnetic fields, defined in [T6] for the frequency range 300 MHz to 3 GHz. If the mobile phone uses emission frequencies outside this interval (for instance a broadband radio local area network operating in the 5 GHz band), the mobile phone must also comply with the requirements of [T9] or [T13]. The compliance of the mobile phone with these specifications implies that it should satisfy the basic restrictions set forth in a Council recommendation on the limitation of exposure of the general public to electromagnetic fields [T2]. In the frequency range 10 MHz to 10 GHz, these basic restrictions concern the specific energy absorption rate (SAR), defined as the rate at which energy is absorbed per unit mass of body tissue, and are:

- a whole body average SAR less than or equal to 0.08 W/kg;
- a localized SAR, averaged over any 10 g of continuous tissue, less than or equal to 2 W/kg over the head and trunk; and
- a localized SAR, averaged over any 10 g of continuous tissue, less than or equal to 4 W/kg over the limbs.

In this § 7, we discuss the relationship between the observed radio performance of a mobile phone and the SAR values measured in accordance with the applicable harmonized standards mentioned above, using an anthropomorphic phantom.

Antenna gain normally refers to a far-field characteristic of an antenna, which has no simple and general relationship with SAR. More precisely, as explained in § 5.2, the absolute gain of the antenna, in a given direction, is the product of its radiation efficiency and its directivity in the given direction. If we assume that the head of the user is in the far field of a mobile phone antenna (the relevance of this assumption depends on frequency and on the shape of the mobile phone), a good directivity (i.e. a directional pattern presenting a high directivity in a direction of maximum radiation, and reduced side lobes) should decrease the SAR over the head during emission by the mobile phone, because a good directivity allows to reduce the radiation intensity toward the head. Conversely, a good radiation efficiency increases the SAR over any part of the body during emission by the mobile phone. Thus, the gain being the product of two factors having opposite influence on the SAR, it is not possible to determine or correlate the effect of an increased gain on the SAR over the head. As regards the SAR over the hand of the user, it is mostly determined by the field values in the near field of the antenna, which has no simple relationship with the absolute gain in the far field.

We have established that the absolute gain of a mobile phone antenna (which, when the direction is not stated, is taken as the maximum value of the absolute gain) is not a very relevant parameter to discuss the SAR. The discussion of § 5.2 indicates that the maximum value of the absolute gain is not a very relevant parameter to study the link budget, and consequently the observed radio performance. Finally, the discussion of § 5.4 indicates that it is not either a very relevant parameter to discuss the TRS and the TRP.

We have shown in § 5.2 that, in the instantaneous link budget (8), the available power, in dBm, at the terminals of the receiving antenna(s), for the signal sent by the transmitting antenna(s), denoted by $P_{AVA\ dBm}$, is determined by a sum containing a term $P_{T\ dBm} + 10\log(e_{MP})$. When the mobile phone is used for emission, this term represents the power actually radiated by the mobile phone when the user is not present. Increasing the term improves the link and increases the SAR (assuming that the directivity pattern is not modified). However, since, as explained in § 6.3, a correct specification of the output power of the mobile phone should be based on the TRP, the term $P_{T\ dBm} + 10\log(e_{MP})$ should be regarded as a fixed characteristic of a mobile phone. As a consequence, this term should not be considered as a parameter which could be varied to obtain a low enough SAR.

We have shown in § 5.2 that, in the instantaneous link budget (8), a body loss expressed in dB, denoted by $L_{BOD5\ dB}$, accounts for the user effects. In the average link budget (9), the corresponding term is $<L_{BOD5}>_{dB}$. If we look at the underlying physics, we see that $L_{BOD5\ dB}$ and $<L_{BOD5}>_{dB}$ are caused by the current induced, in the user, by the electromagnetic fields of the mobile phone. These electromagnetic fields may be referred to as the incident electromagnetic fields. The current induced in the user by the incident electromagnetic fields causes diffracted electromagnetic fields and absorption of energy by the body tissue. Consequently, if the current induced in the user is small, $L_{BOD5\ dB}$ and $<L_{BOD5}>_{dB}$ are close to 0 dB and the SAR is close to 0 W/kg. Thus, the parameters $L_{BOD5\ dB}$ and $<L_{BOD5}>_{dB}$ are relevant to discuss link budgets, the SAR, and the effect of an anthropomorphic phantom on the TRS and the TRP.

