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# MODELS AND PROTECTION DISTANCES FOR TODAY'S RADIO COMMUNICATION HANDSETS

**Germain Broydé *, Evelyne Clavelier ****
(*) student at ENSAM, CER d'Angers, 2 bd du Ronceray - 49035 Angers, germain.broyde@orange.fr
(**) Excem, 12 chemin des Hauts de Clairefontaine - 78580 Maule, eclavelier@excem.fr

**Abstract**. The assessment of the highest possible field strengths at a given distance of a radio communication handset is necessary for specifying immunity limits. For an ideal half-wave dipole antenna, we derive a closed-form expression for the computation of the maximum electric and magnetic field strengths at a given distance from the antenna, which are different from the field strengths in the plane of maximum far-field radiation, at a given distance from the antenna. After a discussion of the applicability of these expressions, we apply them to current types of mobile radio transmitters in order to assess protection distances.

## I. INTRODUCTION

The assessment of electromagnetic fields close to a transmitting antenna is most relevant to EMC, since it should be the basis for setting immunity limits relating to radiated disturbances produced by portable transmitters, and the corresponding protection distances.

Surprisingly, little information can be found on this essential question, both in EMC standards [1, Annex E] and in EMC textbooks. This is possibly because the question is too trivial for antenna experts, while at the same time not amenable to a mere rule of thumb: typically, theoretical approaches require numerical computation, as opposed to a closed-form solution. Also, measurements are difficult in the vicinity of a transmitting antenna, since a naive measurement technique based on the use of an off-the-shelve measuring antenna near the transmitting antenna is often not valid, when the distance between the antennas is not much larger than the largest dimension of the measuring antenna. This is because such a measurement set-up is prone to unpredictable interactions between the antennas, and the measuring antenna is not implemented in a configuration for which it is intended and for which its calibration is applicable. Consequently, a measuring antenna specifically designed and calibrated for such close proximity measurements is needed.

However, EMC engineers often wish to evaluate the highest possible field strengths at a given distance of an antenna, for the purpose of specifying immunity limits. A difficulty is that, in this context, the structure and orientation of the transmitting antenna are often not specified, so that what is needed is an assessment of the maximum field strengths at a given distance, the maximum being taken over all possible orientations. We note that, in the near-field, this maximum is *not* the field strength in the directions of maximum far-field radiation.

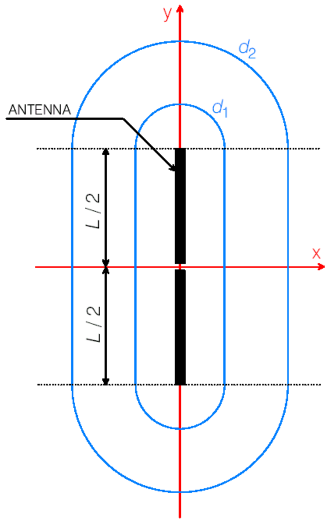


Fig. 1. A dipole antenna and the intersection of surfaces of constant distance to the antenna with a plane containing the antenna, for a distance $d_1$ and a distance $d_2$.

In Section II, we consider two computational models for the assessment of the maximum field strength in the vicinity of an ideal half-wave dipole antenna, which may to some extent be used as a physical model for the radiation of a radio communication handset. Figure 1 shows the geometry of the surfaces of constant distance to a dipole antenna, *which are not the spheres of constant distance to the center of the antenna*. We introduce a closed-form expression for computing the maximum free-space electric and magnetic field strengths as a function of the distance to the antenna, irrespective of the orientation.

The applicability of this result to model the near-field radiation of an unspecified portable transmitter is discussed in Section III. In Section IV, we review the characteristics of some of today's radio communication handsets, focusing on the latest standards and frequency allocations. This review is not exhaustive, because of the large number of available types of radio transmitters and of the great complexity of the European frequency allocation. Using the above-mentioned closed-form expressions, we establish the protection distances for different cases.

## II. TWO SIMPLE ANTENNA MODELS

In this section, we consider the following models for the half-wave dipole antenna: the half-wave dipole with sinusoidal current distribution and the half-wave dipole with an almost exact current distribution.

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The half-wave dipole with sinusoidal current distribution is a hypothetical antenna such that analytical expressions are available for computing the fields at all distances, as a function of zenith angle $\theta$ [2, § 8.11] [3, § 2.7]. This antenna has been used for investigating the near-field of dipole array antennas [4].

