CEPT ECC
Electronic Communications Committee

ECC Report 333

Non-beam Wireless Power Transmission (WPT) applications other than WPT-EV operating in various frequency bands below 30 MHz

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0 EXECUTIVE SUMMARY

This Report evaluates compatibility between non-beam inductive Wireless Power Transmission (WPT) applications in various frequency bands below 30 MHz and radiocommunication services. It was developed based on the information given in the ETSI TR 103 493 [1] and subsequent information received from ETSI Technical Committee (TC) EMC and Radio Spectrum Matters (ERM) along with other contributions.

Based on the information available, the studies conducted in this Report only apply to applications of inductive coupling WPT in power classes up to 30 W, which include mobile phone chargers and Active Implantable Medical Devices (AIMD). The study of higher power WPT applications may be considered in due course.

Many inductive low power WPT applications are in use today and have been in operation for many years. This Report includes measurements that confirm that the generic WPT devices studied operate with emission levels well below the current emission limits for SRDs in section 4. The use of these generic WPT devices has not resulted in any cases of reported interference to radio services to date, according to the survey conducted in ECC via the questionnaire on “WPT Devices that are currently available in the European Market”, handed out to CEPT administrations at the end of 2020 [58].

The studies in this Report are based on the device densities forecast available when conducting the present work and can be found in Table 2 and Table 3. If a larger growth of WPT devices (compared to the one assumed in this Report) is observed in the future, new studies may be needed under the light of the new effective density deployment evolution.

The main applications of WPT with a charging power of less than 30 W are portable devices like smartphones, smart watches or fitness tracker and medical devices. Historically, the band 100-148.5 kHz is standardised through the Qi specification which helped it to become the universal charging solution for portable devices, thus most of portable devices available on the market will be using this band. This is reflected by attributing the highest device density to this band in Table 2 and Table 3. It has to be noted that higher frequency bands will mainly be dedicated to wearable devices for which the coil dimension is smaller to match the dimensions of the device and allows a better efficiency of the charging system.

Some WPT devices can modulate the power carrier in order to transmit information to the charging device. Characteristics, measurement and testing implying this datalink are present in this Report. However, only unmodulated WPT carriers were explicitly taken into account in the compatibility studies (MCL, Monte-Carlo). It is not expected, taking into account data link, would significantly change the compatibility with radiocommunication services.

The studies consider the separation distances and indicate potential interference levels that may cause interference to the respective radio services, but do not present recommended limits.

The emissions of WPT devices in the spurious domain are dominated by harmonics caused by the type of power feed (i.e. power transmission). Therefore, the impact of WPT harmonics needs to be taken into account. The minimum coupling loss studies in this Report address the harmonics but not the Monte-Carlo simulations.

A summary of different sharing studies is provided in the text below and in Table 1.

In the absence of technical parameters and/or deployment information, some studies compared WPT emission levels with the median man-made noise level as provided in Recommendation ITU-R P.372. This Recommendation provides only information about white Gaussian noise (WGN), i.e. broadband noise, but ignores other noise sources. Especially in urban and suburban environments single carrier noise (SCN) emissions are in most locations and often the dominant form of noise (see Recommendation ITU-R SM.1753, section 3 [50]). WPT emissions are in their nature very similar to SCN. Comparing WPT emissions with Recommendation ITU-R P.372, therefore, significantly overestimates the interference impact.

Table 1: Summary of sharing analysis outcome

Study	Outcome
Qi System	The measured spurious emission levels at 10 metres for all units tested (a selection of 5 W and 15 W devices) are some 40 dB below the limit specified in ERC Recommendation 74-01 [11]. At frequencies above 1 MHz, the derived levels at 10 m are below a proposed limit for the protection of amateur service and the fixed/mobile services (see ECC Report 289 [6]) for WPT spurious emissions.
AIMD Neuromodulators	*Spurious and Harmonics* ERC Recommendation 74-01 already has existing spurious emission limits in the range of 150 kHz-30 MHz that are recognised and harmonised to the Radio Equipment Directive. As supported by the data in this Report, spurious emission measurements are below what is currently required for this Recommendation. *Fundamental* 260-320 kHz
Battery recharging of hearing implant systems at 5 MHz and 6.78 MHz	There is a probability of 0.027% that a single AIMD charger is within the 100-metre range of the victim receiver for population densities up to 1000 people/km^2 There is a probability of 0.27% that a single AIMD charger is within the 100-metre range of the victim receiver for population densities up to 10000 people/km^2
The Amateur Service	The worst-case studies suggest that the impact of Qi based systems is likely to be modest based on noise floor levels
Broadcasting Service	Based on currently available low power inductive WPT devices, when measured at 10 m from the device, harmonic levels of -35 dBμA/m would offer a reasonable degree of protection for receiver operating at the edge of coverage
Radionavigation Service	Results were taken from studies in Report ITU-R SM.2449. In these studies, the WPT system transmits with an electrical field strength of -15 dBμV/m at 300 m. In-band interference is considered. Interference to radionavigation service in 90-110 kHz: ▪ Reception on board a ship was found not to be affected by a WPT system on land; ▪ With a WPT system onboard a ship, the minimum separation distance was found to be between 4.5 m and 5.4 m for single entry or between 9.4 m and 11.4 m for aggregate signal levels. It is likely that ships equipped with metallic walls would require smaller separation distances.
Aeronautical Radionavigation Service	Considering ADF/NDB systems operating in 255-535 kHz, and WPT systems with maximum magnetic field level of -15 dBμA/m, all operating at 400 kHz, considering in-band interference, and without considering building entry losses, studies concluded that coexistence is possible.
SFTS Service	Coexistence is possible using the limits defined in ERC Recommendation 70-03 [31], applied for the protection of time signals
Minimum coupling loss (MCL) studies	The minimum coupling loss (MCL) studies (worst-case theoretical modelling) carried out on the protection of the amateur, mobile and fixed services in the spurious domain (from any WPT emission) converged into a level of protection described in the following sections of this Report: -46 dBμA/m at 300 kHz reducing by 7 dB per frequency decade to -60.0 dBμA/m at 30 MHz measured at 10 metres; Note that these levels, although originally calculated in the context of residential median noise levels defined in Recommendation ITU-R P.372, may be more relevant to the rural environment, given the current reality of noise levels as can be found in the ITU noise database.

Study	Outcome
Aggregate Monte Carlo Study (See Note 1)	This study considered interference from a density of 1500 WPT devices per km² deployed in 300-400 kHz and 500 WPT devices per km² in 1610-1800 kHz and 1950-2150 kHz with a maximum transmit level of -15dBµA/m at 10 m to radio services receiving at exactly 400 kHz, 1800 kHz and 2000 kHz, respectively (only one receiver at a time is considered). Building entry losses (BEL) in the far field are modelled according to the ITU-R handbook on ground wave propagation [55][50]. The model is used on top of propagation model of ERC Report 69, although it is supposed to be used with propagation curves of Recommendation ITU-R P.368 [61]. At distances where magnetic coupling is dominant, 10 dB attenuation of attenuation for 30% of cases has been assumed in urban scenario. Potential in-band interference to radio services with a reception bandwidth of 2.7 kHz were considered, taking into account that a WPT device randomly choose its transmitted frequency within its operating band. For WPT emissions at -15 dbµA/m at 10 m distance, two sets of results have been derived. For the first set including the effect of built up structures like buildings it was found that in very dense urban areas, a 1.2 to 1.3 dB noise increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.3 or 0.4 dB respectively for the two frequency ranges. For all other environments (urban and residential) the increase of the median noise is less than 0.4 dB or 0.6 dB, depending on the frequency. For the second set without the effect of built up structures like buildings it was found that in in very dense urban areas, a 1.5 dB noise at 400 kHz, 3.9 dB at 1800 kHz and 4.6 dB at 2000 kHz increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency, respectively. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.4 dB at 400 kHz, 1.3 dB at 1800 kHz and 1.5 dB at 2000 kHz, respectively. For all other environments (urban and residential) the increase of the median noise was lower than in the high density urban case. However, it should be noted, that the in the absence of any reference/recommendation describing the effect of "building exit losses" and losses for built up structures, the first set of results may be underestimating the interference while for the second set of results may be overestimating it. The exact effect of interference impact is somewhere in the presented range. It is noted that the study does not consider emissions at other frequencies, i.e. spurious/harmonics are not studied.
Single Entry Monte Carlo Study (See Note 1)	This study considered three interference scenarios from WPT devices operating at 400 kHz, 1650 kHz, and 2000 kHz with a maximum transmit level of -15dBµA/m at 10 m to radio services receiver operated at the same frequency. At distances where magnetic coupling is dominant, 10dB attenuation of attenuation for 30% of cases has been assumed in urban scenario. In cities and considering BEL in 30% of cases, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 [7] for separation distances between 11 and 14 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 7 m and 9 m. In cities and without BEL, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 12 m and 15 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 7 m and 10 m. In residential areas and without BEL, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for

Study	Outcome
	separation distances between 15 m and 18 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 9 m and 13 m. This single entry study is a worst case analysis, since it assumes that the WPT emissions are always co-channel to the radio service receiver. It is noted that the study does not consider emissions at other frequencies, i.e. spurious/harmonics are not studied.
Note 1: This applies where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, service which are more susceptible to single tone interference.	

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	Explanation
ARRL	American Radio Relay League
AIMD	Active implantable medical device
ADF	Automatic direction finding
a.g.l.	Above ground level
AGV	Automated guided vehicle
AM	Amplitude modulation
BLE	Bluetooth low energy
BPP	Baseline Power Profile
BW	Bandwidth
CDF	Cumulative Distribution Function
CENELEC	European Committee for Electrotechnical Standardization
CEPT	European Conference of Postal and Telecommunications Administrations
CISPR	International special committee on radio interference
DC	Duty cycle
DRM	Digital Radio Mondial
DSL	Digital subscriber line
ECC	Electronic Communications Committee
e.i.r.p.	Equivalent Isotropic Radiated Power
EMC	Electromagnetic Compatibility
EN	European norm
EPP	Extended Power Profile
ERC	European Radiocommunications Committee (of CEPT)
ERM	EMC and Radio Spectrum Matters
e.r.p.	Effective Radiated Power
ETSI	European Telecommunications Standards Institute
EU	European Union
EUT	Equipment under test
EV	Electric vehicle
FOD	Foreign Object Detection
FSK	Frequency shift keying
HF	High Frequency
IARU	International Amateur Radio Union
IN	Impulsive noise
I/N	Interference to noise ratio

Abbreviation	Explanation
IPG	Internal electrical pulse generator (implantable pulse generator)
ISM	Industrial, scientific and medical
ITU-R	International Telecommunication Union – Radiocommunication Sector
LF	Low Frequency
LW	Long Wave
MF	Medium Frequency
MMN	Man-made noise
MW	Medium wave
NDB	Non directional beacon
OATS	Open air test site
OBW	Occupied bandwidth
OFDM	Orthogonal Frequency Division Multiplexing
PTx	Power transmitter
PR	Protection Ratio
PRx	Power receiver
RBW	Resolution Bandwidth
RED	Radio Equipment Directive
RMS	Root Mean Square
SAC	Semi Anechoic Chamber
SCN	Single Carrier Noise
SFTS	Standard frequency and time signal service
S/N	Signal-to-noise ratio
SRD	Short range device
SW	Short wave
TC	Technical Committee
VDSL	Very high-speed digital subscriber line
VHF	Very High Frequency
WGN	White Gaussian Noise
WPC	Wireless Power Consortium
WPT	Wireless power transmission

1 INTRODUCTION

This Report provides the result of the studies examining the compatibility between the various types of low power WPT systems and the incumbent radiocommunications services/systems using the same or adjacent frequency bands below 30 MHz.

Wireless charging is being adopted and developed for application areas such as tablets, laptops, power tools, home and garden appliances, medical/surgical tools, industrial products, eBikes, drones, robots and wearable electronics such as smart watches or fitness trackers use wireless charging.

There has been an increase in multiplicity of wireless charging standards developed for small electronic devices, such as smart phones. In the last few years there has been considerable consolidation of industry standards with the maturing of the technology and its wide consumer adoption, now in the millions of devices. For example, the Qi (pronounced ‘chee’) Standard developed by the Wireless Power Consortium (WPC) has established itself as the most popular global standard for wireless charging. Qi is built into many smartphone models and more than 100 models of automobiles that offer Qi charging.

During 2019, the WPC announced that it is developing a Ki Cordless Kitchen Specification under the logo Ki. Ki (pronounced “key”) utilises smart control to enable convenient cordless kitchen appliances that are safe, efficient and interoperable with transferred power levels up to 2.2 kW.

WPT dedicated to Active Implantable Medical Devices (AIMDs) targets a power transfer to the active implant circuitry or battery for a range of medical applications. Many products in this category have been marketed for over 30 years.

Wireless charging is also used in the workplace for autonomous robots or Automated Guided Vehicles (AGV) and for powering production tools, thus allowing flexible re-arrangement of production lines.

This Report considers only the impact of non-beam inductive low power (below 30 W) wireless power transmission (WPT) systems and AIMD in various frequency bands below 30 MHz and provides the results of the studies examining the compatibility between those applications and the incumbent services/systems using the same or adjacent frequency bands. For the impact of higher power WPT devices further study would be needed.

This Report has been developed based on the information given in the ETSI TR 103 493 [1] and subsequent information received from ETSI Technical Committee (TC) EMC and Radio Spectrum Matters (ERM), and other contributions.

ANNEX 2 provides references to existing documents relevant for the protection of radio services from interference caused by generic WPT operating below 30 MHz and below 30 W.

This Report does not contain compatibility studies for WPT systems operating in the frequency range of 13.56 MHz, since the generic SRD regulation is considered sufficient, adopting the recommendation in ETSI TR 103 493 v1.1.1 (2019-02) to this extent. It is noted that this encompasses the Wireless Charging Technical Specification as published by NFC Forum. The application is charging of small IoT devices, including digital pens, ear buds, hearing aids, fitness trackers, headsets and smart glasses at a transferred power level of up to 1 Watt.

This Report does not contain impact studies for the Maritime Mobile Service. The frequencies for distress alerting and safety as well those for Maritime Safety Information (MSI) are listed in RR App. 15 and require special protection. Further studies would be needed to evaluate the impact of Wireless Power Transmission (WPT) applications on the Maritime Mobile Service.

2 SYSTEM CHARACTERISTICS OF NON-BEAM INDUCTIVE LOW POWER AND AIMD WPT APPLICATIONS

2.1 OVERVIEW

Generic non-beam inductive WPT applications are used to charge or power various devices including mobile phones, tablets, laptops, power tools, kitchen appliances, autonomous vehicles, industrial devices, implantable medical devices. The studies provided in this Report cover the compatibility of the devices below 30 W with radiocommunications services which are allocated frequencies below 30 MHz. In this section, the technical specifications and use cases of various WPT systems studied are provided.

2.2 APPLICATIONS AND USE CASES

2.2.1 Technical requirements and use cases for low power WPT

It should be noted that reference to the power level of the device relates to the transferred power from primary to secondary. According to the device efficiency and physical alignment, a part of that total power propagates beyond the coupling coils and could potentially impact nearby radio reception.

The power transfer is based on near field magnetic inductive coupling between two coils, where most of the power emitted by the transmitting coil is transferred to the receiving coil. In low power systems, this is generally less than 30 W. Qi devices, for example, have coils separated by less than 2 mm and can have efficiency of power transfer above 90%. The applications are not designed for propagation of electromagnetic waves in the far-field. However, the main interference mechanism to receivers is usually by coupling of the receiver antenna into the near field magnetic component of the WPT system. Therefore, there is potential for interference even if the effective radiated power may become negligible.

WPT devices are designed to transfer power from the primary to the secondary coil efficiently, by optimising the inductive coupling between the two coils. An external radiating field is also created because not all the energy arrives at the second coil. When both coils are optimally aligned, the emission of the operating frequency and harmonics (i.e. resulting from this external field) is lower than in the case where they are not aligned. The quality of the alignment is one of the predominant factors determining the level of the emissions. Other factors are power lines feeding the coil and metal structures in the near field of the coils.

2.2.1.1 Wearables, portables, tools and general applications

Wearable electronics combine sensors and wireless communications to allow remote collection of information and human interfaces with technology such as health monitoring, disease detection, robotic interfaces, robotic surgery, driverless cars, Internet of Things, implantable electronics, smart textiles, virtual reality, augmented reality, audio/visual interfaces and smart cities.

Portable devices are devices that can be hand-held or wearable when in use, such as mobile phones.

Qi System

Qi provides a specification for interoperability of contactless power transfer from a power transmitter to a power receiver device. A Baseline Power Profile (BPP) supports power transfer of up to about 5 W and an Extended Power Profile (EPP) supports transfer of up to about 15 W today, with higher power levels under discussion for applications such as laptop charging.

The power transfer is based on near field magnetic induction between coils. Qi devices operate typically over less than a 2 mm range. Qi applications generate high magnetic field strengths close to the transmitter coil to achieve high power transfer efficiency > 90%. Since the applications are designed to efficiently produce electromagnetic energy in the non-radiative near-field, the transmitting coils are not designed to be efficient antennas for propagation of electromagnetic energy in the far-field, resulting in a typical effective radiated power of 2.9 μW.

A simple control system is used to initiate, manage and terminate power transfer. Foreign object detection (FOD) is included in the Qi specifications as a safety feature. WPC runs a certification program to ensure consistent, interoperable and safe operation of Qi certified devices.

The Qi System concept is shown in Figure 1.