Since a small body loss $<L_{BOD5}>_{dB}$ is correlated with a good link and a low SAR, we can say that there is no conflict between a low SAR value and a good observed radio performance. In practice, a small body loss $<L_{BOD5}>_{dB}$ can be obtained with a moderate directivity of the mobile phone, providing a reduced electromagnetic radiation toward the human head [T42, § 7.5.8 and § 7.6.3] [T49]. Thus, it is possible to combine a good observed radio performance and a low user's exposure to electromagnetic fields.

8. Promoting an improved observed radio performance

8.1 Technical feasibility of an improved observed radio performance

Consumers and mobile phone users are likely to benefit from an improved observed radio performance in places where the path loss between the mobile phone and the base station is high. However, the introduction of additional technical requirements and/or of a labeling system promoting this improved observed radio performance will make sense only if the improvement can be brought to market without significant price increase.

The possibility of improvement based on standard technology is demonstrated by:
- the spread in the TRP measurement results among different models of mobile phones, typically of about 4 dB for GSM 1800 in [T45];
- the spread in the TRS measurement results among different models of mobile phones, typically of about 7 dB for GSM 1800 in [T45], 11 dB for GSM 900 and 16 dB for GSM 1800 in [T56] and [T68].

Further improvement of the observed radio performance could use new means for mitigating the user effects, because the user effects is particularly detrimental when the path loss between the mobile phone and the base station is high. Also, in the case of emission, these means should not increase the human exposure to electromagnetic fields.

In the case of a mobile phone using single-antenna operation, among the available techniques for mitigating the user effects, we may mention:
- integral antenna with higher directivity;
- adaptive antenna selection [T42, § 5.3.3.2];
- adaptively controlled tunable integral antenna, presented in § 5.3.2 above; and
- adaptive single-antenna-port antenna tuner, presented in § 5.3.2 above.

In the case of a mobile phone using multiple-antenna operation, among the available techniques for mitigating the user effects, we may mention:
- integral antennas with higher directivity;
- adaptive antenna selection [T64];
- adaptive beamforming;
- adaptively controlled array of tunable integral antennas, presented in § 5.3.3 above; and
- adaptive multiple-antenna-port antenna tuner, presented in § 5.3.3 above.

We note that, for a labeling system comprising several performance levels or classes, different limits would have to be set for the parameters referred to as in the criteria (a), (b), (f) and (g) of § 6.2. For instance, in the case of a labeling system comprising 3 or more classes, the limits of the lowest class could to be set to accept most mobile phones using current technology, and the limits of the highest class could be set to accept only the best that can be offered in a near future.

8.2 Current information of consumers and users

What is today the information available to a consumer who wishes to purchase or rent a mobile phone that can provide a satisfactory observed radio performance in places where the signal from the base station is weak? In some cases, a “detailed specification” is available on the Internet, but we have not found any example where it contained any parameter which is relevant for assessing the observed radio performance in places where the signal from the base station is weak.

According to Article 6(3) of the R&TTE directive, the person responsible for placing the apparatus on the market must *provide information for the user on the intended use of the apparatus, together with a declaration of conformity to the essential requirements*. Unfortunately, the declaration of conformity does not provide any information which is relevant for assessing the observed radio performance in places where the signal from the base station is weak, and moreover, a consumer need not have access to the declaration of conformity corresponding to a given mobile phone which he has not yet acquired.

8.3 Technical feasibility of new technical or labeling requirements

In § 6.2, we have defined a set of criteria which should be satisfied by radiated radio performance tests which could be used to check that a mobile phone will provide a satisfactory observed radio performance in places where the signal from the base station is weak. In § 6.3, we have found that test specifications meeting the 4 most important of these criteria are already available, and that it is possible to define additional test specifications, so as to meet all criteria.