In this paper, the half-wave dipole with an almost exact current distribution model is a numerical model based on the implementation of the method of moments with point matching for the computation of an "almost exact" (in fact it is of course an approximation) current distribution. We have exactly followed the computation technique of § 2.10 and § 2.11 of [3] based on Hallén integral equation, for a thickness of 0.01 times the total antenna length $L$, a total length of $L = 0.48\ \lambda$, and 8 basis functions. The result is accurate at all distances, but the exact antenna characteristics have to be used in the model, which requires a significant computation time when one looks for maximum field strengths.

As with any antenna, the electric field strength $E$ and the magnetic field strength $H$ radiated in the far-field region by both half-wave dipole models are related by $E = \eta_0\ H$, where $\eta_0 \approx 376.7\ \Omega$ is the intrinsic impedance of free space. This simple relation does not apply in the near-field, the border between the near-field and far-field region being usually considered to lie at a distance $R_{FF}$ from the reference point of the antenna [5, § 1-3], [6, p. 33-4], [7], [8], [9] equal to:

$$R_{FF} = \max\left(\frac{2D^2}{\lambda}, \frac{\lambda}{2\pi}\right) \quad (1)$$

where $D$ is the maximum overall dimension of the antenna. This distance $R_{FF}$ is the maximum of two terms, the first corresponding to the outer limit of the radiating near-field region, and the second to the outer limit of the reactive near-field region. In the case of a $\lambda/2$ dipole, we get $R_{FF} = \lambda/2$.

At a given point, the knowledge of $E$ and $H$ are equally important for EMC engineering, since a high-impedance electrically small circuit is mainly susceptible to the electric field whereas a low-impedance electrically small circuit is mainly susceptible to the magnetic field. Consequently, any description of the near-field must provide values for the electric field strength and the magnetic field strength.

We shall use the magnetic electric field strength [10] [11] defined as $E_M \equiv \eta_0 H$, in the place of the magnetic field strength. In the far-field, we have $E_M = E$, but this equality will not hold in the near-field.

In the plane of maximum far-field radiation (i.e. the azimuth plane $\theta = \pi/2$), the field strengths produced by the two models of half-wave dipole have already been compared [10] [11]. In this plane, both antennas produce far-field field strengths corresponding to a gain of 1.64.

If we now leave the plane of maximum far-field radiation, we note that a surface of constant distance $d$ to the antenna is made of a portion of a cylinder and two hemispheres, as shown in Fig. 1. Let us look for maximum field strengths on such surfaces, with $d$ as parameter. For a 300 MHz half-wave dipole antenna, we get the result shown in Fig. 2 if we use the half-wave dipole with sinusoidal current distribution model, and the result shown in Fig. 3 if we use the half-wave dipole with almost exact current distribution model.

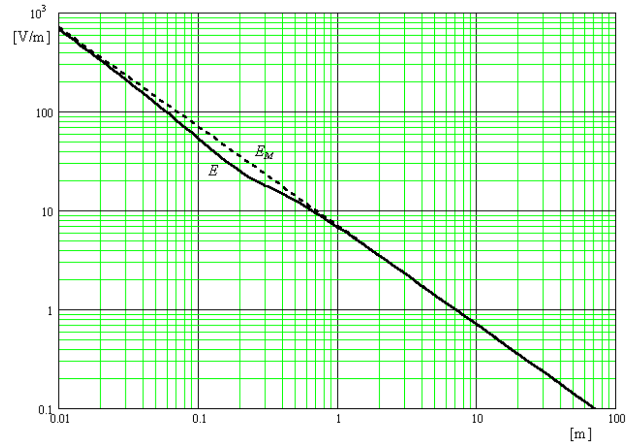


Fig. 2. Maximum rms field strengths produced by a 1W source, as a function of the distance to a $\lambda/2$ dipole, for $\lambda = 1$ m, using the dipole with sinusoidal current distribution model.