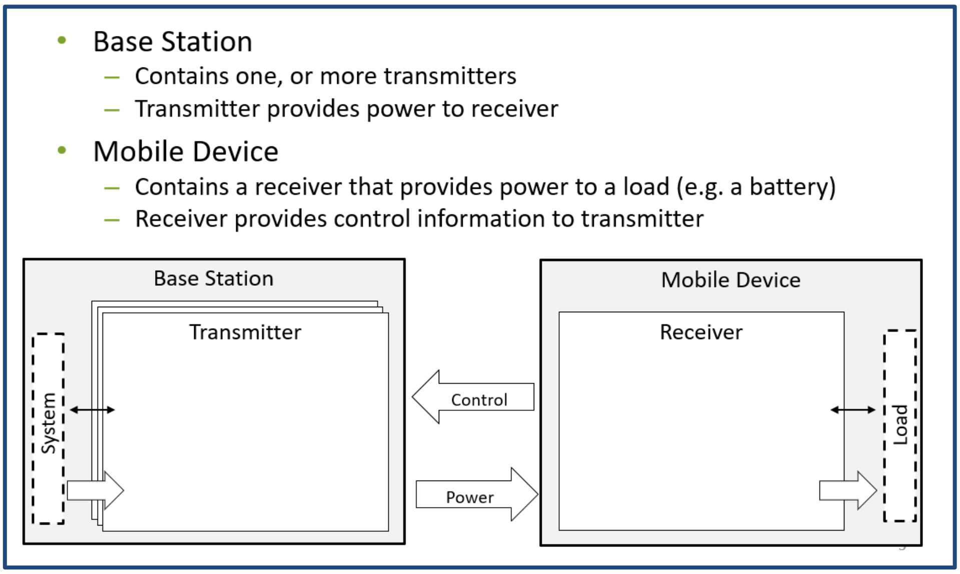

Figure 1: Qi system concept

A power receiver (PRx) is contained within the mobile device when it is placed on top of a power transmitter (PTx), as shown in Figure 2.

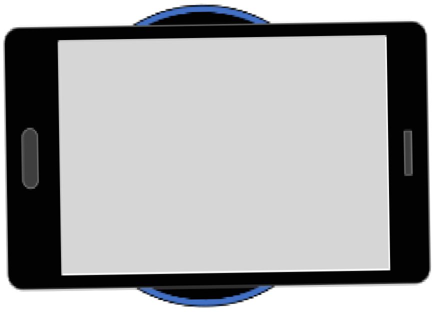

Figure 2: A Qi wireless smartphone on a charging pad

Both the PTx and PRx contain coils, as shown in the conceptual diagram in Figure 3 as well as circuitry that handles the communication and power transfer between them.

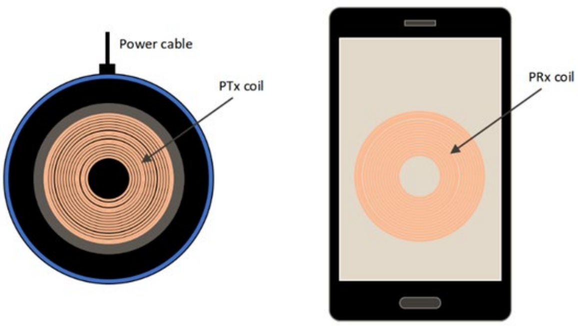

Figure 3: Coils in charger and smartphone

In the Qi based system, illustrated in Figure 3, power is transferred from the PTx contained in the Qi charging pad to a PRx contained in the Qi smartphone. Before charging begins, the PRx and PTx communicate with each other to establish that the mobile device is compatible and capable of being charged, whether it needs to be charged, how much power is required, etc. In short, the communication ensures an appropriate power transfer from the power transmitter to the power receiver.

When charging begins, the power transmitter runs an alternating electrical current through its coil, which generates an alternating magnetic field in accordance with Faraday's law (Figure 4). This magnetic field is in turn picked up by the coil inside the power receiver and transformed by a power converter back into an alternating electrical current that after rectification, can be used to charge the battery.

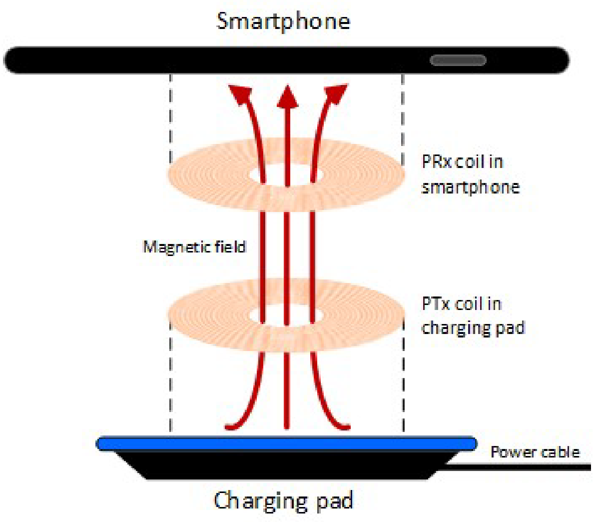

Figure 4: Qi wireless power transmission using magnetic induction

By 2020, most chargers for portable devices including smart phones use Qi based systems in 100-148.5 kHz.

Other WPT Systems for portable devices

Some portables and wearables use charging frequencies higher than 300 kHz, which has been found to be a better frequency, for a number of reasons when integrated into a device that supports a number of other wireless technologies.

So far only non-Qi systems have been deployed or developed in the frequency band above 300 kHz. The communication between the transmitter and receiver is carried out by using Frequency Shift Keying (FSK).

The charging and communication between base-station and a wearable, e.g. fitness tracker is shown in Figure 5.

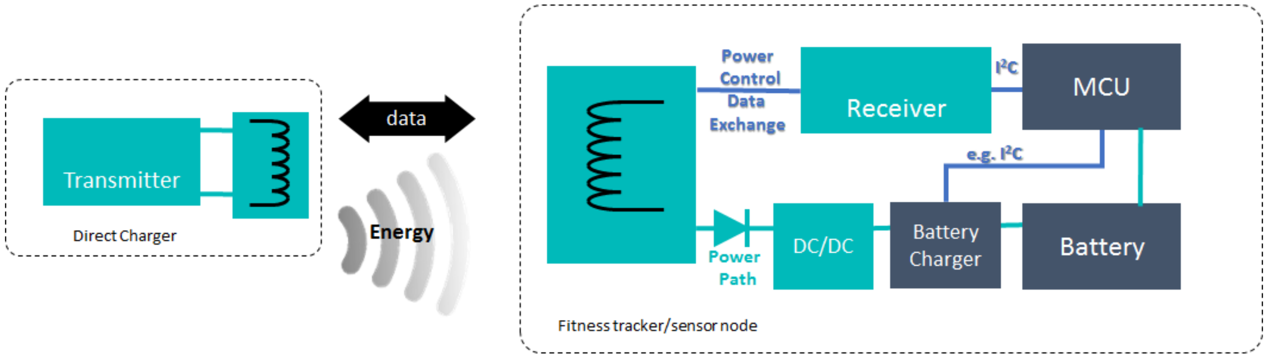

Figure 5: Working principle for WPT systems (wearables/portables)

2.2.1.2 Medical implantable WPT devices

The WPT dedicated to Active Implantable Medical Devices (AIMDs) targets a power transfer to the active implant circuitry or battery for, but not limited to, the following medical treatments: stimulation of brain, cardiac, cochlea, retina, sacral, spinal cords, vestibuli, bone anchored actuators, monitoring of brain seizure devices, epilepsy. These medical implants require power from the closely coupled body worn primary coil on a daily or weekly basis depending on the treatment and the system. WPT dedicated to Active Implantable Medical Devices (AIMDs) transmits power to an active implant circuitry or battery. Medical WPT devices normally use the same or part of the same frequency range used for power transmission for information exchange, e.g. by applying load modulation and/or On-Off keying.

2.2.2 Summary of Low Power inductive WPT (<30 W)

Low power WPT devices are capable of transferring power/ energy of less than 30 W.

Table 2 and Table 3 below summarise the technical requirements and use cases for low power WPT systems (<30 W).

Table 2: Use cases for low power WPT systems covering wearables, portables, tools and generic applications

Permitted frequency range of operation	Use-cases/ Notes	Environment/ Density/ Activity
100–148.5 kHz	Today: Mainly smartphones Future: Many types of small devices (tablets, cameras, loudspeakers)	Charging time usage typically 1 hr/day. Standby: Transmitter pads utilise a ping mode to look for power receivers. Current transmit capable deployment density at 5% market penetration, is assumed between 10 and 200 devices / km^2. From 2018 to 2019 the number of Qi Tx units shipped globally increased from 81 to 127 million units, an increase of 57% year on year. The Wireless Power Consortium estimates that the number of transmit devices globally expected to be more than 1 billion by 2030. Note: No information is available at the European level market.
300–400 kHz	Wearables, portables	Assumed deployment: 1-2 hr/day Dense Urban: 1500 devices/km² Urban: 375 devices/km² Residential: 150 devices/km²
1610-1800 kHz	Wearables	Assumed deployment: 1-2 hr/day Dense Urban: 500 devices/km² Urban: 125 devices/km² Residential: 50 devices/km²

Permitted frequency range of operation	Use-cases/ Notes	Environment/ Density/ Activity
1950–2150 kHz	Wearables	Assumed deployment:1 -2 hr/day Dense Urban: 500 devices/km² Urban: 125 devices/km² Residential: 50 devices/km²
13.56 MHz	NFC charging of small IoT devices < 5W NFC Charging, meeting requirement of ERC Recommendation 70-03, annex 9, item i [31], and ETSI EN 300 330 [12] of 42µA/m at 10m. Energy transfer from the primary to the secondary device coils typically at 2-5 mm (less than 20 mm) distance. NFC used for Communication as defined in NFC Forum's Wireless Charging Specification.	WPT of small IoT devices < 5W / Low density, a few ten million solutions worldwide, expected grow by a factor of 10 over the next 5 years. / Charging time and interval varies from 30 min to 2 hours per day.

Table 3: Use cases for medical implantable low power WPT systems

Permitted frequency range of operation	Use-cases/ Notes	Environment/ Density/ Activity
8.4-9.4 kHz (Note 1)	Deep Brain Modulation Energy transfer from primary to the secondary device typically at 1 cm distance. Communication at 175 kHz.	WPT client in-vivo / 25000 in Europe / 60 minutes, once a week. Duty cycle charging 100%.
8.4-9.4 kHz (Note 1)	Neuromodulation / Energy transfer from primary to the secondary device typically at 1 cm distance. Communication at 175 kHz.	WPT client in-vivo / Low density / Up to 4 hours, 1-2 weekly. Duty cycle charging 100%.
36-46 kHz (Note 1)	Spinal Cord Stimulation / Energy transfer from primary to the secondary device typically at 3 cm distance. Communication at 175 kHz.	WPT client in-vivo / 28000 in Europe / Up to 4 hours, once a week. Duty cycle charging 100%.
36–46 kHz (Note 1)	Neuromodulation / Energy transfer from primary to the secondary device typically at 3 cm distance. Communication at 175 kHz.	WPT client in-vivo / Low density / 60 minutes, once a week. Duty cycle charging 100%.

Permitted frequency range of operation	Use-cases/ Notes	Environment/ Density/ Activity
47.5-52.5 kHz (Note 1)	Neuromodulation / Energy transfer from the primary to the secondary device typically over a few cm (3-5 cm) distance.	WPT client in-vivo / 350000 of a particular device in the field worldwide. / Charging time can vary from one hour or less every two weeks or more and up to three hours (fully discharged IPG battery) every week.
76-87 kHz (Note 1)	Neuromodulation / Energy transfer from the primary to the secondary device typically over a few cm (1-3 cm) distance. No active communications from charger to implant but load based modulation on backlink.	WPT client in-vivo / 20000 users of AIMD-chargers in the EU / Charging session up to three hours every week. Duty cycle during active charging ≤ 100%.
100-120 kHz (Note 1)	Sacral neuromodulation / Energy transfer from primary to the secondary device typically at 2.5 cm distance. Communication at 175 kHz.	WPT client in-vivo / 12000 in Europe / 60 minutes, once a week. Duty cycle charging 100%.
120-140 kHz (Note 1)	Neuromodulation / Energy transfer from primary to the secondary device typically of 1 to 4 cm distance. Communication from secondary to primary.	WPT client in-vivo / Low density / Few minutes each day. Duty cycle charging < 0.1%.
120-130 kHz	Neuromodulation / Energy transfer from primary to the secondary device typically over a few cm (1-5 cm) distance. Backscatter comms -20 dBc; charging BW.	WPT client in-vivo / Low density / Charging session up to three hours, daily to monthly. Duty cycle during active charging: ≤ 100%. Communications duty cycle ≤ 50%.
120-140 kHz (Note 1)	Neuromodulation / Energy transfer from primary to the secondary device typically of 1 to 4 cm distance. Ping to wake up implant. Communication from implant to peripheral to indicate battery status.	WPT client in-vivo / Low density / Varies from once per week, only few minutes or less every two weeks (fully discharged battery) every week. Duty cycle charging < 0.1%.

Permitted frequency range of operation	Use-cases/ Notes	Environment/ Density/ Activity
120-140 kHz (Note 1)	Cardiac / Energy transfer from primary to the secondary device in close proximity. Communication from secondary to primary.	WPT client in-vivo / Low density / Daily usage. Duty cycle charging > 50%.
121-129 kHz	Neuromodulation / Energy transfer from the primary to the secondary device typically over a few cm (1-3 cm) distance. No active communications from charger to implant but load based modulation on backlink.	WPT client in-vivo / 20000 users of AIMD-chargers in the EU / Charging session up to three hours every week. Duty cycle during active charging ≤ 100%.
200 kHz	Neurostimulator pelvic gastro therapy Energy transfer from primary to the secondary device in close proximity. Communication from secondary to primary.	WPT client in-vivo / Low density / Daily usage. Duty cycle charging > 50%.
260-320 kHz	Neuromodulation / Energy transfer from the primary to the secondary device typically over a few cm (3-5cm) distance.	WPT client in-vivo / 350000 of a particular device in the field worldwide. / Charging time can vary from one hour or less every two weeks or more and up to three hours (fully discharged IPG battery) every week.
275-300 kHz	Neuromodulation / Energy transfer from the primary to the secondary device typically over a few cm (1-5 cm) distance. Backscatter comms -20 dBc; charging BW.	WPT client in-vivo / Charging session up to three hours, daily to monthly. Duty cycle during active charging ≤ 100%. Communications Duty Cycle ≤ 50%.
4.0-5.9 MHz (Note 1)	Neurostimulation, cochlear, vestibular, sleep apnea, retinal, bone anchored, brain stimulation, monitoring of brain seizures, epilepsy, etc. / Energy and data transfer from the primary to the secondary device coils typically at 5 mm (less than 20 mm) distance. Communication from secondary to primary.	WPT client in-vivo / Devices within CEPT today: 150000 2022: 180000 2025: 250000 2030: 350000 / 8 to 24 hours per day, daily Duty cycle power transfer ≤ 100%. Communications duty cycle ≤ 100%.
4.1-5.9 MHz	Implant battery recharging of hearing implant systems / Energy transfer from the primary to the secondary device coils typically at 5 mm (less than 20 mm) distance. Forward and backward communication, all over same WPT frequency. The implant battery charging use case may be interleaved in time with the external hearing use case (4.0–5.9 MHz).	WPT client in-vivo / Low density, a few hundreds Cochlear recipients in Europe, expected grow by a factor of 10 over the next 10 years. / Charging time and interval varies from one hour up to three hours (fully discharged implant battery) every day. Duty cycle charging ≤ 100%. Communications duty cycle typical ≤ 1% (load modulation).

Permitted frequency range of operation	Use-cases/ Notes	Environment/ Density/ Activity
5.88-7.68 MHz	Implant battery recharging of hearing implant systems / Energy transfer from the primary to the secondary device coils typically at 5 mm (less than 20 mm) distance. Forward and backward communication, all over same WPT frequency. The implant battery charging use case may be interleaved in time with the external hearing use case (4.0–5.9 MHz).	WPT client in-vivo / Low density, a few hundreds Cochlear recipients in Europe, expected grow by a factor of 10 over the next 10 years. / Charging time and interval varies from one hour up to three hours (fully discharged implant battery) every day. Duty cycle charging ≤ 100%. Communications duty cycle typical ≤ 1% (load modulation).
13.56 MHz (Note 1)	Implant battery recharging of hearing implant systems / Energy transfer from the primary to the secondary device coils typically at 5 mm (less than 20 mm) distance. Forward and backward communication, all over same WPT frequency. The implant battery charging use case may be interleaved in time with the external hearing use case.	WPT client in-vivo / Low density, a few hundred Cochlear recipients in Europe, expected grow by a factor of 10 over the next 10 years. / Charging time and interval varies from one hour up to three hours (fully discharged implant battery) every day. Duty cycle charging ≤ 100%. Communications duty cycle ≤ 1%.
Note 1: These are old and existing AIMD applications dedicated to AIMDs meeting the limits in ERC Recommendation 70-03, annex 9 [31] and current ERC Recommendation 74-01 [11]. These are in the market (i.e. are in use) since many years (i.e. more than 10 years) with no problem to any other system or radio service		

3 SYSTEM CHARACTERISTICS OF RADIOCOMMUNICATION SERVICES BELOW 30 MHZ

3.1 RADIO NOISE ENVIRONMENT BELOW 30 MHZ

For some of the frequency ranges studied, no parameters and/or deployment scenarios of the radio services were available. In order to provide some information on the potential impact of WPT on radio services the level of WPT emissions is compared to the noise level.