The result of tests satisfying the criteria could be used to determine a compliance with new mandatory technical requirements. The requirements could be different for voice and data transmission. However, being based on radiated radio performance tests which are neutral as regards the internal design of the mobile phone, the new mandatory technical requirements could be applied systematically and consistently to mobile phones placed on the market in the European Union. According to this approach, all products would meet the new mandatory technical requirements, and no labeling of products would be necessary.

We note that several voluntary certification programs currently require radiated radio performance tests. The corresponding "voluntary" certifications are in fact required by wireless network operators when they purchase mobile phones for their customers. Such certification programs are offered by the *Global Certification Forum*, which seems to be required by many European wireless network operators, and by *CTIA - The Wireless Association*, which seems to be required by many non-European wireless network operators. The existence of such certification programs could be used as an argument against the introduction of new mandatory technical requirements. This argument would be moot because many mobile phones are "open market", meaning that they are not customized for and/or retailed by a wireless network operator.

The result of suitable tests could alternatively (or additionally) be an information to be provided to consumers, for instance in the form of a code defined in a systematic and consistent classification system. Based on the discussion of § 8.1 and on the accuracy of TRP and TRS measurements, indicated in § 5.4, it seems that at least 3 or 4 classes could be defined and referred to as performance levels.

Thus, we can say that:

- new systematic and consistent technical requirements for placing a mobile phone on the market in the European Union, which would guarantee that the mobile phone should provide a satisfactory observed radio performance in places where the signal from the base station is weak, are technically feasible;
- such new technical requirements might duplicate some of the requirements of current voluntary certification programs;
- new labeling requirements for placing a mobile phone on the market in the European Union, which would ensure that consumers are informed of the observed radio performance to be expected of a mobile phone in places where the signal from the base station is weak, are technically feasible and could use at least 3 performance levels.

9. Technical references

9.1 Directives, related documents and regulations

[T1] Directive 1999/5/EC of the European Parliament and of the Council of 9 March 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity.

[T2] Council recommendation 1999/519/EC of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz).

[T3] Proposal for a Directive of the European Parliament and of the Council on the harmonization of the laws of the member states relating to the making available on the market of radio equipment, European Commission, COM(2012) 584 final, 17 October 2012.

[T4] "Commission communication in the framework of the implementation of the Directive 1999/5/EC of the European Parliament and of the Council of 9 March 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity", *Official Journal of the European Union*, dated 23 October 2012, pages C 321/21 to C 321/54.

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[T6] EN 50360:2001 + EN 50360:2001/A1:2012 + EN 50360:2001/AC:2006
Product standard to demonstrate the compliance of mobile phones with the basic restrictions related to human exposure to electromagnetic fields (300 MHz - 3 GHz).

[T7] ETSI TS 151 010-1 V4.9.0 (2002-07)
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[T8] ETSI EN 301 511 V9.0.2 (2003-03)
Global System for Mobile communications (GSM); Harmonized EN for mobile stations in the GSM 900 and GSM 1800 bands covering essential requirements under article 3.2 of the R&TTE directive (1999/5/EC).

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[T10] ETSI TR 125 913 V9.0.0 (2010-02)
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Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN) (3GPP TR 25.913 version 9.0.0 Release 9).

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[T12] ETSI TS 125 211 V8.7.0 (2010-10)
Universal Mobile Telecommunications System (UMTS); Physical channels and mapping of transport channels onto physical channels (FDD) (3GPP TS 25.211 version 8.7.0 Release 8).

[T13] EN 62479:2010
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[T14] ETSI TS 125 101 V8.14.0 (2011-04)
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IMT cellular networks; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive; Part 1: Introduction and common requirements.

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[T20] ETSI TS 136 101 V10.7.0 (2012-07)
LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 10.7.0 Release 10).