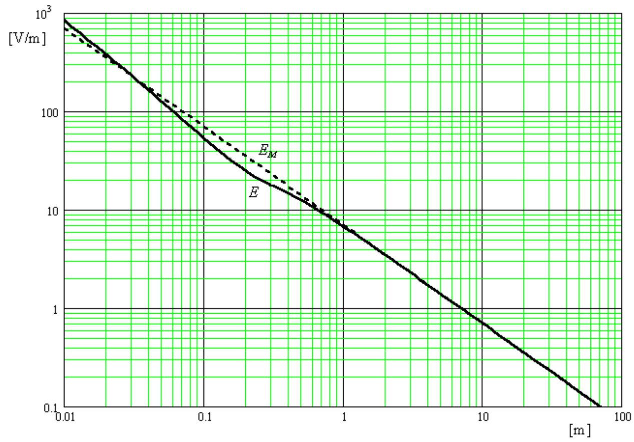


Fig. 3. Maximum rms field strengths produced by a 1W source, as a function of the distance to a $\lambda/2$ dipole, for $\lambda = 1$ m, according to the dipole with almost exact current distribution model.

For the computation based on the almost exact current distribution, a different antenna thickness would produce a similar characteristic, but the electric field strength would differ somewhat in the radiating near-field region: a thinner antenna would produce a curve closer to the one applicable to the sinusoidal current distribution, because in this case the absolute value of the difference between the almost exact current distribution and the sinusoidal current distribution decreases [12, Fig. 8.13]. Changing the antenna thickness would leave the magnetic field strength unchanged. The numerical computations leading to Fig. 2 and 3 were performed using a standard set of Mathcad worksheets [13].

Fig. 2 and Fig. 3 differ only for the electric field strength, at very short distances from the antenna (for $d < 5$ cm $\approx \lambda/20$), and by a small amount. Consequently, using the half-wave dipole with sinusoidal current distribution model may provide a suitable accuracy down to very short distances from the antenna.

The maximum rms electric field strength produced by the half-wave dipole with sinusoidal current distribution may also be obtained using

$$E = \frac{\eta_0}{2\pi d}\sqrt{\frac{W}{R_0}}\ g \qquad (2)$$

where $R_0 \approx 73.13\ \Omega$, $W$ is the power delivered to the antenna and

$$g = 1 - \frac{3.24\frac{d}{\lambda}}{\left(1+6.3\frac{d}{\lambda}\right)\left(1-3.5\frac{d}{\lambda}+17\left(\frac{d}{\lambda}\right)^2\right)} \qquad (3)$$

The maximum rms magnetic electric field strength produced by the half-wave dipole with sinusoidal current distribution is given by

$$E_M = \frac{\eta_0}{2\pi d}\sqrt{\frac{W}{R_0}} \quad . \qquad (4)$$

Equation (2) is only a rational approximation of the results obtained numerically, but it is accurate to 0.1 dB. Using $g = 1$ instead of (3) in (1) introduces a maximum error of about 3 dB. Equation (4) is exact.

## III. APPLICATION AND DISCUSSION

The closed-form expressions (2)-(4) are useful for assessing the maximum field strength produced in free-space by the half-wave dipole antennas with sinusoidal current distribution. They are applicable to all field regions. The comparison of Fig. 2 and Fig. 3 shows that (2)-(4) can also be used as a simplified model of a real half-wave dipole antenna, though it becomes somewhat inaccurate at very short distances.

The maximum rms field strengths may be put into the form

$$E = \frac{k_1\sqrt{W_{ERP}}}{d}\,g \qquad (5)$$

and

$$E_M = \frac{k_1\sqrt{W_{ERP}}}{d} \qquad (6)$$

where:

$W_{ERP}$ is the effective radiated power (ERP), defined as the product of the power delivered to the antenna by the maximum antenna gain, divided by 1.64 (i.e. the maximum gain of an ideal $\lambda/2$ dipole antenna);

$d$ is the distance between the point of measurement and the antenna, as defined above and shown in Fig. 1;

$E$ is the rms electric field strength; and

$$k_1 = \frac{\eta_0}{2\pi\sqrt{R_0}} \approx 7.01\,\Omega^{1/2} \qquad (7)$$

The equations (5) and (6) look like the classical formula for the electric field strength in the direction of maximum far-field radiation in free-space [1] [14, ch. 6], [15]:

$$E = \frac{k_1\sqrt{W_{ERP}}}{r} \qquad (8)$$

where $r$ is the distance to the electrical center of the antenna. However, this resemblance is misleading, since (8) is established for any antenna, but only in the far-field.