The radio noise environment below 30 MHz in cities and residential areas is mostly dominated by man-made noise (MMN). Recommendation ITU-R P.372 [7] specifies that the representation of man-mad noise is described in Recommendations ITU-R SM.1753 [50] and SM.2093 [51]. There are three types of noise present in this frequency range (see Recommendation ITU-R SM.1753): Impulsive Noise (IN), Single Carrier Noise (SCN) and White Gaussian Noise (WGN):

Impulsive Noise (IN) can be very significant, but its impact on radio service receivers depends very much on the actual receiver design and it is not generally used as a basis for analysis.

Single Carrier Noise (SCN) is often present or even dominant when it comes from a source close to the measurement location. Recommendation ITU-R SM.1753 clarifies that SCN originates from a range of sources, including wired computer networks, computers and switched mode power supplies. These noise sources are predominantly encountered inside buildings. Recommendation ITU-R SM.2093 considering b) states that SCN from single and identifiable sources is the dominant form of man-made noise inside buildings which cannot be described by the metrics of Recommendation ITU-R P.372.

White Gaussian Noise (WGN), as it is specified in Recommendation ITU-R P.372 describes that part of man-made noise that cannot be attributed to a single noise source and so specifically excludes emissions from single, identifiable sources (see Recommendation ITU-R SM.1753) although the aggregation of a number of individual sources is approximated to white Gaussian noise and is also contained in the WGN values of Recommendation ITU-R P.372. This definition of WGN leads to a constraint in the use of Recommendation ITU-R P.372 as its applicability is limited to distances from the indoor environment where the combination of individual sources can be approximated to Gaussian noise. Consequently, the man-made noise values from Recommendation ITU-R P.372 should not be used in any compatibility analysis, either where the receiving antenna of the victim service is located indoors (e.g. portable receivers with integrated antennas) or where the receiving antenna of the victim service is close to sources of noise within an adjacent building. Nevertheless, some amateur service antennas may be located as close as 10 m from the outside wall of a building containing WPT [56].

Conclusions drawn on the interference impact of WPT, where the radio service antenna is close to a building should be treated with care as they may be invalid. Man-made noise values from ITU-R P.372 are not applicable to analysis of radio service receivers located indoors.

The situation that is faced by radio service antennas close to the next building is not very clear. Following results based on a measurement campaign in Spain [60], the median value of noise inside is generally higher than outdoors but the variance is generally far greater. The exterior wall has only limited impact because there is only limited attenuation due to building materials in the near field, so the external field is largely dependent on the internal field distribution.

Regarding the situation where both victim and interferer are located indoors, Recommendation ITU-R P.372 contains some limited information on man-made WGN indoors, although this does not extend to frequencies below 200 MHz; additional information on the noise level inside buildings (residences or office buildings) is also very limited. A measurement campaign carried out in Spain [60] indicated that the median noise levels in buildings are significantly higher than Recommendation ITU-R P.372 (City) would predict, e.g. 30-35 dB at 1.9 MHz, although the variance around the median is also considerable. Recommendation ITU-R SM.2093 acknowledges that noise levels derived from the current version of Recommendation ITU-R P.372 have very little meaning in indoor environments. Little is known so far, since there are no measurement results documented that were taken that followed Recommendation ITU-R SM.2093.

DSL connections and powerline communications are two noise factors that were not present when the regression lines in Recommendation ITU-R P.372 were set. Emissions from DSL that use OFDM appear as additional White Gaussian Noise to radio service receivers. Emissions from powerline communications also use OFDM but are only active when data packets are transmitted which makes the interference much more like impulsive noise. In addition, powerline communications are normally notched out in parts of the spectrum (e.g. the amateur service or the broadcasting service bands), so may not add significantly to existing levels in these bands. The same can apply to VDSL and Gfast.

Recently carried out measurements in the Netherlands [54] indicated that, for certain locations, the actual noise level is about 10 dB higher than what Recommendation ITU-R P.372 [7] states. Furthermore, they explicitly took into account realistic distances between buildings where most noise sources would be located and placed the measurement points at least 10 m from any building.

3.2 AMATEUR SERVICE

The amateur service is a low signal service, where communication is limited only by environmental noise levels. There are frequency allocations to the service throughout the radio spectrum, including 12 bands below 30 MHz.

The following frequency bands are allocated to the amateur service on a primary or Secondary basis through the ITU Radio Regulations:

Table 4: Amateur service primary and secondary frequency allocations below 30 MHz

Frequency range	Allocation status
135.7-137.8 kHz	Secondary allocation
472.0-479.0 kHz	Secondary allocation
1800-2000 kHz	Part primary, part secondary
3500-4000 kHz	Primary allocation
5351.5-5366.5 kHz	Secondary allocation
7000-7300 kHz	Primary allocation
10100–10150 kHz	Secondary allocation
14000-14350 kHz	Primary allocation
18068-18168 kHz	Primary allocation
21000-21450 kHz	Primary allocation
24890-24990 kHz	Primary allocation
28.0-29.7 MHz	Primary allocation

Communication at these frequencies uses a range of transmission modes, including A1A, J1E, J3E, J3F, F2D. Typical emission bandwidths are up to 2.8 kHz. Communication uses both ground-wave and sky-wave propagation modes. Typical signal-to-noise ratios (500 Hz bandwidth) are shown in Figure 6 , drawn from over 500000 data points.

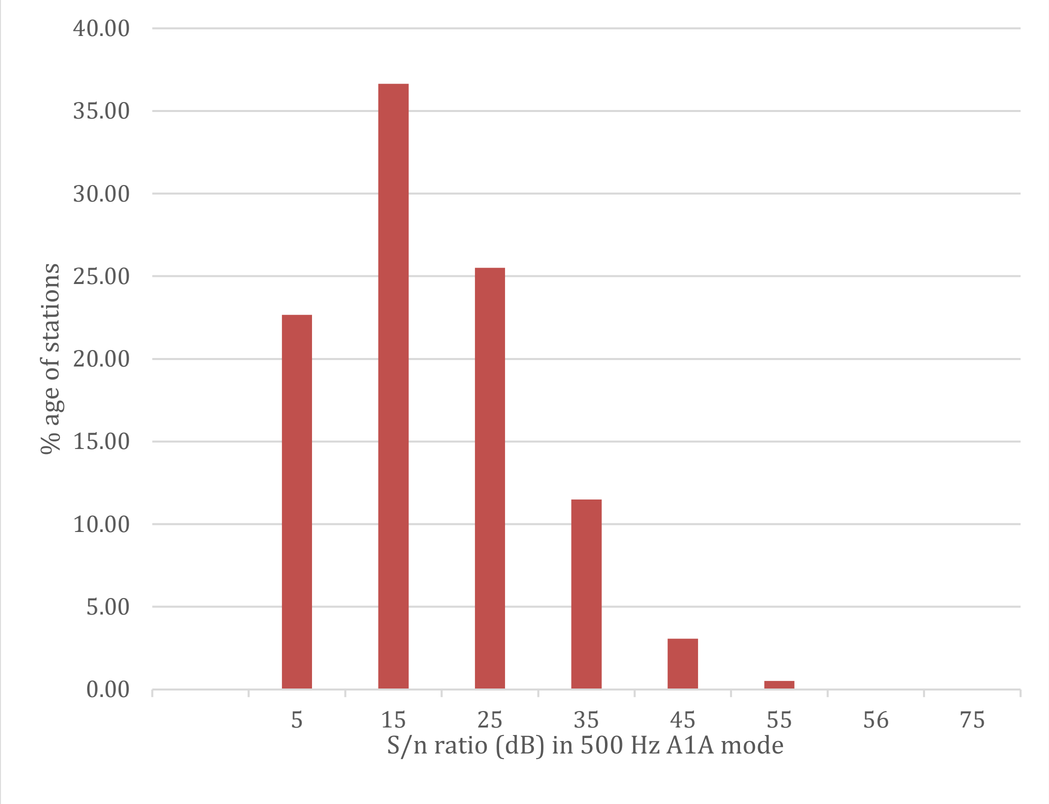

Figure 6: Typical signal to noise ratio for the amateur service

Stations in the amateur service are typically housed in residential properties, with their antennas located in house gardens, or on rooftops in residential areas. Spacing to other residential units is often small, and to avoid EMC problems, transmit power levels in the amateur service are often relatively low. Extensive global use is made of the HF spectrum allocations to the amateur service. Median signal to noise ratios are around 15 dB (ANNEX 6).

3.3 BROADCASTING SERVICE (SOUND)

The following frequency bands are allocated to the Broadcasting Service (Sound) on a primary basis through the ITU Radio Regulations:

- 148.5-283.5 kHz Band 5 (LF)
- 526.5-1606.5 kHz Band 6 (MF)
- 3.2-26.1 MHz[1] Band 7 (HF)

These bands are used for conventional analogue amplitude modulated (AM) broadcasting (Sound). To a limited extent they are or have been used for Single Sideband AM and for digital transmission using the Digital Radio Mondiale (DRM) system. The spectrum of an AM broadcast comprises a carrier wave component and two sidebands which contain the audio signal modulation.

[1] The HF broadcasting band (Band 7) is divided into 14 sub-bands: 2.30 – 2.495, 3.20 – 3.40, 3.90 – 4.00, 4.75 – 5.06, 5.80 – 6.20, 7.20 – 7.45, 9.40 – 9.90, 11.60 – 12.10, 13.57 – 13.87, 15.10 – 15.83, 17.48 – 17.90, 18.90 – 19.02, 21.45 – 21.85 and 25.60 – 26.10; all in MHz

3.4 RADIOCOMMUNICATION SERVICES AT 5 MHZ AND 6.78 MHZ

Incumbent services/systems in 5 MHz range are the broadcast, fixed/land mobile and space research services. The Standard Frequency and Time Signal Service is also present.

Table 5: Radiocommunication services in 5 MHz range (Source: ERC Report 25 [47], November 2020)

Frequency range (kHz)	Allocations
4850-4995	Broadcasting, Fixed, Land mobile, Land military systems
4995-5003	Standard frequency and time signal (5000kHz)
5003-5005	Standard frequency and time signal, Space Research
5005-5060	Broadcasting, Fixed, Land military systems
5060-5250	Fixed, Mobile except aeronautical mobile, Land military systems, Maritime military systems

The incumbent services/systems in 6.78 MHz range are considered to coexist with applications respecting the ISM frequency band and emission mask as defined in ERC Recommendation 70-03 [31] and ETSI EN 300 330 [12].

Table 6: Radiocommunication services in 6.78 MHz range (Source: ERC Report 25 [48], October 2021)

Frequency range (kHz)	Allocations
6765-7000	Fixed, Mobile except aeronautical mobile (R)

3.5 AERONAUTICAL RADIONAVIGATION SERVICE IN 255-535 KHZ

The responsible group within ITU-R provided the basis to analyse the impact as listed in Table 7

Table 7: Automatic direction finding (ADF)/Non-directional Beacon (NDB) permissible interference limit

Services	Frequency range (kHz)	ADF/NDB receiver bandwidth (kHz)	Permissible Interference limit (dBμV/m)
Aeronautical Radionavigation	255-535	2.7	21.9

This permissible interference level was used as a basis for ECC Report 67 [44] which studied the impact of inductive applications. At that time, no aeronautical safety margin was applied. The studies here are carried out with and without the aeronautical safety margin of 6 dB.

Non directional beacon (NDB) is used for safety aeronautical application (non-precision instrument approach aid). ICAO (DOC 9718) [43] defines an aeronautical safety margin and recommends including it into any study as follows:

"*Aeronautical safety applications are required to have continued operation through worst case interference, so all factors which contribute to harmful interference should be considered in analyses involving those* *applications. An aviation safety margin is included in order to address the risk that some such factors cannot be foreseen (for example impacts of differing modulation schemes). This margin is applied to the system protection criteria to increase the operational assurances to the required level. Traditionally for aviation systems/scenarios an aviation safety margin of 6–10 dB is applied. Until established on the basis of further study on a case-by-case basis, an aviation safety margin of not less than 6 dB should be applied.*"

3.6 MOBILE AND FIXED SERVICE BELOW 30 MHZ

The following frequency bands are allocated to the Fixed and/or Mobile service on a primary basis through the ITU Radio Regulations.

Table 8: Non-exhaustive overview of the Armed Forces uses, associated to mobile and fixed services

Operation	Services	Frequency band operated	Channel widths	Number of channels assigned
Air traffic control Air navigation	Mobile	3 to 30 MHz	3 kHz	>150
Rescue	Mobile	2 to 12 MHz	3 kHz	>50
Metropolitan network	Fixed	3 to 17 MHz	3 kHz	>30
Mobile cooperation	Mobile	2.4 to 24 MHz	3 kHz	<30
Training Regular exercises	Fixed, Mobile	3 to 30 MHz	3 kHz	>300
One-off exercises	Fixed, Mobile	2 to 30 MHz	3 kHz	> 100
Trials Qualifications	Mobile	2 to 25 MHz	3 or 6 kHz	>250
	Fixed	2 to 30 MHz (mainly 2 to 10 MHz)	3 kHz	<110

3.6.1 Military

Military applications are used in the Mobile and Fixed allocations from 2 to 30 MHz.

Table 8 provides a non-exhaustive overview of Mobile and / or Fixed frequency allocations used by the military forces of France.

Other uses in the 1.5-30 MHz frequency band must be considered for specific operations, international organisations and temporary operations with other countries.

Different frequency bands used relate to the propagation modes used:

- Ground wave: in low relief environments (e.g. lowland and sea) where stations are close to the earth surface, this mode of radio propagation allows communication over short to medium distances. For these waves, it is preferable to transmit on frequencies from lower HF spectrum in order to reach greater distances;
- Sky wave: by small scale refractions assimilated to large scale reflections on the ionospheric layers, this mode of radio propagation allows communication over short to very long distances. For these waves, it is preferable to transmit on higher passing frequency. As received noise (e.g. man-made noise) decreases when frequency increases, operating these frequencies allows optimising the radio link budget. Sky waves are widely used but it is the most variable mode of radio propagation. The ionospheric propagation channel varies with solar activity, time (years, months, days) and station location.

Fixed and mobile stations are used in urban, residential or rural environments for reception and/or emission, particularly by the military stations. The maritime mobile stations can also be used near an urban environment or residential environment, when the ships are located in a harbour, and the fixed stations they are communicating with can also be near an urban, residential or rural environment.

HF mobile stations are used in operational contexts in city, residential, rural and calm environments. They are mounted on vehicles or carried by people (e.g. manpack radio). All types of HF fixed stations with reception capabilities are also used in these environments.

Some transmission sites are distant by several kilometres from reception sites in order to limit interferences caused by very high power transmitters (> 10 kW) in co-located environments.

3.6.2 Aviation

Aeronautical HF communications (parts of the frequency band 2.850-22 MHz) provide the main long-distance air-ground communication system in areas where VHF communication is not practicable, e.g. in oceanic and remote areas, low-level overseas paths, and area coverage where the area is large. Single sideband amplitude modulation voice is used. Data transmission over HF frequencies is permissible and has increasing applications.

3.7 STANDARD FREQUENCY AND TIME SIGNAL SERVICE

In the ITU Radio Regulations (§1.53) [30] a standard frequency and time signal (SFTS) service has been defined as “a radiocommunication service for scientific, technical and other purposes, providing the transmission of specified frequencies, time signals, or both, of stated high precision, intended for general reception.” §26.4 invites administrations to cooperate in reducing interference in the frequency bands to which the SFTS service is allocated.

The reference signals of frequency and time are a means of transfer of unit sizes and time scales and represent carrier oscillations modulated in amplitude, phase or the frequency of the signals containing the timestamps of the time scale, and information about current values of time, date and other additional information.

A variety of receiver designs are utilised for the reception of the signals, from sophisticated receivers as part of industrial or scientific installations to low-cost receivers for domestic use.

3.7.1 French Time signal ALS162

The time signal is transmitted in dual-band amplitude modulation (A3E mode) on the frequency of 162 kHz with an output power of 800 kW, 24 hours a day. The occupied bandwidth (OBW) is 250 Hz from 161.875 kHz to 162.125 kHz.

The detailed description of the technical specifications of the Allouis radio signal transmitter is developed in the French standard NF C90-002 (1988) [42] Broadcasting and telecommunication: Data broadcasting system compatible with AM sound broadcasting (version available only in French). The limits necessary for the protection of the French SFTS service are specified in ERC Recommendation 70-03, annex 9 [31].

4 RESULTS OF STUDIES

4.1 QI BASED WPT SYSTEMS

4.1.1 Field tests / measurements for Qi system

Detailed testing was performed by the IARU supported by WPC in the spring of 2019 on a selection of popular 5 W and 15 W Qi devices in the market at that time.

The results are summarised as follows.

The results are presented in Figure 7. The data represents the worst-case misalignment of the mobile phone on the charger. It will be seen that at 1 MHz, the measured spurious emission levels at 10 meters for all units tested are some 40 dB below the limit specified in ERC Recommendation 74-01 [11]. At frequencies above 1 MHz, the derived levels at 10 m are below a proposed limit for the protection of amateur service and the fixed/mobile services (see ECC Report 289 [6]) for WPT spurious emissions.