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LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channel and modulation (3GPP TS 36.211 version 10.5.0 Release 10).

[T22] ETSI TS 136 521-1 V10.3.0 (2012-10)
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Appendix A: averaging of the polarization loss factor

In this appendix, we consider an antenna used for reception. Let us use G_P to denote the polarization mismatch factor given by [T29, § 5.2] [T31, § 2.12]:

$$G_P = \frac{\left|\mathbf{h} \cdot \mathbf{E}_i\right|^2}{\left\|\mathbf{h}\right\|^2 \left\|\mathbf{E}_i\right\|^2} \tag{A1}$$

where $\mathbf{E}_i$ is an electric field, incident on an antenna used for reception, specified by two complex coordinates along orthogonal directions which are orthogonal to the direction of propagation, and where $\mathbf{h}$ is the effective complex length of the antenna for the corresponding direction. G_P is a power gain and $G_P \le 1$. The polarization loss L_P is given by

$$L_P = \frac{1}{G_P} = \frac{\left\|\mathbf{h}\right\|^2 \left\|\mathbf{E}_i\right\|^2}{\left|\mathbf{h} \cdot \mathbf{E}_i\right|^2} \tag{A2}$$

There exist three real angles φ_1, φ_2 and α such that

$$\frac{\mathbf{E}_i}{\left\|\mathbf{E}_i\right\|} = \begin{pmatrix} e^{\varphi_1} \cos\alpha \\ e^{\varphi_2} \sin\alpha \end{pmatrix} \tag{A3}$$

and three real angles θ_1, θ_2 and β such that

$$\frac{\mathbf{h}}{\left\|\mathbf{h}\right\|} = \begin{pmatrix} e^{\theta_1} \cos\beta \\ e^{\theta_2} \sin\beta \end{pmatrix} \tag{A4}$$

We have

$$\frac{1}{L_P} = \left| \frac{\mathbf{h}}{\left\|\mathbf{h}\right\|} \cdot \frac{\mathbf{E}_i}{\left\|\mathbf{E}_i\right\|} \right|^2 = \left| e^{j(\varphi_1+\theta_1)} \cos\alpha \cos\beta + e^{j(\varphi_2+\theta_2)} \sin\alpha \sin\beta \right|^2 \tag{A5}$$

so that

$$\frac{1}{L_P} = \left(\cos\alpha \cos\beta\right)^2 + \left(e^{j\phi} + e^{-j\phi}\right) \cos\alpha \cos\beta \sin\alpha \sin\beta + \left(\sin\alpha \sin\beta\right)^2 \tag{A6}$$

where $\Phi = \varphi_1 + \theta_1 - \varphi_2 - \theta_2$. We may then write

$$\frac{1}{L_P} = \left(\cos\alpha \cos\beta + \sin\alpha \sin\beta\right)^2 + 2\left(\cos\phi - 1\right) \cos\alpha \cos\beta \sin\alpha \sin\beta \tag{A7}$$

and we finally obtain

$$\frac{1}{L_P} = \cos^2\left(\alpha - \beta\right) + \frac{\cos\phi - 1}{2} \sin 2\alpha \sin 2\beta \tag{A8}$$

In a scattering-rich environment, we may assume that α is a uniformly distributed random variable and that $\varphi_1 - \varphi_2$ is random and independent of α. Consequently, Φ is random and independent of α, so that the expectation of $G_P = 1/L_P$ is given by

$$\left\langle \frac{1}{L_P} \right\rangle = \frac{1}{2\pi} \int_0^{2\pi} \cos^2\left(\alpha - \beta\right) d\alpha + \frac{1}{2\pi} \frac{\left\langle \cos\phi \right\rangle - 1}{2} \sin 2\beta \int_0^{2\pi} \sin 2\alpha \, d\alpha = \frac{1}{2} \tag{A9}$$