The formulas (2)-(4) assume lossless antennas. This assumption may be realistic for a real half-wave dipole installed at the top of a mast, but in the case of a radio communication handset, significant losses are unavoidable in the radiating element and/or in the matching circuit. We may assume that losses in an antenna will reduce the field strengths in the near-field region by the same coefficient as in the far-field. In this case, (5) and (6) remains applicable.

We also want to use (5)-(6) as models for assessing the maximum magnetic electric field strength at a given distance of the antenna of a mobile transmitter. Such an antenna has a low directivity, like a half-wave dipole, but it is not an half-wave dipole. Since, in the near-field, the fields strongly depend on the antenna type and characteristics, such a quick estimate would clearly be an approximation. However, this approximation is reasonable, since it will not conflict with the physics of antennas. What else can we do anyway, when little is known about the antenna? If this approximation is used, we should keep in mind that:

- the so-called "monopole antennas" used in many portable transmitters behave as asymmetric dipoles [16];
- monopole antennas implemented with a large enough ground plane, for instance a car-roof-mounted UHF antennas, have a larger gain than $\lambda/2$ dipole antennas (the maximum gain is 3.28 for an ideal $\lambda/4$ monopole);
- real transmitters using an integral antenna might eventually exhibit a behavior differing significantly from our models [17];
- when $W_{ERP}$ is not known, one should consider that the planar antennas used as integral antennas in many modern UHF handsets suffer from a low efficiency, typically below 50 %.

## IV. PROTECTION DISTANCES

### IV.1 Introduction

In this section, we will consider some standards representative of the radio communication handsets which may be used in Europe. We are mainly interested in the radiated power and the operating frequencies. The radiated power may be expressed as the power at the output of the transmitter, the effective radiated power (e.r.p.), denoted by $W_{ERP}$, or the isotropic radiated power (e.i.r.p.), equal to $1.64 \times W_{ERP}$, according to the type of device. We eventually mention the type of modulation, because it may have a strong influence on the effect produced on a susceptible device. The word "transportable" refers to transceivers intended to be operated in a vehicle, whereas the word "portable" refers to transceivers intended to be carried in the hand (handsets).

### IV.2 The case of GSM

In this section, GSM includes GPRS (2.5 G) and EDGE (2.75 G). In Europe, requirements for the operating frequencies for "mobile transmit, base receive" are [18, § 9]:

a) for Standard GSM 900 Band (P-GSM): 890 MHz to 915 MHz;

b) for the Extended GSM 900 Band (E-GSM, includes Standard GSM 900 band): 880 MHz to 915 MHz;

c) for GSM 1800, also called DCS 1800 Band: 1710 MHz to 1785 MHz.

The GMSK (Gaussian Minimum Shift Keying) is used for the standard GSM networks (2G) [19, § 13.3.1] [20, § 7.8.2.]. GPRS systems (2.5G) also use GMSK. EDGE systems (2.75G) use 8-PSK [21]. Different power classes have been defined [22]:

– For GSM 900 there are four power classes, the maximum power class having 8 W peak output power and the minimum power class having 0.8 W peak output power.

– For DCS 1800 there are three power classes having 4 W peak output power, 1 W peak output power and 0.25 W peak output power.

For equipment with integral antenna only, a reference antenna with 0 dBi gain shall be assumed [22]. Consequently, for handsets, the above-mentioned power levels are equivalent isotropic radiated powers (e.i.r.p.).

We may assume [23, p. 13] that the GSM 900 transportable sets are in power class 2 (8W) and the GSM portable sets are in power class 4 (2W). Typical DCS 1800 portables are in power class 3 (1W). Since we are interested in maximum power levels we will not take into account the reduction of transmitted output power eventually applied by adaptive power control [20, § 10.2.1] [22, § 4.1.1].

The GMSK and 8-PSK modulation used in GSM are constant envelop modulations. However, the TDMA structure creates a OOK-like modulation. Conventional 2G GSM uses one time slot per frame, resulting in a period of 4.615 ms (hence a fundamental modulation frequency of 217 Hz) [19, § 6.3.2]. We note that 2.5G and 2.75G transmitters may use more than one time slot per frame.

### IV.3 The case of PMR

PMR is the abbreviation for Professional Mobile Radio or Private Mobile Radio. According to the European Common Allocation [24], the frequency bands allocated to PMR extend from 30.01 MHz to 921 MHz. There are several types of PMR mobile transceivers, intended for licensed or license-free operation [19, chap. 12].