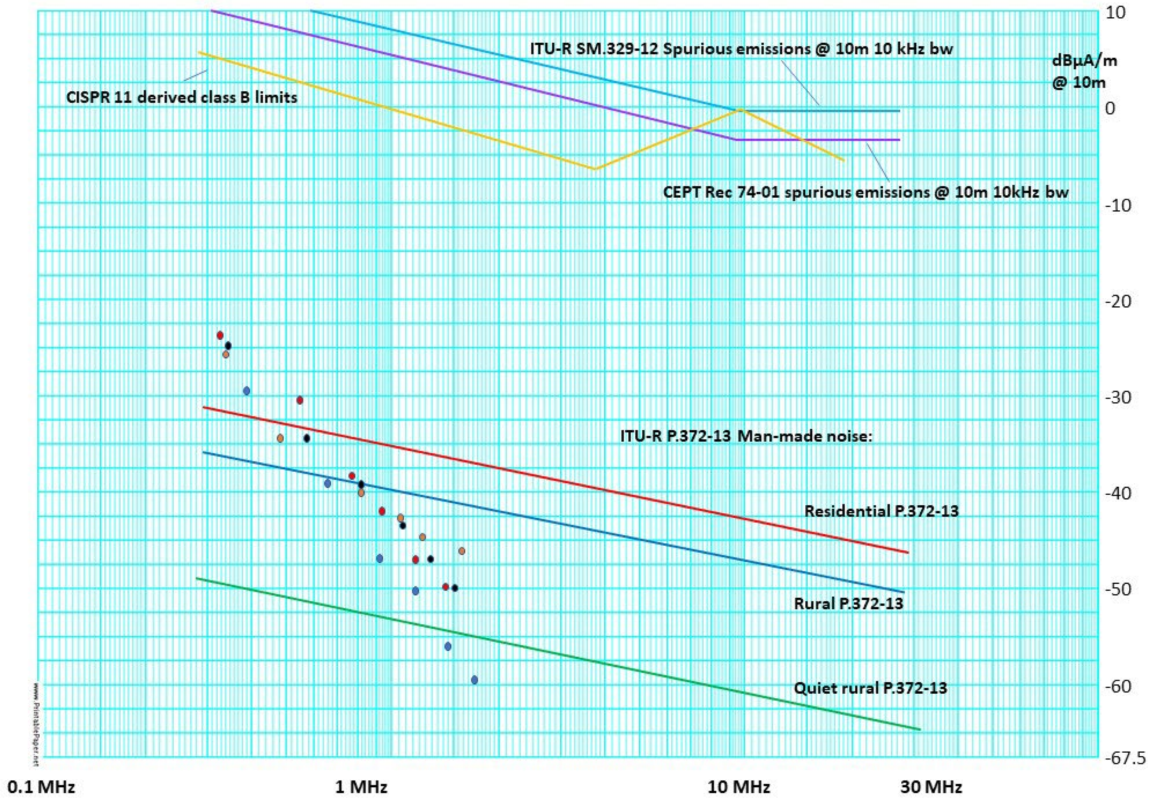

Figure 7: Graphical presentation of test results

Note: Environmental noise levels are derived from Recommendation ITU-R P.372 [7], assuming far field conversion factor of 377 Ω.

4.2 NEUROMODULATORS BETWEEN 260-320 KHZ

WPT medical implants below 500 kHz operate between 8.4 kHz and 320 kHz and have emissions at the fundamental of between 10 and 66 dBµA/m @10m. The chargers typically use high-Q LC resonant wire loop inductive coils (low harmonics) that are less than 10 cm in diameter. Free space magnetic field strength unit conversion shows low e.i.r.p. For example, 30 dBuA/m @ 10m = 81.5 dBµV/m @ 10m = 0.47 mW e.i.r.p. The occupied bandwidth is less than 1% of the operating frequency due to the resonant inductive operation. The centre frequency may vary ±15% to optimise WPT from mutual inductance effects when coupled to an IPG due to implant depth, clothing thickness or alignment.

Resonant inductive wire loop transmitter coils typically used in neuromodulation WPT chargers produce negligible propagation in the far field because the wire loop antennas are several orders of magnitude too physically small to be efficient antennas at the frequencies between 50 kHz and 500 kHz.

Existing regulations in the medical implant industry place a difficult patient safety tissue heating requirement that directly results in an inherent limit to WPT field strengths now and in the future. WPT heats any implanted metal (case, battery, circuitry) due to eddy current losses. Physical temperature-time limits on heating tissue are given by CEM43 of ISO 14708-3 [2], where the temperature of the implanted metal must stay below 43 °C. The temperature limit effectively limits the transmitter electrical drive power to a few watts (5 W maximum) and the use of resonant sine wave WPT drivers instead of more complicated switchers and their harmonics.

4.2.1 Communications between charger and implant

Like many WPT devices, load modulation from the implant occurs so the charger can determine when and if the charging levels should be adjusted or turned off. Data transfers do not occur at the charging frequency. Communication of implant charge status is only through Bluetooth low energy (BLE) which is outside the scope of this study.

4.2.2 Implantable Wireless Power Transmission (WPT) operating in 260-320 kHz range

4.2.2.1 Background

A subset of medical WPT devices is used to recharge implantable pulse generators within proximity of the torso or extremities.

Detailed background on the technology, use cases and density for medical WPT can be found in section 2. The data within this study uses the same fundamental technology, but the key difference is the frequency range being used when compared to other medical WPT already on the market. This study is to measure the radiated fundamental and spurious harmonic strength. This data can be used to help make decisions on how this technology compares to existing WPT devices and the potential interference to amateur radio, fixed/mobile, broadcast and radio-navigation services that operate on or near the frequency range of major concern (150 kHz-30 MHz).

4.2.2.2 Brief technical background

A charging signal from the proposed charger is a resonant signal based on the alignment of the charger and implant. For the most efficiency, the coil is actively tuned to match the resonant frequency of the coil. This resonant frequency range is 260-320 kHz. Many position variations were investigated and the resonant frequency that produced the highest fundamental signals were typically in the range of 279-302 kHz.

The charging signal does not use any form of frequency, phase, or amplitude modulation like a typical communication device as the propagation is for energy transfer and not for radiocommunication that needs a modulation component to carry encoded information (i.e. data, video and audio).

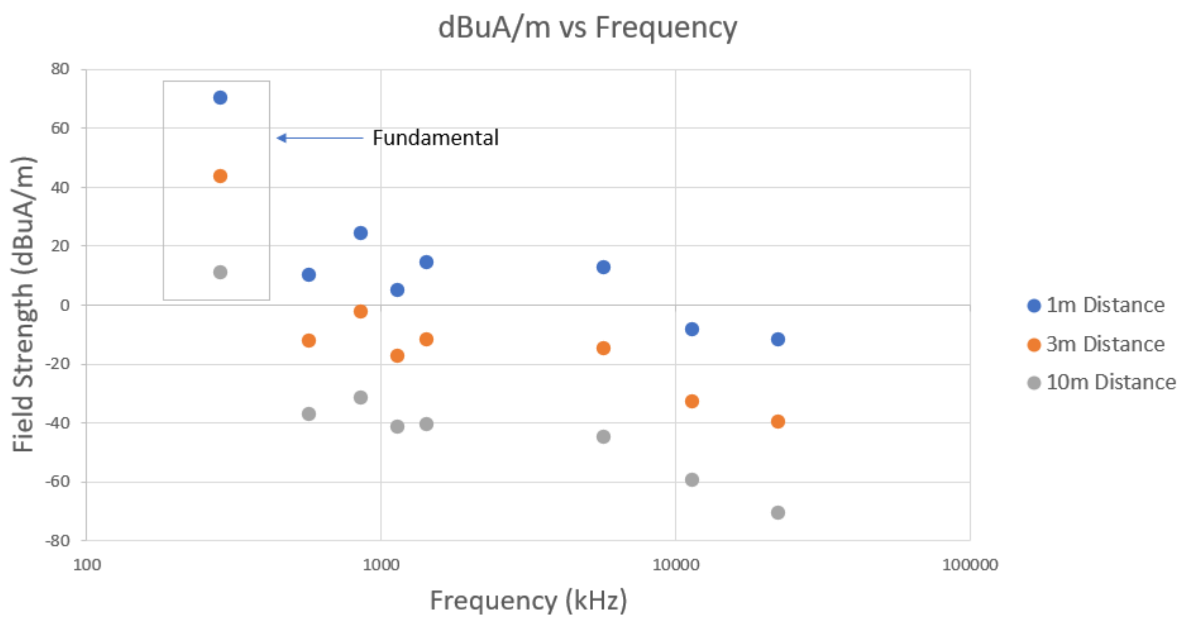

Figure 8: Field Strength Levels of Fundamental and Spurious using 60 cm Magnetic Loop

Table 9 summarises the highest levels from hundreds of permutations using EN published test methods.

Table 9: Highest Fundamental and Spurious signal levels

Point	1 m Test Distance (dBµA/m)	3 m Test Distance (dBµA/m)	10 m Test Distance (dBµA/m)
Fundamental 284 kHz	70.5	43.7	11.3
Highest 2nd harmonic	10.4	-12.1	-36.8
Highest 3rd harmonic	24.5	-2.2	-31.5
Highest 4th harmonic	5.0	-17.1	-41.3
Highest 5th harmonic	14.6	-11.6	-40.3
Highest spurious 1.5-10 MHz (20th harmonic)	13.0	-14.5	-44.6
Highest spurious (10-20 MHz)	-8.1	-32.5	-59.2
Highest spurious (20-30 MHz)	-11.7	-39.7	-70.4

4.2.2.3 Conclusions

There are different methods for measuring radiated magnetic fields, but many related to the ERC Recommendation 70-03 and Radio Equipment Directive 2014/53/EU [4].

Spurious and Harmonics

ERC Recommendation 74-01 [11] already has existing spurious emission limits in the range of 150 kHz-30 MHz that are recognised and harmonised to the Radio Equipment Directive. As supported by the data in this study, spurious emission measurements are below what is currently required for this Recommendation. The detailed examination of measured levels of the fundamental and analysis are given in ANNEX 7.

4.3 AIMD AT 5 MHZ AND 6.78 MHZ

4.3.1 AIMD inductively powered by the transcutaneous communication channel at 5 MHz

The estimated deployment of these systems in Europe is 350 k in 2030. The activity factor is 8 to 24 hours per day.

The ECC Report 67 [44] studied the impact of inductive applications on the protection of the radio services. The following generic limit was proposed in the Report for the frequency range 148.5-30 MHz:

- A maximum field strength of -15 dBµA/m @10 m in a bandwidth of 10 kHz allowing
- A total field strength up to -5 dBµA/m @10 m for systems with an operating bandwidth larger than 10 kHz whilst keeping the density limit above.

Compliance measurements for devices at very low magnetic field strength are performed at 3 metre range from the equipment under test (EUT) (implant system) for practical reasons. ETSI EN 300 330 [12] allows field measurements to be done at 3 metres and defines the conversion factor from 10 metres to 3 metres at +28.5 dB @ 5 MHz (EN 300 330 V2.1.1, annex H - H-field measurements at 3 m and 30 m). These measurements show that the implant devices operating in the 3.75-6.25 MHz band meet the H-field limit of 13.5 dBµA/m @ 3m[2] at 5 MHz. Various variable parameters from the system distribution such as the type and the level of the therapeutic stimulation, the skinflap thickness and the coil losses result that the mean value of the fundamental H-field is at 3 dBµA/m @ 3 m. These H-fields decrease strongly in the near field with a slope of $1/r^3$ (60 dB/decade) e.g. within 10 m. At larger distances the far field applies, and the slope decreases to 1/r (20 dB/decade) above 100 m. The spurious emissions are typically 20 dB or more below the limits of ERC Recommendation 74-01 [11].

Based on a deployment of 350k implant devices equally spread over Europe (747526639 inhabitants today) in 2030 results in a density of 0.00047 implant devices per person. Population densities of typically 34 per km^2 in Europe result in 0.016 devices per km^2 or 1 device per 62.83 km^2.

Densities are much higher in urban areas and the urban population in 2030 is expected to grow up to 77.3% as predicted by the United Nations, Department of Economic and Social Affairs, Population Division[3].

In example a density of 1000 persons per km^2 would result in 0.468 devices per km^2 or 1 device per 2.14 km^2. A density of 5000 persons per km^2 would result in 2.34 devices per km^2 or 1 device per 0.43 km^2. A volumetric approach may be applied for higher population densities e.g. Monaco.

The probability that a victim receiver is within 10 metres, 25 metres or 50 metres range from the implant device was calculated for various density scenarios. For this, the area was split-up in a grid of equal squares with sides of respectively 20, 50 and 100 metres.

The adequate protection distance between the AIMD system as interferer and the victim radio receiver was estimated between 10 m to 100 m when assuming the receiver system operates just above the H-field threshold levels of the human made noise as derived from Recommendation ITU-R P.372 [7]. The effect of the loop antenna directivity was not considered in the study.

The summarised result of the probability study for a victim receiver to be within the 25-metre range of a single AIMD device is as follows:

- There is a probability of 0.59% that a single AIMD is within the 25-metre range of the victim receiver for population densities of 5000 people/km^2;
- There is a probability of 1.17% that a single AIMD is within the 25-metre range of the victim receiver for population densities of 10000 people/km^2.

The likelihood to see a victim receiver in a range of 50 m is 4 times higher compared to the 25 m range.

[2] -15dBµA/m @ 10 m + 28.5dB = +13.5 dBµA/m @ 3 m

[3] https://www.worldometers.info/world-population/europe-population/

The volumetric approach applied on areas with large population densities (20000 people/km^2) shows that there is a probability of 0.12% that a single AIMD is within the 25-metre range of the victim receiver and 0.96% within the 50-metre range.

These implant devices operate typically 16 hours per day with a mean duty cycle of 50% wherein the TXON time varies between 50 µs to 1000 µs. In case of large implant clusters (which is unlikely to occur) a 50% reduced duty cycle may mitigate the interference to the victim receivers.

Radiated emissions in the far field from a small loop coil can be 'theoretically' derived for such typical AIMD coil system design and results in 30 dBµV/m at 3 metres. This is because the coil diameter is typically 3 cm which is much smaller than the wavelength at 5 MHz (60 m). Measurement results and analysis are found in ANNEX 5:.

4.3.2 Battery charging of the hearing implant system at 5 MHz

The estimated deployment of these systems in Europe would be <5k in 2030. The charging time and interval varies from one hour up to three hours (fully discharged implant battery) every day.

The power transfer for charging the implant battery at 5 MHz is interleaved with the radio communication channel at 5 MHz (e.g. for external hearing) over the same implant coil interface. The ECC Report 67 [44] studied the impact of inductive applications on the protection of the radio services. The following generic limit was proposed for the frequency range 148.5-30 MHz:

- A maximum field strength of -15 dBµA/m @ 10 m in a bandwidth of 10 kHz allowing;
- A total field strength up to -5 dBµA/m @ 10 m for systems with an operating bandwidth larger than 10 kHz whilst keeping the density limit above.

Compliance measurements for these charger devices at very low magnetic field strength are performed at 3 metres range from the EUT (implant system) for practical reasons. ETSI EN 300 330 [12] allows field measurements to be done at 3 metres and defines the conversion factor from 10 metres to 3 metres at +28.5 dB @ 5 MHz (ETSI EN 300 330, annex H – H-field measurements at 3 m and 30 m). These measurements show that compliance to the H-field limits for the power carrier at +15.2 dBµA/m @ 3 m[4] averaged is met and closely aligned to the -15 dBµA/m @ 10 m outcome from ECC Report 67, and values are always below +23.5 dBuA/m @ 3 m for the maximum hold trace measurement (display function). The 10 dB difference between the average and the maximum hold trace reflects restrictions on the duty cycle of the WPT carrier required for interleaved operation. The H-field of the radio communication function is at least 10 dB below the magnetic field strength of the power carrier.

Various variable parameters from the system distribution such as the coil diameter, the primary coil current, the implant battery charging current and duration, the coil losses, the skinflap thickness and the type and the level of the therapeutic stimulation result that the mean value of the fundamental H-field is typically 5 dB lower than the proposed limits. These H-fields decrease strongly in the near field with a slope of $1/r^3$ (60 dB/decade) e.g. within 10 m. At larger distances, the far field applies and the slope decreases to 1/r (20 dB/decade) above 100 m. The spurious emissions are typically 10 dB or more below the limits of ERC Recommendation 74-01 [11].

Based on a deployment of 5000 implant chargers equally spread over Europe (747526639 inhabitants today) in 2030 results in a density of 0.000007 charger devices per person. Population densities of typically 34 per km^2 in Europe result in 0.00023 devices per km^2 or 1 device per 4398 km^2.

Densities are much higher in urban areas and the urban population in 2030 is expected to grow up to 77.3% as predicted by the United Nations, Department of Economic and Social Affairs, Population Division[5].

[4] -15dBµA/m @10m + 28.5dB = +13.5 dBµA/m @ 3 m

[5] https://www.worldometers.info/world-population/europe-population/

In example a density of 1000 persons per km² would result in 0.007 devices per km² or 1 device per 150 km². A density of 5000 persons per km² would result in 0.033 devices per km² or 1 device per 30 km². A volumetric approach may be applied for higher population densities e.g. Monaco.

The probability that a victim receiver is within a 50 metre, 100 metre or 200 metre range from the implant device was calculated for various density scenarios. For this the area was split-up in a grid of equal squares with sides of respectively 100, 200 and 400 metres.

The adequate protection distance between the AIMD system as interferer and the victim radio receiver was estimated to be at least 100 m when assuming the receiver system operates just above the H-field threshold levels of the human made noise as derived from Recommendation ITU-R P.372 [7]. The effect of the loop antenna directivity was not considered in the study.

The summarised result of the probability study for a victim receiver to be within the 100-metre range of a single AIMD charger is as follows:

- There is a probability of 0.027% that a single AIMD charger is within the 100-metre range of the victim receiver for population densities up to 1000 people/km²;
- There is a probability of 0.27% that a single AIMD charger is within the 100-metre range of the victim receiver for population densities up to 10000 people/km².