Appendix B: radiation efficiency

In this appendix, we consider antennas used for emission. For a single antenna presenting a impedance Z_{ANT} and a radiation resistance R_{RAD}, the power received by the antenna at the antenna port, denoted by P_{ANT}, and the power radiated by the antenna, denoted by P_{RAD}, are given by

$$P_{ANT} = |I|^2 R_{ANT} \qquad\qquad P_{RAD} = |I|^2 R_{RAD} \tag{B1}$$

where R_{ANT} = Re(Z_{ANT}) and where I is the current flowing into the antenna port. Consequently, the radiation efficiency of the mobile phone antenna, denoted by e_{MP}, is given by

$$e_{MP} = \left(\frac{P_{RAD}}{P_{ANT}} \right)_{I \neq 0} = \frac{R_{RAD}}{R_{ANT}} \tag{B2}$$

For an n-port antenna array presenting an impedance matrix $\mathbf{Z}_{ANT}$ and a radiation resistance matrix $\mathbf{R}_{RAD}$, the power received by the antenna, denoted by P_{ANT}, and the power radiated by the antenna, denoted by P_{RAD}, are given by

$$P_{ANT} = \mathrm{Re}\left(\mathbf{I}^* \mathbf{Z}_{ANT} \mathbf{I}\right) = \mathbf{I}^* \frac{\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}}{2} \mathbf{I} \tag{B3}$$

and

$$P_{RAD} = \mathrm{Re}\left(\mathbf{I}^* \mathbf{R}_{RAD} \mathbf{I}\right) = \mathbf{I}^* \frac{\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}}{2} \mathbf{I} \tag{B4}$$

where the star denotes the Hermitian adjoint and where $\mathbf{I}$ is the column vector of the currents flowing into the antenna ports. $\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}$ and $\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}$ are Hermitian matrices. Since losses are always present in actual devices in which currents flow, $\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}$ is positive definite. $\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}$ is positive semidefinite. Thus, P_{ANT} and P_{RAD} given by (B5) are nonnegative, and they are positive for $\| \mathbf{I} \| \neq 0$. The radiation efficiency of the mobile phone antennas, denoted by e, is given by

$$e = \left(\frac{P_{RAD}}{P_{ANT}} \right)_{\|\mathbf{I}\| \neq 0} = \left(\frac{\mathbf{I}^* \left(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}\right) \mathbf{I}}{\mathbf{I}^* \left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right) \mathbf{I}} \right)_{\|\mathbf{I}\| \neq 0} \tag{B5}$$

In (B5), e is a function of the complex vector $\mathbf{I}$ such that $\| \mathbf{I} \| \neq 0$. Moreover, e is real and $e \geq 0$. Energy conservation entails $e \leq 1$. Thus, we have $0 \leq e \leq 1$.

Let $\mathbf{A}$ be a positive definite matrix. We know that [T30, § 7.2] there exists a unique positive definite matrix $\mathbf{B}$ such that $\mathbf{B}^2 = \mathbf{A}$. The matrix $\mathbf{B}$ is referred to as the unique positive definite square root of $\mathbf{A}$, and is denoted by $\mathbf{A}^{1/2}$. It satisfies $(\mathbf{A}^{1/2})^{-1} = (\mathbf{A}^{-1})^{1/2}$, and we write $\mathbf{A}^{-1/2} = (\mathbf{A}^{1/2})^{-1} = (\mathbf{A}^{-1})^{1/2}$. Let us introduce the new variable $\mathbf{x} = (\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT})^{1/2}\, \mathbf{I}$. Since $\mathbf{I} = (\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT})^{-1/2}\, \mathbf{x}$, we have

$$e = \left(\frac{\mathbf{x}^* \mathbf{M}\, \mathbf{x}}{\mathbf{x}^* \mathbf{x}} \right)_{\|\mathbf{x}\| \neq 0} \tag{B6}$$

where

$$\mathbf{M} = \left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{-1/2} \left(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}\right) \left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{-1/2} \tag{B7}$$