- The transceivers operating in the 446 MHz band (PMR446) are license-free. Typically, the corresponding maximum e.r.p. of a portable unit is 0.5 W.
- Some licensed PMR portable transceivers operate in the frequency band 66 MHz to 88 MHz, with a maximum output power of 5 W.
- Some licensed PMR portable transceivers operate in the frequency band 403 MHz to 470 MHz, with a maximum output power of 4 W.

### IV.4 The case of TETRA

TETRA (TErrestrial Trunked RAdio) is a set of standards describing a mobile radio communication infrastructure throughout Europe. This infrastructure is targeted primarily at the mobile radio needs of public safety groups (such as police and fire departments), utility companies, and other enterprises that provide voice and data communications services. It is likely that TETRA will gradually replace PMR for such applications.

The radio spectrum allocation for TETRA in Europe is the following, for transmission by the mobile transceiver (uplink) [25] [26]:

– emergency services use the RF frequency band 380 MHz to 385 MHz;

– the European non-emergency services TETRA frequencies are mainly allocated in the 410 MHz to 420 MHz band and in the 870 MHz to 876 MHz band, some countries allocating frequencies in the 450 MHz to 460 MHz band;

– countries that are not members of NATO can sometimes allocate radio frequencies in the 385 MHz to 390 MHz band for non-public safety TETRA users.

Phase modulation or QAM (Quadrature Amplitude Modulation) may be used in TETRA. We note that, unlike phase modulation, QAM is not a constant envelop scheme, and is therefore likely to produce different effects in susceptible devices.

The nominal transmitter power for mobile stations range from 30 W (power class 1), to 0.56 W (power class 4L) for phase modulation and from 30 W (power class 1), to 0.18 W (power class 5L) for QAM [27]. We neither tried to compute nor found in the literature the corresponding peak power values. The typical transmission power is 3W for a portable set and 10W for mobile set fitted in a vehicle [28]. The relatively high power transmissions plus the time division multiplex access (TDMA) with long burst periods used by TETRA induce unwanted low-frequency components in susceptible devices [28].

### IV.5 The case of UMTS

The UMTS (Universal Mobile Telephone System) is the third generation of mobile telecommunication (3G). The transfer rate is higher than with the GSM. In Europe [29] [30] [31], the two technologies for its implementation are WCDMA (i.e. FDD) and TDCDMA (i.e. TDD), and the frequencies are [32] [33]:

- for WCDMA (i.e. FDD) (uplink),

– 1920 MHz to 1980 MHz (band I);

– 1710 MHz to 1785 MHz (band III);

– 2500 MHz to 2570 MHz (band VII);

– 880 MHz to 915 MHz (band VIII);

- for TDCDMA (i.e. TDD) (uplink and downlink),

– 1900 MHz to 1920 MHz and 2010 MHz to 2025 MHz (band a);

– 2570 MHz to 2620 MHz (band d).

For WCDMA, the UE (User Equipment) maximum output power ranges are [29], [34]:

| | Table I : Protection distance for the electric field strength E and magnetic field strength H | | | | |
|---|---|---|---|---|---|
| | Frequency | Power | Protection distance for 3 V/m | Protection distance for 10 V/m | Protection distance for 30 V/m |
| Case A | 70 MHz | 5 W | 2.70 m for E; 2.90 m for H | 0.63 m for E; 0.87 m for H | 0.24 m for E; 0.29 m for H |
| Case B | 151 MHz | 5 W | 2.86 m for E; 2.90 m for H | 0.72 m for E; 0.87 m for H | 0.22 m for E; 0.29 m for H |
| Case C | 415 MHz | 3 W | 2.24 m for E; 2.25 m for H | 0.65 m for E; 0.68 m for H | 0.16 m for E; 0.23 m for H |
| Case D | 446 MHz | 1/2 W | 0.90 m for E; 0.92 m for H | 0.22 m for E; 0.28 m for H | 0.07 m for E; 0.09 m for H |
| Case E | 900 MHz | 2 W e.i.r.p. | 1.43 m for E and H | 0.42 m for E; 0.43 m for H | 0.12 m for E; 0.14 m for H |
| Case F | 1780 MHz | 1 W e.i.r.p. | 1.01 m for E and H | 0.30 m for E and H | 0.09 m for E; 0.10 m for H |
| Case G | 2530 MHz | 1/4 W e.i.r.p. | 0.51 m for E and H | 0.15 m for E and H | 0.04 m for E; 0.05 m for H |
| Case H | 5500 MHz | 1 W e.i.r.p. | 1.01 m for E and H | 0.30 m for E and H | 0.10 m for E and H |