The volumetric approach applied on areas with large population densities (20000 people/km2) shows that there is a probability of 0.11% that a single AIMD charger is within the 100-metre range of the victim receiver.

These charger devices operate typically one to three hour per day with a typical duty cycle of 50%.

Theoretical studies show that radiated E-field emanating from a small sized coil is low. This is because the coil diameter is typically 3 cm which is much smaller than the wavelength of the operation frequency (60 m). Measurement results and analysis are found in ANNEX 5.

4.3.3 Battery charging of the hearing implant system at 6.78 MHz

The estimated deployment of these systems in Europe would be <5k in 2030. The charging time and interval varies from one hour up to three hours (fully discharged implant battery) every day.

The power transfer for charging the implant battery at 6.78 MHz is interleaved with the radio communication channel at 5 MHz (e.g. for external hearing) over the same implant coil interface.

The proposed WPT emission mask follows the emission mask of ETSI EN 300 330 [12] from Annex I as referred in ERC Recommendation 70-03, annex 9 [31] sub-band 'f' narrowed to 9 dBµA/m @ 10 m due to the human tissue heating safety limits.

Compliance measurements for these charger devices at low magnetic field strength are performed at 3 metres range from the EUT (implant system) for practical reasons. ETSI EN 300 330 allows field measurements to be done at 3 metres and defines the conversion factor from 10 metres to 3 metres at +26.7 dB @ 6.78MHz (ETSI EN 300 330, annex H - H-field measurements at 3 m and 30 m). These measurements show typical values of +20 dBuA/m @ 3 m[6] for the maximum hold trace measurement (display function). Various variable parameters from the system distribution such as the coil diameter, the primary coil current, the implant battery charging current and duration, the coil losses, the skinflap thickness and the type and the level of the therapeutic stimulation results in a typical margin of 15 dB to the 9 dBµA/m @ 10 m H-field limit. These H-fields decrease strongly in the near field with a slope of $1/r^3$ (60 dB/decade). At larger distances the far field applies and the slope decreases to 1/r (20 dB/decade) above 100 m. The spurious emissions are typically 10 dB or more below the limits of ERC Recommendation-74-01 [11].

Based on a deployment of 5000 implant chargers equally spread over Europe (747526639 inhabitants today) in 2030 results in a density of 0.000007 charger devices per person. Population densities of typically 34 per km² in Europe result in 0.00023 devices per km² or 1 device per 4398 km².

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[6] 20 dBµA/m @ 3 m - 26.7dB = - 6.7 dBµA/m @10m

Densities are much higher in urban areas and the urban population in 2030 is expected to grow up to 77.3% as predicted by the United Nations, Department of Economic and Social Affairs, Population Division[7].

In example a density of 1000 persons per km^2 would result in 0.007 devices per km^2 or 1 device per 150 km^2. A density of 5000 persons per km^2 would result in 0.033 devices per km^2 or 1 device per 30 km^2. A volumetric approach may be applied for higher population densities e.g. Monaco.

The probability that a victim receiver is within 50 metres, 100 metres or 200 metres range from the implant device was calculated for various density scenarios. For this the area was split-up in a grid of equal squares with sides of respectively 100, 200 and 400 metres.

The adequate protection distance between the AIMD system as interferer and the victim radio receiver was estimated to be at least 100 m when assuming the receiver system operates just above the H-field threshold levels of the human made noise as derived from Recommendation ITU-R P.372 [7]. The effect of the loop antenna directivity was not considered in the study.

The summarised result of the probability study for a victim receiver to be within the 100-metre range of a single AIMD charger is as follows:

- There is a probability of 0.027% that a single AIMD charger is within the 100-metre range of the victim receiver for population densities up to 1000 people/km^2;
- There is a probability of 0.27% that a single AIMD charger is within the 100-metre range of the victim receiver for population densities up to 10000 people/km^2.

The volumetric approach applied on areas with large population densities (20000 people/km^2) shows that there is a probability of 0.11% that a single AIMD charger is within the 100-metre range of the victim receiver. These charger devices operate typically one to three hour per day with a typical duty cycle of 50%.

Theoretical studies show that the unwanted radiated E-field emanating from small sized coil is low. This is because the coil diameter is typical 3 cm which is much smaller than the wavelength of the operation frequency (44 m). Measurement results and analysis are found in ANNEX 5:.

4.4 IMPACT ON THE AMATEUR SERVICE

4.4.1 Amateur service at frequencies between 1.8 and 30 MHz

ANNEX 1 studies typical signal levels in the amateur service at frequencies between 1.8 and 30 MHz. Amateur service communication is noise-limited, without any minimum service levels. Median signal levels in the order of -45 dBμA/m are noted.

ANNEX 1 models the impact of unwanted emissions from WPT devices should they be at the limits of ERC Recommendation 74-01 [11] and concludes that devices operating at this limit can cause harmful interference when the spacing between device and radio antenna is of the order of 10m and where there is frequency coincidence. Modelling of the decay of unwanted emissions with distance at this level show that the impact can extend to several hundred metres.

In the case of low power generic WPT devices, modelling is also undertaken in ANNEX 1 which shows that, based on the likely installed density of devices, separation distances are statistically unlikely to exceed 10 m and that emissions from several devices are not likely to impact any location.

ANNEX 1 then models the probability of frequency co-incidence between generic WPT device unwanted emissions and amateur service communications and concludes that for a single WPT device operating near to 100 kHz, the probability is of the order of 3%. With more devices impacting a particular location, this probability can rise. Given the variable frequency nature of WPT device, this probability rises with increased frequency shift. Given that the study shows that several WPT devices may impact any one location, the overall probability of frequency coincidence rises to the order of 24%.

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[7] https://www.worldometers.info/world-population/europe-population/

From the modelling carried out in these studies, an assessment of unwanted emission levels to provide more or less full protection to the amateur service has been developed. These have been developed taking into account the Recommendation ITU-R F.240 [10] protection ratio as applied to the median signals in the amateur spectrum and also the conventional measure of I/N (see section A1.6). Both methods yield comparable results, which suggest a level of:

-46 dBµA/m at 300 kHz reducing by 7 dB per frequency decade to -60.0 dBµA/m at 30 MHz measured at 10 metres.

It is recognised that this level of protection may be difficult to implement. This fact should be considered in the light of the current capabilities of the WPT technology.

ANNEX 1 contains a study into the impact of generic WPT devices on communications in the amateur service. The study confirms that with the exception of the 136 kHz amateur band, the emissions at the operating frequency (as opposed to unwanted emissions) from the generic WPT tested are not likely to cause harmful interference at the levels envisaged.

4.4.1.1 System tests

Tests have been undertaken on low power generic devices and a report is available in ANNEX 1. This shows that the spurious emissions from the generic low power WPT systems tested are well below the levels in Recommendation ITU-R SM.329 [40] and ERC Recommendation 74-01 [11].

4.4.1.2 Summary

The low power WPT systems which have been measured and tested have spurious and harmonic emission levels which allow satisfactory coexistence with radiocommunication services.

4.4.2 Amateur Service in 135.7-137.8 kHz

The potential impact from WPT emissions onto a co-channel Amateur station in the band 135.7-137.8 kHz was evaluated. A single-entry case as well as an aggregate scenario was evaluated. The details can be found in ANNEX 11.

Table 10 summarises the results of the simulations. Based on the simulation results, it can be concluded that non-beam WPT mobile charging devices do not impact amateur service receivers when the devices are placed more than 51.3 m from the receiver antenna as a worst case.

Table 10: Summary of results for a single WPT frequency

Scenario	Permissible interference level (dBµV/m)	Separation distance (m)
Single-entry scenario 1	25.6	15.3
Single-entry scenario 2	25.6	28.1
Aggregate scenario 1	25.6	23.8
Aggregate scenario 2	25.6	51.3

The exact location (e.g. height difference) and the actual radiation pattern of the Amateur service receiver antenna would mitigate the interference impact. Also, it is unlikely that all WPT chargers will operate on the same frequency which would further reduce the interference impact.

4.5 BROADCASTING SERVICE

The BBC and UK Ofcom have conducted laboratory based tests to evaluate the emission levels from a selection of low power WPT devices of 5 Watt and to develop separation distances for satisfactory coexistence.

Methods and results of BBC measurements are published in White Paper [39]. Methods and results of Ofcom-UK measurements are described in ANNEX 9.

Table 11 outlines the results of the measured levels in both sets of tests and compares these with the limits of ERC Recommendation 74-01 [11].

Table 11: Measured values from BBC and Ofcom-UK, and limits of ERC Recommendation 74-01

	ERC Recommendation 74-01 dBμA/m	BBC measurements dBμA/m	OFCOM measurements dBμA/m
Spurious (operating) 9 kHz – 10 MHz (9 kHz descending 10 dB/decade) 900 kHz	27 7		
Spurious (standby) 9 kHz – 10 MHz 900 kHz	5.5 -14.5		
Fundamental (charging)		<65 at 1 m <5 at 10 m	
Fundamental (idle/charging)			<35/<30 at 3 m <3.6/<-1.4 at 10 m
5th harmonic (charging)		< 30 at 1 m <-30 at 10 m	<0 at 3 m <-31.4 at 10 m
7th harmonic (charging)		<25 at 1 m <-35 at 10 m	<-8 at 3 m <-39.4 at 10 m
5th harmonic (idle)			<5 at 3 m < -26.4 at 10 m
7th harmonic (idle)			<0 at 3m <-31.4 at 10 m

The values at 10 m are calculated from those at 1 m and 3 m by applying the inverse Cube-law for the decrease of the magnetic field at the concerned distances.

When normalised to 10 m it is clear from Table 11 that both Organisations measured very similar results for both the 5th and 7th harmonics. This tends to validate the calibration and geometry of the experimental configurations.

With reference to Table 11, the limit from ERC Recommendation 74-01 [11] for a frequency of 900 kHz, generated as the 7th harmonic of the WPT device is around 7 dBμA/m. From BBC and UK measurements, the average for the 7th harmonic (in the logarithmic domain) of the WPT devices under test is -35 dBμA/m.

These levels are 42 dB lower than the limits in ERC Recommendation 74-01.

Further information on the Ofcom-UK measurements:

- The unwanted emissions from all the devices tested were significantly (up to 40 dB) below the limits set out in ERC Recommendation 74-01;
- The highest level at the operating frequency of any device measured in idle mode at 3 metres was 36.7 dBμA/m and the highest 5th harmonic was 5.2 dBμA/m, which corresponds to -26 dBμA/m at 10 m, i.e. 11.5 dB below the ERC Recommendation 74-01 (spurious limit at 900 kHz).

- The highest level at the operating frequency of any device measured in charging mode at 3 metres was 33.5 dBµA/m and the highest 5th harmonic was -0.3 dBµA/m, which corresponds to -31 dBµA/m at 10 m, i.e. 38 dB below the ERC Recommendation 74-01 [11] (spurious limit at 900 kHz).
- The operating frequencies and therefore the harmonics of the devices tested varied. Therefore, it is unlikely to have the aggregation of many devices.

Tests conducted by the BBC with a laboratory generated carrier signal offset by 2 kHz from the centre frequency of the broadcast receiver had a greater perceptible impairment of the audio, while subsequent tests conducted by Ofcom-UK to try to replicate this using the real WPT devices had only a minor perceptible impact on the audio impairment.

4.6 RADIONAVIGATION SERVICE

The following sections describe relevant parts of Report ITU-R SM.2449-0 technical characteristics and impact analyses of non-beam inductive wireless power transmission for mobile and portable devices on radiocommunication services.

Report ITU-R SM.2449-0 conducted an impact analysis of WPT devices for mobile and portable devices on various radiocommunication services in the frequency range 100–148.5 kHz. The studies on the Radionavigation Services are fully applicable to the scope of this Report.

4.6.1 Summary of potential WPT interference to the Radionavigation Service in 90–110 kHz

Loran-C was considered as the potentially affected system. Two scenarios were considered. In each scenario, the WPT system transmits with an electrical field strength of -15 dBµV/m at 300 m.

The first scenario analysed the impact from WPT devices on land onto a ship-based receiver. A single entry as a well as aggregate interference were considered. It was found that the reception onboard the ship was not affected. Elements such as building entry loss of the WPT devices and summation based on the signal phase were not considered.

The second scenario analysed the use of WPT systems onboard a ship. Depending on the location of the WPT device(s) the minimum distance was found to be between 4.5 and 5.4 m for single entry or between 9.4 and 11.4 m for aggregate signal levels. This scenario considered only 10 dB wall penetration loss regarding the walls of the ship. In fact, it is most likely that those walls are made of metal (steel or aluminium), i.e. the much higher wall penetration in such a case would further decrease those distances.

4.7 STUDY OF NON-BEAM INDUCTIVE WPT APPLICATIONS IN 300–400 KHZ ON THE AERONAUTICAL RADIONAVIGATION SERVICE

A study contained in ANNEX 10 looked at the impact of WPT devices on ADF/NDB systems. All WPT devices for the study were assumed to be using the same frequency (400 kHz), while in real life quite a spread of the actual charging frequencies depending on the actual implementation, charging status etc. can be observed.

Maximum magnetic field emission of WPT transmitters was assumed to be -15 dBµA/m at 10 m.

The simulations have shown that WPT chargers for mobile and portable devices do not interfere with the reception of ADF/NDB signals. Building entry loss (roof/ceilings) were not included in the calculation/simulation but would further reduce the interference from WPT devices to ADF.

4.8 IMPACT ON THE FIXED AND MOBILE SERVICES BELOW 30 MHZ (MINIMUM COUPLING LOSS)

The following analysis is based on a theoretical worst-case minimum coupling loss calculation. It has to be noted that the study carried out in this section uses a different bandwidth than the defined for mobile and fixed services in section 3.6.

4.8.1 HF current man-made noise

The radio frequency noise picked up by the receiver antennas has an impact on the quality of reception and thus on the radio link's performance. In the HF frequency band (1.5 to 30 MHz), the most powerful constantly present noise picked by the receiver is the man-made noise.

This noise level as defined in Recommendation ITU-R P-372 [7] is particularly for outdoor antennas, aggregated unintended radiation from electrical machinery, electrical and electronic equipment and networks, power transmission lines, or from internal combustion engine ignition. This noise is higher than the HF receive chains self-noise and constitutes a background noise.

In Recommendation ITU-R P.372, the median man-made noise is characterised by a noise factor for different environments. The noise in city environments is the most powerful man-made noise and the noise encountered in quiet rural environments is the lowest.

The relation between the noise factor and the electrical field is given in this Recommendation. Assuming the well-known relation between electrical field and magnetic field verified ($\frac{E}{H} = 377\ \Omega$), the level of magnetic field corresponding to the median man-made noise is obtained as described in Figure 9.

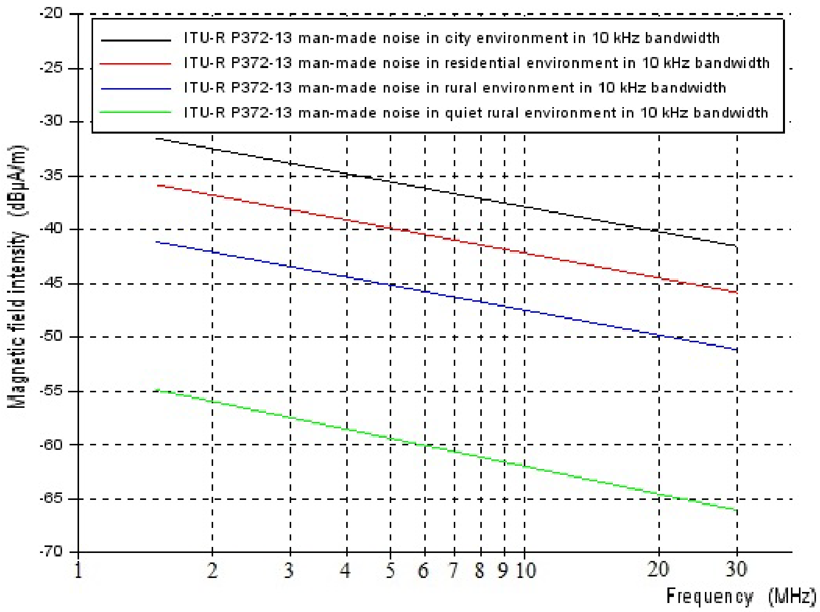


Figure 9: Magnetic field corresponding to Recommendation ITU-R P372 median man-made noises in 10 kHz receive bandwidth, versus frequency

These curves are median values. There are variations of the curve according to the location of the transmission and the time characterised in this Recommendation for city, residential and rural environments. Deviation values are not given for a quiet rural environment (see Table 12).

Table 12: Values of decile deviations of man-made noise, from Recommendation ITU-P.372

Category	Decile	Variation with time (dB)	Variation with location (dB)
City	Upper Lower	11.0 6.7	8.4 8.4
Residential	Upper Lower	10.6 5.3	5.8 5.8
Rural	Upper Lower	9.2 4.6	6.8 6.8

4.8.2 Comparison between ERC Recommendation 74-01 spurious limits and Recommendation ITU-R P.372 man-made noise levels

WPT transmissions will generate electromagnetic waves whose energy is mainly contained in their operating band. However, a part of the energy emitted is contained outside this band. For the unwanted emissions in the 1.5–30 MHz, the following comparison can be made between ERC Recommendation 74-01 [11] and Recommendation ITU-R P.372 [7] man-made noise levels.