The matrix $\mathbf{M}$ is clearly Hermitian. Since $e \geq 0$, $\mathbf{M}$ is positive semidefinite. Let us use $\lambda_1, \ldots, \lambda_n$ to denote the eigenvalues of $\mathbf{M}$, counting multiplicity, which are real, these eigenvalues being labeled in ascending order. By the Rayleigh-Ritz theorem [T30, § 4.2] and (B6), we have

$$0 \leq \lambda_1 = \min_{\mathbf{x} \neq 0} \left(\frac{\mathbf{x}^* \mathbf{M}\, \mathbf{x}}{\mathbf{x}^* \mathbf{x}} \right) \leq e \leq \lambda_n = \max_{\mathbf{x} \neq 0} \left(\frac{\mathbf{x}^* \mathbf{M}\, \mathbf{x}}{\mathbf{x}^* \mathbf{x}} \right) \leq 1 \tag{B8}$$

Consequently, we have found that λ_1 and λ_n are the minimum value and the maximum value of e, respectively, when $\mathbf{I}$ takes on any possible values. At this stage, to obtain λ_1 and λ_n, we need to compute $\mathbf{M}$ using (B7), and then to computes its eigenvalues. The computation can be simplified significantly if we observe that

$$\left(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}\right)\left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{-1} = \left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{1/2} \mathbf{M} \left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{-1/2} \tag{B9}$$

so that $\mathbf{M}$ is similar to $(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD})(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT})^{-1}$. Thus, $\mathbf{M}$ and $(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD})(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT})^{-1}$ have the same eigenvalues, counting multiplicity [T30, § 1.3]. Consequently $\lambda_1,..., \lambda_n$ are the eigenvalues of $(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD})(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT})^{-1}$, counting multiplicity, which are real, these eigenvalues being labeled in ascending order.

In the case where $\mathbf{I}$ is known, e can be computed and e lies in $[\lambda_1, \lambda_n] \subset [0, 1]$. In the case where $\mathbf{I}$ is not known, $\mathbf{I}$ can be considered as a random complex vector. In this case, if we had suitable information on the statistics of $\mathbf{I}$, we could derive the expectation $< e >$ of e, which lies in $[\lambda_1, \lambda_n]$. In our problem, the complex vector $\mathbf{I}$ is not known, and we have no information on the statistics of $\mathbf{I}$. Following a different approach, we note that the Courant-Fischer "min-max theorem" [T30, § 4.2] provides a variational characterization of the eigenvalues of the Hermitian matrix $\mathbf{M}$. According to this theorem and (B6), each eigenvalue of $\mathbf{M}$ is a stationary point of e. We can define an "average" value of e, denoted by e_{MP}, as the average of these eigenvalues. Since

$$\sum_{i=1}^{n} \lambda_i = \operatorname{tr}\left(\mathbf{M}\right) = \operatorname{tr}\left(\left(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}\right)\left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{-1}\right) \tag{B10}$$

where tr($\mathbf{A}$) denotes the trace of a matrix $\mathbf{A}$, our average value e_{MP} is given by

$$e_{MP} = \frac{1}{n} \operatorname{tr}\left(\left(\mathbf{R}_{RAD} + \mathbf{R}^*_{RAD}\right)\left(\mathbf{Z}_{ANT} + \mathbf{Z}^*_{ANT}\right)^{-1}\right) \tag{B11}$$

We note that e_{MP} lies in $[\lambda_1, \lambda_n]$, and that e_{MP} can be regarded as an expectation of e for an assumed statistics of $\mathbf{I}$. Let us also note that, if the multiport antenna array does not contain any non-reciprocal device (such as circulators and isolators), then $\mathbf{Z}_{ANT}$ and $\mathbf{R}_{RAD}$ are symmetric matrices. In this case, we obtain

$$e_{MP} = \frac{1}{n} \operatorname{tr}\left(\mathbf{R}_{RAD} \mathbf{R}^{-1}_{ANT}\right) \tag{B12}$$

where $\mathbf{R}_{ANT} = \operatorname{Re}(\mathbf{Z}_{ANT})$.