▪ for the operating band I,
– power class 1: 2 W or 33 dBm;
– power class 2: 0.5 W or 27 dBm;
– power class 3: 0.250 W or 24 dBm;
– power class 4: 0.125 W or 21 dBm;
▪ for the operating band III,
– power class 3: 0.250 W or 24 dBm;
– power class 4: 0.125 W or 21 dBm;
▪ for the operating band VII and VIII,
– power class 3: 0.250 W or 24 dBm;
– power class 3bis: 0.200 W or 23 dBm;
– power class 4: 0.125 W or 21 dBm.

For TDCDMA, for single code operation, the UE maximum output power ranges are [T30] [T35]:
– power class 1: 1 W or 30 dBm;
– power class 2: 0.250 W or 24 dBm;
– power class 3: 0.125 W or 21 dBm;
– power class 4: 0.01 W or 10 dBm.

Maximum output power levels are measured at the antenna connector of the UE. For UE with integral antenna only, a reference antenna with a gain of 0 dBi is assumed. The UE antenna performance has a significant impact on system performance, and minimum requirements on the antenna efficiency are therefore intended to be included in future versions of UMTS specifications. Up to now, there is no specified limit of the e.i.r.p. for WCDMA (FDD) or TDCDMA (TDD).

In Europe, the following restrictions apply.
▪ For TDCDMA (TDD), only power classes 2 and 3 are allowed [T33]. Consequently, the maximum output power for single-code for TDCDMA (TDD) is the power class 2 (0.250 W or 24 dBm).
▪ For WCDMA (FDD), only power classes 3, 3bis (where applicable) and 4 are allowed for single-code and multi-code transmission modes [T32]. Consequently, the maximum output power for WCDMA (FDD) is the power class 3 (0.250 W or 24 dBm).

### IV.6 The case of Wi -Fi

The operating frequencies available in Europe for Wi-Fi equipments are [36] [37] [38] [39]:
▪ 2.4 GHz to 2.485 GHz band;
▪ 5.150 GHz to 5.350 GHz band;
▪ 5.470 GHz to 5.725 GHz band.

For *Data transmission equipment operating in the 2.4 GHz ISM band and using wide band modulation techniques* [36], the maximum e.i.r.p. is 100 mW or 10 dBm. For *Broadband Radio Access Networks (BRAN)* [39], the e.i.r.p. is 200 mW or 23 dBm for 5.150 GHz to 5.350 GHz band and 1 W or 30 dBm for 5.470 GHz to 5.725 GHz band.

### IV.7 Computed protection distances

In order to take into account the 80 % amplitude modulation used during applicable tests for the immunity to radiated radio-frequency fields [1], Table I is based on the following assumption: the susceptible device (victim) is not disturbed by 1.8 times the electric field strength or magnetic electric field strength applicable to a given column of the table. For instance, the column “Protection distance for 3 V/m” corresponds to a distance from the source such that the field strength of 5.4 V/m is not exceeded. The frequency/power combinations considered in Table I are the following.
Case A: 70 MHz - 5 W at the output of the transmitter (a case of licensed PMR).
Case B: 151 MHz - 5 W at the output of the transmitter (a case of licensed PMR).
Case C: 415 MHz - 3 W at the output of the transmitter (case of TETRA).
Case D: 446 MHz - 0.5 W e.r.p. (case of license-free PMR).
Case E: 900 MHz - 2 W e.i.r.p. (case of portable GSM with or without GPRS) [T23, Annex A, p. 13].
Case F: 1780 MHz - 1 W e.i.r.p. (case of DCS with or

without GPRS, also covers UMTS FDD Band I and Band III and UMTS Band a for 0.250 W at the output of the transmitter).

Case G: 2.5 GHz - 0.250 W e.i.r.p. (case of UMTS FDD band VII unit with integral antenna, also covers WiFi at 2.4 GHz and UMTS TDD Band d).

Case H: 5.5 GHz - 1 W e.i.r.p. (case of Wi Fi in the 5 GHz band).

Table I may be compared to [1, Table E.1].

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