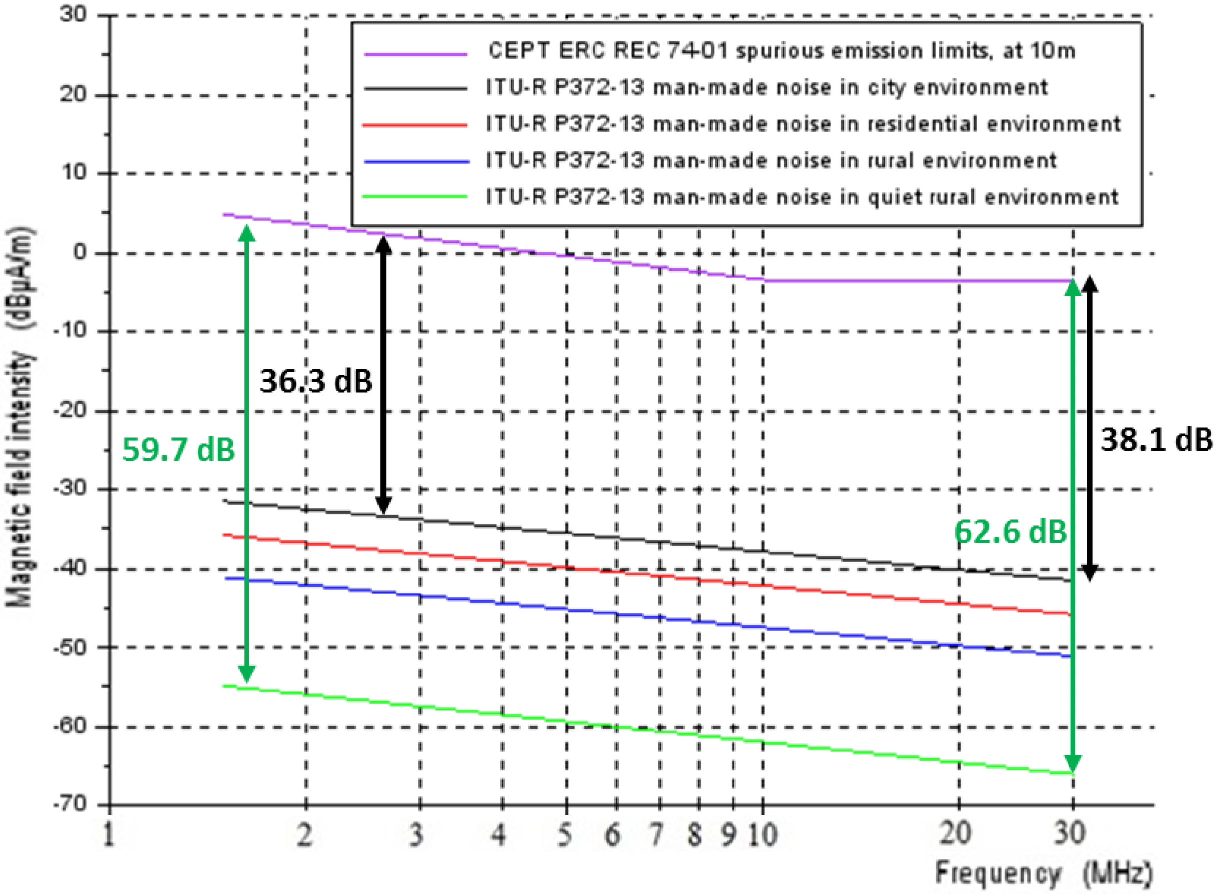


Figure 10: ERC Recommendation 74-01 spurious emission limits at 10 m in 10 kHz bandwidth compared to Recommendation ITU-R P372 median man-made noise curves in 10 kHz bandwidths

In order to avoid significant losses in HF mobile and fixed services links performances, it is necessary to avoid significant rise in interference picked up by antennas of HF mobile and fixed stations used in their operational use contexts. Thus, it is necessary to avoid WPT spurious emissions limits allowing significant increase in the man-made noise perturbations picked-up by these stations.

4.8.2.1 Attenuation to apply at distances different from 10 metres

In order to estimate the magnetic field level for the 1.5 MHz; 30 MHz band at different distances, attenuation conversion factors must be applied to limits in ERC Recommendation 74-01. Attenuation values vary with the regions of the electromagnetic field considered, such as near and far fields. Thus, for a fixed distance, its value varies with the wavelength of the radiated signal.

For the 1.5 MHz, 30 MHz band, the radiated element of the systems described in section 2 is electrically small. Thus, considering λ the wavelength of the radiated signal, the following regions could be defined:

- the reactive near-field region where the magnetic field level falls off as $\frac{1}{r^3}$, equivalent to a 60 dB/decade decay rate. This region is defined for distances well below $\frac{\lambda}{2\pi}$ from the radiating element;

- the far-field region where the magnetic field strength falls off as $\frac{1}{r}$, equivalent to a 20 dB/decade decay rate. In the literature, for electrically small antennas, this region is defined for distances higher to $3.\lambda$ from the radiating element;
- the transition zone including the radiative near-field region. This zone is defined for distances between a value well below $\frac{\lambda}{2\pi}$ and $3.\lambda$ from the radiating element. In this region, the magnetic field attenuation to consider is not clearly defined. The decay rate remains smaller than for the reactive near-field region: inferior to 60 dB/decade.

Conversion factors C_{30m} & C_{3m} versus frequency curves from ETSI EN 300 330, annex I [12] confirm these boundaries and decay rates.

In this study, these factors will be applied. For distances not equal to 30 m or 3 m, hypothetical conversion factors will be estimated from these curves.

4.8.2.2 Effect of WPT transmitting near a fixed or mobile station on the noise rise in city and residential environments

In order to evaluate the WPT spurious emissions at ERC Recommendation 74-01 [11] limits received by HF stations, in city and residential operational use conditions, scenarios are evaluated:

- for a mobile station: a 5 metres minimum distance in city environment and a 10 metres minimum distance in residential environment;
- for a fixed station: a 10 metres minimum distance in city and residential environments.

At 5 meters, in the 1.5 MHz; 30 MHz band, a hypothetical 5 metres conversion curve is considered following the same shape as the C_{3m} conversion factor versus frequency curve at 3 metres, from ETSI EN 300 330, annex I. This curve takes the near field to far-field attenuation and its variations with wavelength into account. Thus, at 5 metres, the ERC Recommendation 74-01 limits would increase by approximately 17.8 dB at 1.5 MHz to 7 dB at 30 MHz.

If the Recommendation ITU-R P.372 [7] median man-made noise values are considered as the current perturbations picked-up by these HF mobile or fixed stations and only one WPT transmitter operating at ERC Recommendation 74-01, the WPT emissions would increase the median man-made noise level by:

- Approximately 54 dB at 1.5 MHz to 45 dB at 30 MHz, in city environment at 5 metres;
- 36.3 dB at 1.5 MHz to 38.1 dB at 30 MHz, in city environment at 10 metres;
- 40.6 dB at 1.5 MHz to 42.4 dB at 30 MHz, in residential environment at 10 metres.

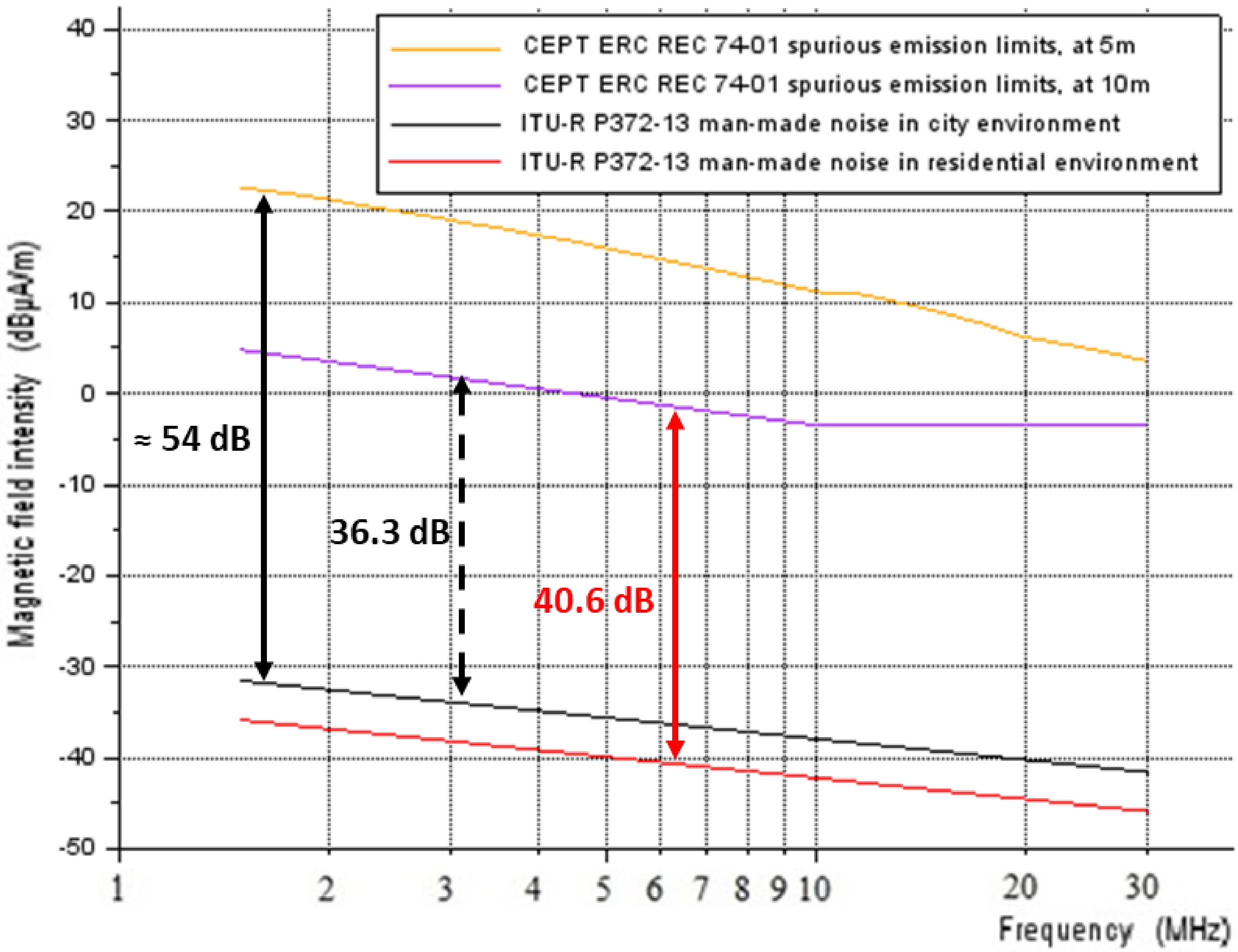


Figure 11: ERC Recommendation 74-01 spurious emission limits estimated at 5 & 10 metres in 10 kHz bandwidths compared to Recommendation ITU-R P.372 [7] median man-made noise curves in 10 kHz bandwidths

4.8.2.3 Effect of WPT transmitting near fixed or mobile station on the noise rise in rural environments

In order to evaluate the WPT spurious emissions at ERC Recommendation 74-01 [11] limits, in these rural or quiet rural operational use conditions, between a HF station and a WPT transmitter, a 70 metres minimum distance is estimated in rural environment.

At 30 metres, on the 1.5 MHz; 30 MHz band, the C_{30m} conversion factor is considered versus frequency curve at 30 m from the standard ETSI EN 300 330, annex I [12]. This curve takes the near field to far-field attenuation effect and variation with wavelength into account.

Thus, at 30 metres, the ERC Recommendation 74-01 limits would decrease by 26.5 dB at 1.5 MHz to 9.5 dB at 30 MHz.

If the Recommendation ITU-R P.372 [7] median man-made noise values are considered as the current perturbations picked-up by these HF mobile or fixed stations and only one WPT transmitter, the WPT emissions would increase the median man-made noise level by 19.4 dB at 1.5 MHz to 38.2 dB at 30 MHz, in rural environment at 30 metres.

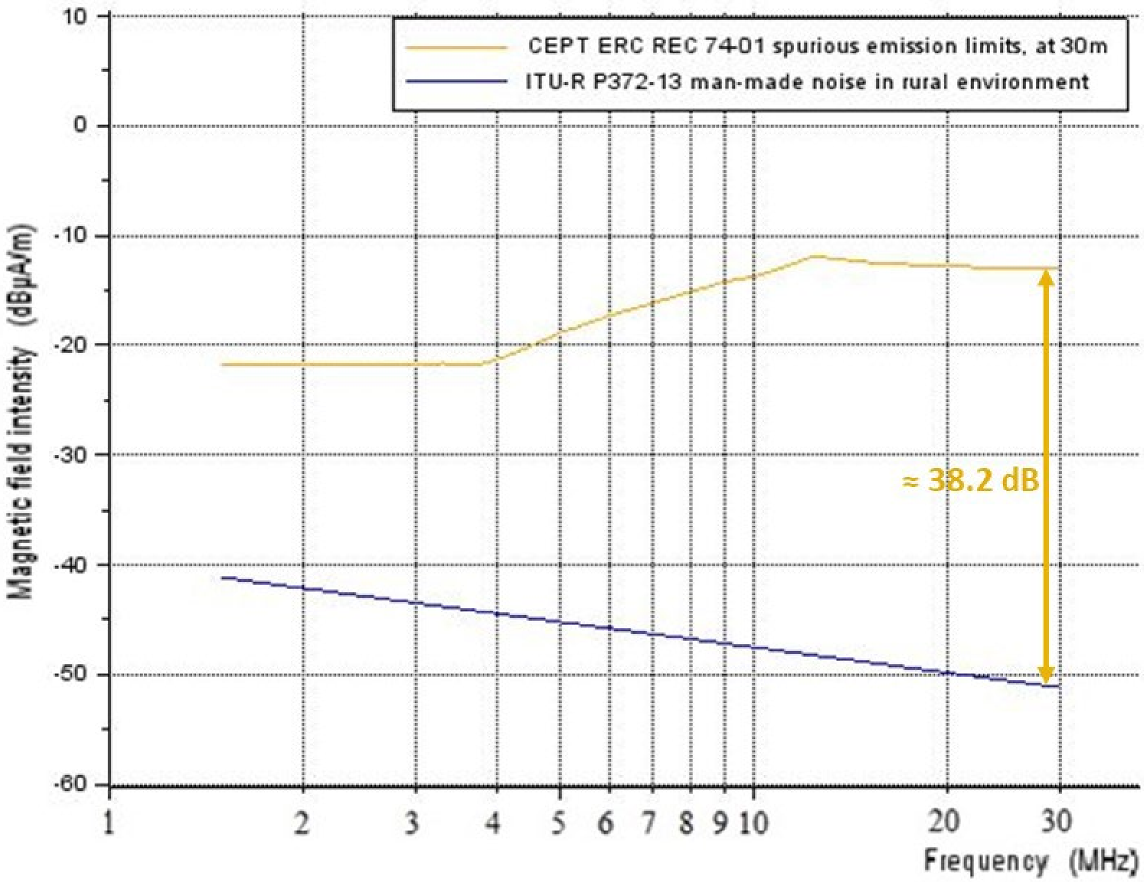


Figure 12: ERC Recommendation 74-01 spurious emission limits estimated at 30 & 50 metres in 10 kHz bandwidth compared to ITU-R P.372 [7] median man-made noise curves in 10 kHz bandwidth

4.8.3 Conclusion on the mobile and fixed services below 30 MHz

This theoretical worst-case MCL analysis is based on hypothetical scenario of compatibility of ERC Recommendation 74-01 [11] spurious emission limits with HF mobile and fixed stations use in their operational contexts. It showed that if applying the ERC Recommendation 74-01 spurious emission limits, the instantaneous man-made noise level is 36 dB or higher than the median HF man-made noise estimated by Recommendation ITU-R P.372 [7] in the 1.5-30 MHz HF frequency band at a distance of 10 m.

It has to be noted these results were obtained using a different bandwidth than the one specified for mobile and fixed as defined in section 3.6.

The minimum coupling loss (MCL) studies (worst-case theoretical modelling) carried out on the protection of the amateur service in the spurious domain (from any WPT emission) converged into a level of protection described in A1.6. This is also relevant for the protection of fixed and mobile services.

-46 dBµA/m at 300 kHz reducing by 7 dB per frequency decade to -60.0 dBµA/m at 30 MHz measured at 10 metres.

Note that these levels, although originally calculated in the context of residential median noise levels defined in ITU-R P.372, may be more relevant to the rural environment, given the current reality of noise levels as can be found in the ITU noise database.

The separation distances required for a limit exceedance of 0 dB, 5 dB, 10 dB, 15 dB, 20 dB and 25 dB is shown in Figure 13.

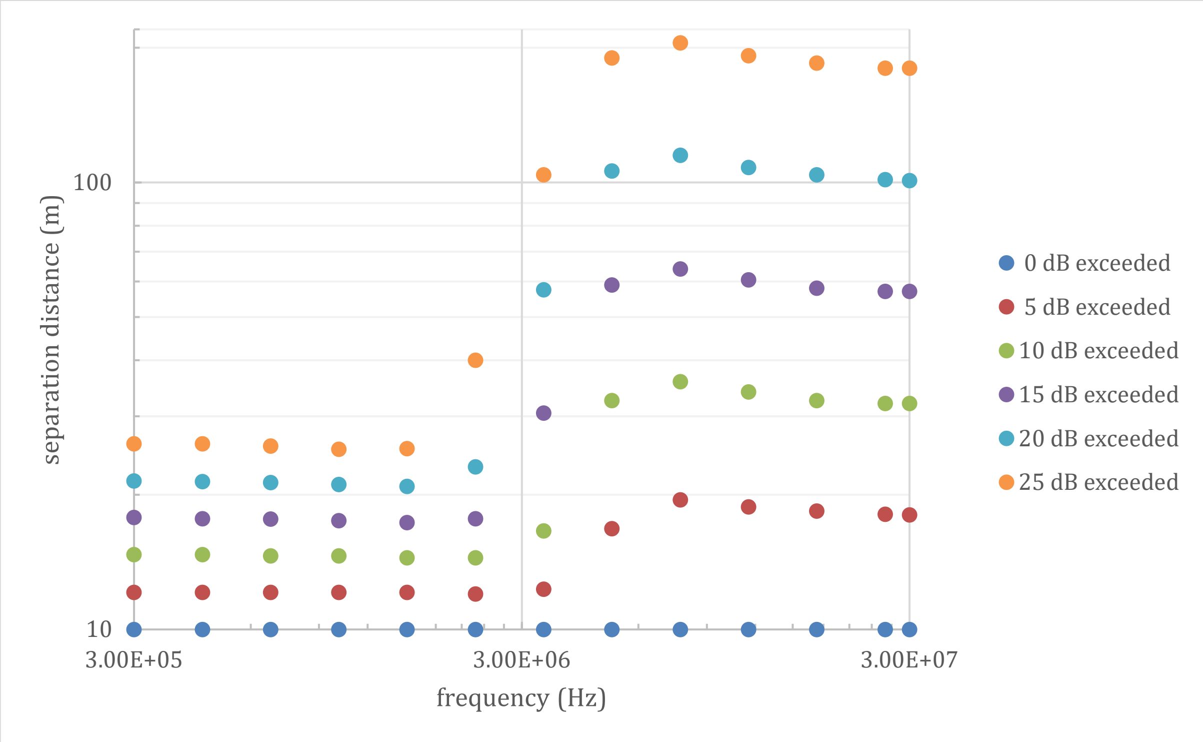


Figure 13: Separation distance for interference signals exceeding the limit by 0 dB to 25 dB

It is recognised that this level of protection may be difficult to implement. This fact should be considered in the light of the current capabilities of the WPT technology.

4.9 MONTE CARLO STUDY ON THE POTENTIAL INTERFERENCE FROM WPT (300-400 KHZ, 1610 - 1800 KHZ AND 1950-2150 KHZ) TO RADIO SERVICES

ANNEX 6: includes a Monte Carlo study that analyses the impact to radio service receivers from WPT devices operating in 300-400 kHz, 1610-1800 kHz and in 1950-2150 kHz. The maximum emission level is -15 dBµA/m. The scenario applies to fixed and mobile services digital mode receivers. It can also apply to amateur radio service digital mode receivers. The study does not consider the emissions at other frequencies (i.e. spurious / harmonics).

This study analyses the amount of interference that falls inside a receiver's bandwidth by comparing it to the received noise level. It therefore only applies to systems where interference can be treated as additional noise. Importantly, therefore, the study does not apply to analogue systems, including AM broadcasting and amateur service communication which is susceptible to single tone interference as well as increased wideband noise.

This study considered interference from a density of 1500 WPT devices per km² deployed in 300-400 kHz and 500 WPT devices per km² in 1610-1800 kHz and 1950-2150 kHz with a maximum transmit level of -15 dBµA/m at 10 m, to radio services receiving at exactly 400 kHz, 1800 kHz and 2000 kHz, respectively (only one receiver at a time is considered).

Building entry losses (BEL) in the far field are modelled according to the ITU-R handbook on ground wave propagation [55]. The model is used on top of propagation model of ERC Report 69 [52], although it is supposed to be used with propagation curves of Recommendation ITU-R P.368 [61]. At distances where magnetic coupling is dominant, 10 dB attenuation of attenuation for 30% of cases has been assumed in urban scenario.

Potential in-band interference to radio services with a reception bandwidth of 2.7 kHz were considered, taking into account that a WPT device randomly choose its transmitted frequency within its operating band.

For WPT emissions at -15 dbµA/m at 10 m distance, two sets of results have been derived. For the first set including the effect of build up structures like buildings it was found that in very dense urban areas, a 1.2 to 1.3 dB noise increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.3 or 0.4 dB, respectively for the two frequency ranges. For all other environments (urban and residential) the increase of the median noise is less than 0.4 dB or 0.6 dB, depending on the frequency.

For the second set without the effect of build up structures like buildings it was found that in in very dense urban areas, a 1.5 dB noise at 400 kHz, 3.9 dB at 1800 kHz and 4.6 dB at 2000 kHz increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency, respectively. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.4 dB at 400 kHz, 1.3 dB at 1800 kHz and 1.5 dB at 2000 kHz, respectively. For all other environments (urban and residential) the increase of the median noise was lower than in the high density urban case.

However, it should be noted, that the in the absence of any reference/recommendation describing the effect of “building exit losses” and losses for built up structures, the first set of results may be underestimating the interference while for the second set of results may be overestimating it. The exact effect of interference impact is somewhere in the presented range.

These levels represent peak charging times that occur at night. During daytime, the median increase in noise was found to be lower.

The actual noise environment at less than 10 m distance from the WPT device can be higher or lower than the noise levels that were used as a reference; i.e., Recommendation ITU-R P.372 median levels and man-made noise measurements carried out in the Netherlands. The actual impact of WPT on the noise environment at such close distances to buildings or inside buildings could not be evaluated because of a lack of sources on man-made noise levels for that case.

This study analyses the amount of interference that falls inside a receiver’s bandwidth by comparing it to a man-made noise level. This is relevant to cases where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, which are more susceptible to single tone interference (see A3.3.1).

In addition, the study does not consider emissions at other frequencies (i.e. spurious / harmonics) nor does it consider the situation of indoor reception, both of which are more relevant for AM broadcasting.

4.10 SINGLE-ENTRY STUDY ON POTENTIAL INTERFERENCE FROM WPT (300-400 KHZ, 1610-1800 KHZ AND 1950-2150 KHZ) ON RADIO SERVICES

The study in ANNEX 8 considered three interference scenarios from WPT devices operating at 400 kHz, 1650 kHz, and 2000 kHz with a maximum transmit level of -15 dBµA/m at 10 m to radio services receiver operated at the same frequency.

At distances where magnetic coupling is dominant, 10 dB attenuation of attenuation for 30% of cases has been assumed in urban scenario.

In cities and considering BEL in 30% of cases, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 11 and 14 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 7 and 9 m.

In cities and without BEL, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 12 and 15 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 7 m and 10 m.

In residential areas and without BEL, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 15 and 18 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 9 and 13 m.

This single entry study is a worst case analysis, since it assumes that the WPT emissions are always co-channel to the radio service receiver.

This study compares the median interference level to a median man-made noise level and identifies the point below which the interference exceeds the man-made noise level. This is relevant to cases where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, which are more susceptible to single tone interference (see A3.3.1).

In addition, the study does not consider emissions at other frequencies (i.e. spurious / harmonics) nor does it consider the situation of indoor reception, both of which are more relevant for AM broadcasting.

5 CONCLUSIONS

5.1 QI BASED SYSTEM AS EXAMPLE OF LOW POWER WPT APPLICATIONS

Qi transmitter devices operate at 100-148.5 kHz range and typically transfer 5-15 W of power. In addition to the wanted power transfer, there is a small leakage of energy. Devices are typically measured with field strength levels between -10 to +10 dBµA/m at 10 m, when operating in power transfer mode. Taking as an example,
+10 dBµA/m = 61.5 dBuV/m is an e.r.p. of 2.9 µW.

Testing of a selection of popular 5 W and 15 W Qi devices available on the market in 2019 has shown that, these generic low power WPT devices can operate with levels of harmonic emission are reasonably low and for derived levels at 10 m distance, the measurements at 1 MHz and above, are below the rural man-made noise floor as defined in Recommendation ITU-R P.372 [7].

Level increase with misalignment of the target device and the emissions have a directional element to them, can be minimised or maximised in a particular direction by rotating the EUT and target device in three planes.

Whilst devices all varied considerably in harmonic emissions, the measured levels are already close to those needed to properly protect radiocommunication services at frequencies above 1 MHz.

5.2 AIMD NEUROMODULATORS

It can be concluded, from the information and result of studies provided in this Report, that the interference probability from the AIMD neuromodulator systems to the incumbent services, operating in the 260-320 kHz range, is very small and negligible. A measurement carried out on a prototype charging system shows a wanted pure narrow bandwidth peak (< 30 dBµA/m @ 10 m) and spurious emission at 150 kHz around 1 dBµA/m @ 10 m decreasing to -30 dBµA/m @ 10 m at 10 MHz.

The density of patients is inherently very low, so the probability of incumbent service interference is also very low. Additionally, patients charge their implants at home for a few hours per week on average, which is a low weekly duty cycle (< 2%).

5.3 BATTERY RECHARGING OF HEARING IMPLANT SYSTEMS AT 5 MHZ AND 6.78 MHZ

5.3.1 Battery recharging of the hearing implant system at 5 MHz

Due to the very low number of deployment and the level restrictions in the inductive power transfer and accompanied communication function there will be low risk of interference or coexistence issues. The field strength levels are aligned with today's ERC Recommendation 70-03 [31] and ECC Report 67 [44] for averaged H-field recordings.

5.3.2 Battery recharging of the hearing implant system at 6.78 MHz

Due to the very low number of deployment and the level restrictions in the inductive power transfer and accompanied communication function there will be low risk of interference or coexistence issues.

5.4 THE AMATEUR SERVICE

The amateur service is a low-signal service. Its antennas are generally deployed in residential areas. The potential interference from WPT system emissions on communication in the amateur service maybe two-fold:

i) From emissions at the operating frequency of the WPT system.

ii) From emissions at other frequencies - mainly harmonics of the operating frequency

The worst-case studies suggest that the impact of (a) is likely to be modest.

In respect of (b), low power WPT systems, similar to those under the Qi standard, show themselves in tests to present little threat to the amateur service, as their performance has been measured as significantly below the ERC Recommendation 74-01 [11] limits.

The contribution of multiple WPT sources propagated via sky wave to the more general noise level in the radio spectrum has not been assessed in the studies to date.

5.5 BROADCASTING SERVICE

Tolerable levels of interference can readily be assessed using existing ITU-R Recommendations which have the specific purpose of defining acceptable interference criteria. The results of these assessments are presented above in the Report and or in the related Annexes.

Permitted levels of interference specified in ERC Recommendation 70-03 [31] and ERC Recommendation 74-01 [11] are high in the context of the sensitivity of any AM receiver. The receiver's defence against harmful interference at these levels depends on a number of factors but principally separation distance between the interferer and the receiver and intermittency of operation of the interferer. ECC Report 67 [44] studies compatibility of generic limits for the wanted emission levels of inductive SRDs below 30 MHz. It states that: "the protection distances from SRD to the victim broadcast receiver range from 8 to 238 m for the LF, MF and HF bands and a field strength in 10 kHz varying from -5 dBµA/m@10m to -25 dBµA/m@10m". The relationship between separation distance and tolerable interfering field strength levels is summarised in Figure 14, showing the unwanted emission limit at 10m, if the protection of -43 dBµA/m (as derived in ANNEX 3) is provided at AM receivers spaced either 1m or 3m from the WPT device.

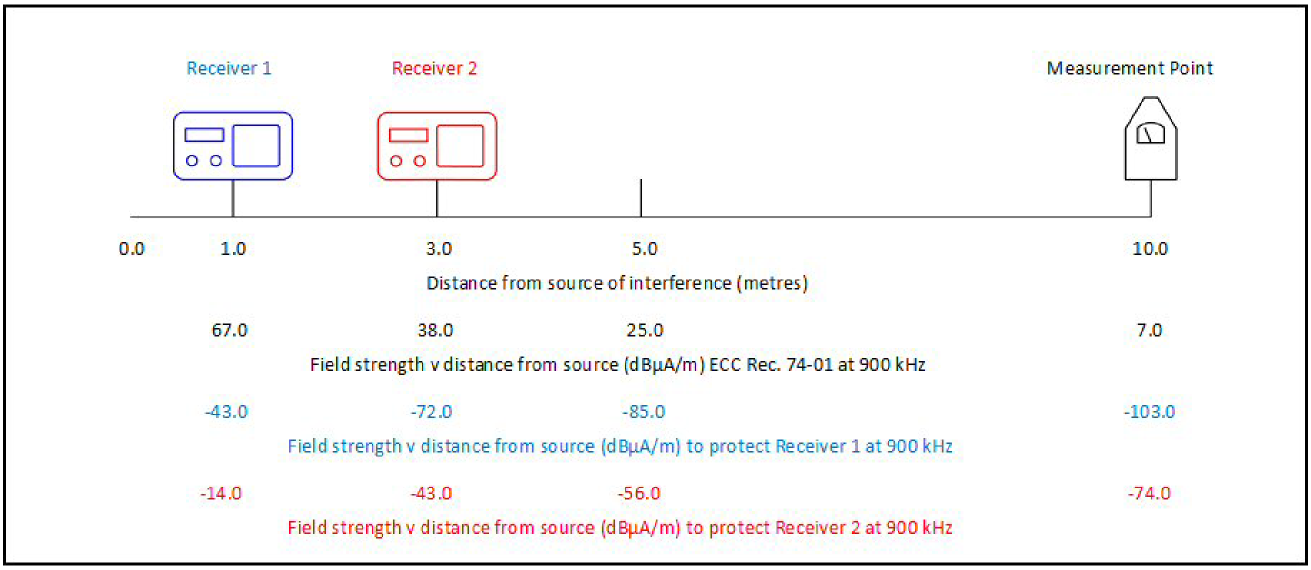


Figure 14: Variation of field strength with distance from source

WPT systems in a domestic environment where AM receivers are in use will be unlikely to be well separated from the receiver nor intermittent in their operation.

Several practical measurement campaigns were performed with commercially available low-power WPT devices. Methods and results of BBC measurements are published in White Paper [39]. Methods and results of OFCOM-UK measurements are described in ANNEX 9.

The separation distances required for co-existence between an AM receiver and a range of low-power WPT devices were evaluated by both the BBC and Ofcom. Derivations of distance are treated separately as, although both organisations measured very similar levels of harmonic emissions from the devices, differences in the methodology for assessment of interference account for some differences in separation values obtained.

5.5.1 Ofcom measurements

A wanted field strength of 66 dBµV/m is produced at the AM receiver, this is equivalent to being located on the edge of the broadcast coverage area according to UK planning parameters.

Frequency relationship between WPT harmonic and AM receiver is adjusted to be as close as possible to the worst case i.e. 2 kHz (although the harmonic frequency output of WPT devices varies quite rapidly during the charging cycle).

The separation between the AM receiver and the WPT device is increased incrementally - compatibility is assumed if the interference is judged to be imperceptible or perceptible but not annoying.

For a selection of commercial low-power inductive WPT devices the level of audio impairment was subjectively assessed. Separation distances of 2-3 m were measured with one device requiring 5.8 m separation.

5.5.2 BBC measurements

The levels of the unwanted harmonic emissions from the WPT device are measured at 1 m.

The required separation distance is evaluated applying an inverse cube field strength/distance relationship.

The separation distance is calculated based on a wanted field strength at the receiver of 60 dBµV/m (equivalent to being located on the edge of the broadcast coverage area according to ITU planning parameters) and a worst-case protection requirement (sustained 2 kHz frequency relationship) of 56 dB as documented in Recommendation ITU-R BS.560, annex 3 for 'imperceptible' interference, Additional adjustments for noise masking as outlined in ANNEX 4 are applied bringing the final protection requirement to 52 dB.

Separation distances calculated as above are between 8 m and 17 m.

It should be noted that, the above condition of a sustained and stable 2 kHz frequency offset was not generally observable in the generic low-power WPT devices tested due to the changing nature of their fundamental frequency and associated harmonic emissions, also that the interference grading criterion applied in ITU R Rec. BS-560 is quite stringent. As a result, the BBC derived separation distances are understandably greater than those measured by Ofcom using commercially available WPT devices.

Despite some measurements and associated subjective assessments showing that the current range of low-power WPT devices only require 2–3 m (and in one case 5.8 m) separation distances, some caution must be exercised here. It is seen in ANNEX 9 that the protection of AM Broadcasting afforded in this case is only around 27 dB (rather than the approx. 52 dB derived in Recommendation ITU-R BS.560, annex 3 for a sustained 2 kHz frequency offset). This suggests that a combination of a less stringent subjective interference grading and the modulation, frequency instability and/or frequency 'hopping' of the WPT device, has revised its interference potential by 52 - 27 i.e. 25 dB. This may not necessarily be the case for all current or future devices.

Nevertheless, based on currently available low power inductive WPT devices, when measured at 10m from the device, an average of the Ofcom and BBC 7th harmonic measurements (in the logarithmic domain) suggests a value of -35 dBµA/m would offer a reasonable degree of protection for receiver operating at the edge of coverage.

5.6 RADIONAVIGATION SERVICE AND AERONAUTICAL RADIONAVIGATION SERVICE

The studies have shown that WPT chargers for mobile and portable devices do not impact the reception of the aeronautical Radionavigation service (ADF/NDB signals). Building entry loss (roof/ceilings) were not included in the calculation/simulation but would further reduce the interference impact from WPT devices to ADF.

Furthermore, the findings of Report ITU-R SM.2449 [48] that WPT portable and mobile devices do not cause interference to the Radionavigation Service in 90-110 kHz (LORAN-C) is confirmed.

5.7 STANDARD FREQUENCY AND TIME SIGNAL SERVICE

The limits defined in ERC Recommendation 70-03, annex 9 [31] are relevant for the protection of the SFTS service.

5.8 MOBILE AND FIXED SERVICES BELOW 30 MHZ

The theoretical worst-case conducted MCL analysis is based on hypothetical scenario of compatibility of ERC Recommendation 74-01 [11] spurious emission limits with HF mobile and fixed stations use in their operational contexts. It showed that if applying the ERC Recommendation 74-01 spurious emission limits, the instantaneous man-made noise level is 36 dB or higher than the median HF man-made noise estimated by Recommendation ITU-R P.372 [7] in the 1.5-30 MHz HF frequency band at a distance of 10 m.

It has to be noted these results were obtained using a different bandwidth than the one specified for mobile and fixed as defined in section 3.6.

The minimum coupling loss (MCL) studies (worst-case theoretical modelling) carried out on the protection of the amateur service in the spurious domain (from any WPT emission) converged into a level of protection described in A1.6. This is also relevant for the protection of fixed and mobile services.

-46 dBμA/m at 300 kHz reducing by 7 dB per frequency decade to -60.0 dBμA/m at 30 MHz measured at 10 metres.

Note that these levels, although originally calculated in the context of residential median noise levels defined in ITU-R P.372, may be more relevant to the rural environment, given the current reality of noise levels as can be found in the ITU noise database.

The separation distances required for a limit exceedance of 0 dB, 5 dB, 10 dB, 15 dB, 20 dB and 25 dB is shown in Figure 15.

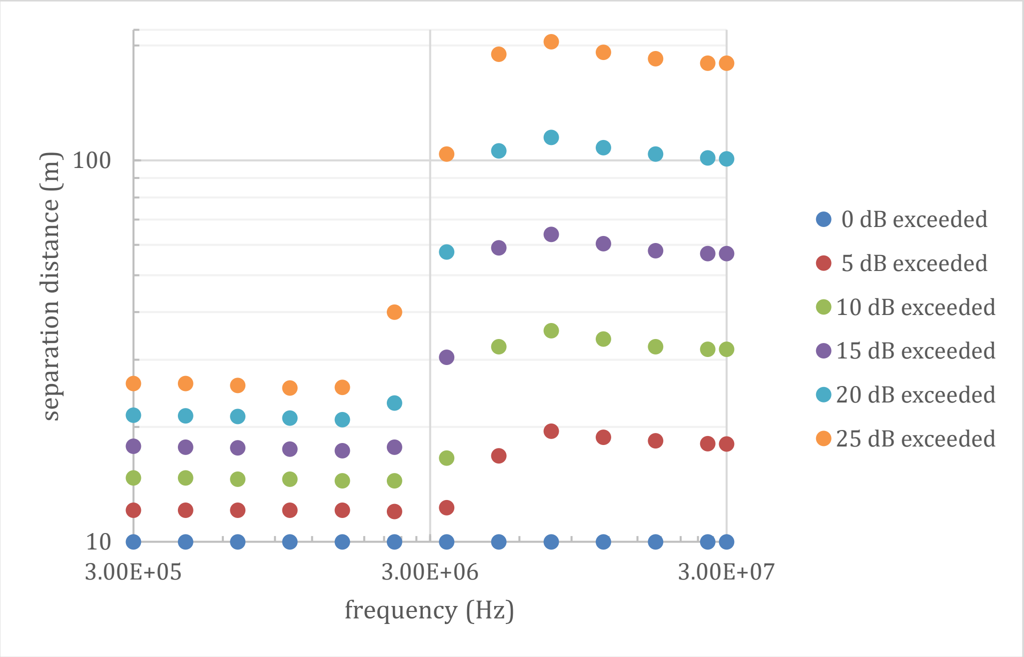


Figure 15: Separation distance for interference signals exceeding the limit by 0 dB to 25 dB

It is recognised that this level of protection may be difficult to implement. This fact should be considered in the light of the current capabilities of the WPT technology.

5.9 GENERIC STUDY FOR RADIO SERVICES IN 300-400 KHZ, 1610-1800 KHZ AND 1950-2150 KHZ

5.9.1 Aggregate Monte Carlo study

This study considered interference from a density of 1500 WPT devices per km² deployed in 300-400 kHz and 500 WPT devices per km² in 1610-1800 kHz and 1950-2150 kHz with a maximum transmit level of -15 dBµA/m at 10 m, to radio services receiving at exactly 400 kHz, 1800 kHz and 2000 kHz, respectively (only one receiver at a time is considered).

Building entry losses (BEL) in the far field are modelled according to the ITU-R handbook on ground wave propagation [55]. The model is used on top of propagation model of ERC Report 69, although it is supposed to be used with propagation curves of Recommendation ITU-R P. 368 [61]. At distances where magnetic coupling is dominant, 10 dB attenuation of attenuation for 30% of cases has been assumed in urban scenario.

Potential in-band interference to radio services with a reception bandwidth of 2.7 kHz were considered, taking into account that a WPT device randomly choose its transmitted frequency within its operating band.

For WPT emissions at -15 dbµA/m at 10 m distance, two sets of results have been derived. For the first set including the effect of build up structures like buildings it was found that in very dense urban areas, a 1.2 to 1.3 dB noise increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.3 or 0.4 dB, respectively for the two frequency ranges. For all other environments (urban and residential) the increase of the median noise is less than 0.4 dB or 0.6 dB, depending on the frequency.

For the second set without the effect of build up structures like buildings it was found that in in very dense urban areas, a 1.5 dB noise at 400 kHz, 3.9 dB at 1800 kHz and 4.6 dB at 2000 kHz increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency, respectively. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.4 dB at 400 kHz, 1.3 dB at 1800 kHz and 1.5 dB at 2000 kHz, respectively. For all other environments (urban and residential) the increase of the median noise was lower than in the high density urban case.

However, it should be noted, that the in the absence of any reference/recommendation describing the effect of “building exit losses” and losses for built up structures, the first set of results may be underestimating the interference while for the second set of results may be overestimating it. The exact effect of interference impact is somewhere in the presented range.

These levels represent peak charging times that occur at night. During daytime, the median increase in noise was found to be lower.

This study analyses the amount of interference that falls inside a receiver's bandwidth by comparing it to the man-made noise level. This is relevant to cases where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, which are more susceptible to single tone interference (see A3.3.1).

It is noted that, the study does not consider emissions at other frequencies (i.e. spurious/harmonics) nor does it consider the situation of indoor reception, both of which are more relevant for AM broadcasting.

5.9.2 Single-entry Co-Channel Monte Carlo study

The study in ANNEX 8 considered three interference scenarios from WPT devices operating at 400 kHz, 1650 kHz, and 2000 kHz with a maximum transmit level of -15 dBµA/m at 10 m to radio services receiver operated at the same frequency.

At distances where magnetic coupling is dominant, 10 dB attenuation of attenuation for 30% of cases has been assumed in urban scenario.

In cities and considering BEL in 30% of cases, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 11 and 14 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 7 and 9 m.

In cities and without BEL, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 12 and 15 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 7 m and 10 m.

In residential areas and without BEL, emissions due to WPT as seen by the radio receiver fall below the median level predicted in Recommendation ITU-R P.372 for separation distances between 15 and 18 m, and fall below the level from actual measurements of radio noise in the Netherlands for separation distances between 9 and 13 m.

This single entry study is a worst case analysis, since it assumes that the WPT emissions are always co-channel to the radio service receiver.

This study compares the median Interference level to a median man-made noise level and identifies the point below which the interference exceeds the man-made noise level. This is relevant to cases where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, which are more susceptible to single tone interference (see A3.3.1).

It is noted that, the study does not consider emissions at other frequencies (i.e. spurious / harmonics) nor does it consider the situation of indoor reception, both of which are more relevant for AM broadcasting.

ANNEX 1: STUDIES INTO IMPACT OF WPT EMISSIONS ON THE AMATEUR SERVICE

This annex contains the results of studies into the potential impact of emissions from WPT devices on communications in the amateur service.

It is divided into seven sections:

1 Assessment of median signals in the amateur service

2 Assessment of the potential interference from a single WPT device

3 Review of current emission limits

4 System tests on production systems

5 Protection considerations

6 Derivation of protection level

7 Summary of all studies in the Annex

Consideration is only given to low power systems operating in the 100-148.5 kHz range. Data for the analysis is drawn from published information about the amateur service, WPT systems and from existing reports and studies in CEPT, ITU and CISPR/CENELEC.

Section 3.2 of this Report briefly describes the characteristics of the amateur service.

A1.1 ASSESSMENT OF MEDIAN SIGNALS IN THE AMATEUR SERVICE

In considering the potential impact of WPT devices on radio communications systems, the typical level of signals in the relevant radiocommunications service is an important input in considering protection issues. This section of the Annex provides information about signals measured with a software-defined radio (SDR) in the amateur bands, drawn from off-air measurements, and overlays as reference points the spurious emission limits defined in ERC Recommendation 74-01 [11] for inductive SRDs.

A1.1.1 The measurement objective

The measurements set out to determine two things:

- The general level of signals in the amateur service. There are no minimum service levels defined in the amateur service and it is a "low signal" service. The off-air measurements conducted provide detail on the actual levels of signal in everyday communication;
- The background noise level at the rural test site[8].

Equipment used comprised the following:

A wideband calibrated SDR receiver RSP1A: https://www.sdrplay.com/docs/RSP1Adatasheetv1.9.pdf;

- SDR software giving access to FFT length data to allow accurate conversion of measurements to other bandwidths: https://www.sdrplay.com/docs/SDRplay_SDRuno_User_Manual.pdf;
- A calibrated signal source Elecraft XG3: https://elecraft.com/products/xg3;
- A vertical monopole - Titanex V160HD (feed point at ground level);
- A vertical monopole for 10 MHz (feed point 1m above ground);
- A three-element Yagi antenna (SteppIR 3-element yagi) at 12m above ground;
- A screened 50Ω termination resistor.

[8] 52.480301 N, 2.856970 W - England

Three sets of measurements were taken:

- The noise level with the input to the receiver terminated with 50Ω;
- The noise level with the antenna connected;
- The spectrum of signals with the antenna connected.

In carrying out these tests, it became evident that measurements of background noise levels using an SDR are not straightforward, and that care is needed to understand how the relevant SDR software conducts an analysis of the FFT bins in the receiver. Initial tests with two types of SDR software (SDR# and SDR Console) yielded inaccurate results. These software packages did not allow access to the FFT data and so misleading noise bandwidth data was measured. A third software package and SDR (RSP1A) gave full information on the FFT length and resulting measurement bandwidth which was validated as accurate to within the measurement accuracy of the system.

Measurements are only presented for the 1.8-14 MHz amateur bands as the maximum impact of WPT emissions is expected in this part of the spectrum.

A1.1.2 Measurement steps

A1.1.2.1 Calibration

A calibrated 50 Ω signal source was injected into the receiver on each frequency band measured at various levels. The levels were compared with the dBµV scale on the receiver. The tracking from 0 dBuV to +74 dBuV was seen to be well within +/- 1 dB.

A1.1.2.2 50Ω termination

The system noise was measured to confirm that the receiver noise factor would not influence the overall measurement integrity. The measurements confirmed a suitably low level of receiver noise to conduct valid measurements, with inherent noise being at least some 15 dB or more below off-air background noise.

A1.1.2.3 Off-air measurements

Vertical monopoles were generally used for the off-air measurements (but a 3-element yagi antenna 7.4 dBi forward gain was used for 14 MHz). They had antenna factors as shown in Table 13. The table also notes the off-air background noise at the test site.

Table 13: Antenna factors of the antennas used in the tests

Frequency (MHz)	Antenna	Gain dBi	Gain (G) multiple	Antenna factor	Background noise dBuA/m
1.8	Vertical monopole	0	1.00	-24.7	-56.1
3.5	Vertical monopole	0	1.00	-18.9	-56.0
7	Vertical monopole	1.2	1.32	-14.1	-58.3
10	Vertical monopole	0	1.00	-9.8	-56.1
14	3 element Yagi	7.4	5.5	-14.0	-60.6

Spectrum plots were then taken of amateur service traffic, together with a note of the background RMS noise level. Measurements were taken late afternoon with the exception of 1800 kHz where the measurements were taken in the evening to ensure presence of radiocommunications traffic. However, checks were taken at other times of the day to ensure that the data presented is suitably representative. There are times of day when signal levels are significantly lower than shown.

A1.1.3 Results

Spectrum scans were taken for the 1.8, 3.5, 7, 10.1 and 14 MHz amateur bands. As an example the scan for the 7 MHz amateur service spectrum is shown below. For the purpose of comparison, lines have been added showing the emission levels ERC Recommendation 74-01 [11] at 10m from the WPT device. Data at 20m has also been included in the case of the CISPR proposal.

Conversion of all data has been carried out to ensure that a consistent RBW is used for all data – noise, signals, emission limit lines.

It will be noted that the general level of signals and signal/noise ratio is broadly consistent with that shown in Figure 16, which suggests mean level of signals in the amateur service of 15-20 dB above noise level. For the purpose of this study, the modelling has been done assuming that the receiving antenna is a magnetic loop, although the signal levels measurements have been undertaken using E-field antennas and converted to H-field units.

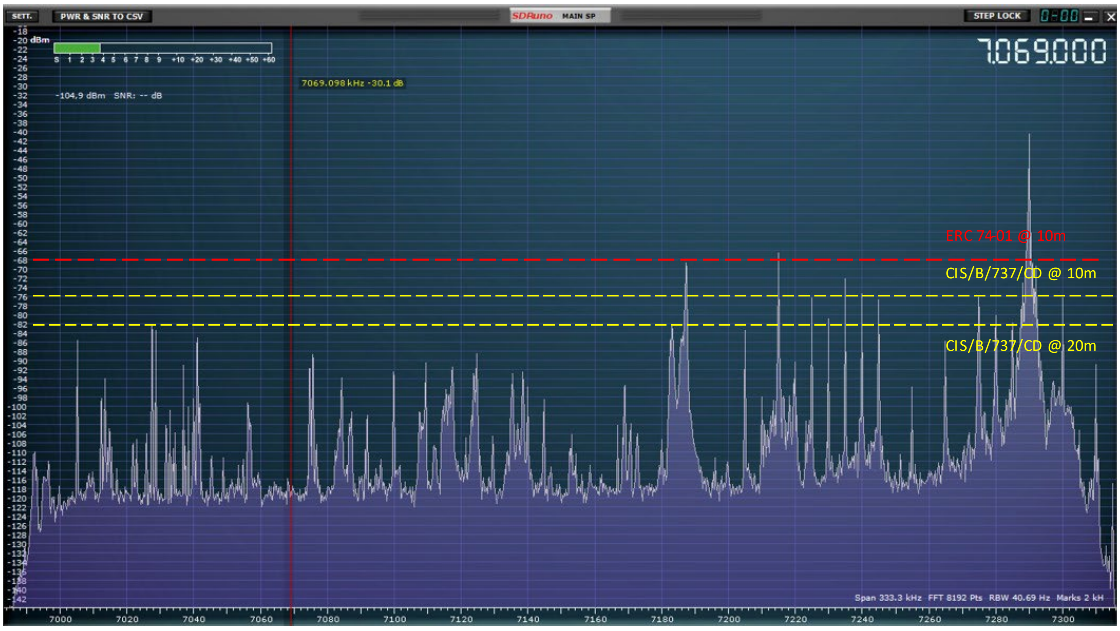


Figure 16: 7 MHz spectrum – late afternoon March 2021

Measurement bandwidth= 3 kHz;
FFT BIN = 40.69 Hz;
Noise in SDR RBW = -104.9 dBm

Outputs from calculation:

- ERC Recommendation 74-01 [11] level: -67.7 dBm scale;
- CIS/B/737/CDV level: -75.7 dBm scale;
- Noise level in 9.5 kHz (compromise between ERC Recommendation 74-01 and CIS/B/737/CDV RBWs): -57.9 dBµA/m;
- Median signal level approximately -45 dBuA/m.

These results can be taken as being representative of the measurements made in other parts of the amateur spectrum in this study, The study has measured the typical levels of signals in the amateur service bands between 1.8 and 14 MHz. It shows a broadly consistent result, from which it will be seen that:

a) The measured level of signals in one rural location in the amateur service bands indicated have S/N ratios of some 10-30 dB at the receiver with a median of some 20 dB. Median signal levels were typically -45 dBuA/m.

b) According to measurements from an SDR at one location, emissions at the limits of ERC Recommendation 74-01 [11] at a measurement distance of 10 m could exceed the levels of amateur service signals by 10-30 dB or more when using a magnetic loop antenna.

When using an E-field antenna, the comparative levels cannot be stated for sure, but for 7, 10 and 14 MHz at least, 10 m spacing places the antenna in the far field and so emissions are likely to be close to the H-field levels converted in the conventional way.

A1.2 POTENTIAL INTERFERENCE FROM A SINGLE WPT DEVICE

Data provided by WPT developers can be used to help model the likely levels of interference should WPT devices operate at the current unwanted emission limits.

Earlier in this Report, indications are given of projected installed densities for low power WPT devices. Using this data, a uniform distribution of these units on a grid has been used, the grid spacing is derived from the projected installed density of devices. For example, an installed density of 5000 units/km^2 gives a grid of 14 m spacing. These grid spacings can then be developed to ascertain distances from each point source for assessing emission levels (see Figure 17).

There are two distances for consideration:

- The half-way point between two "point sources" (Emission point A). Self-evidently this is half the grid spacing. At this point, the victim receiver is subject to emissions of equal strength from two WPT systems (and lower emissions from others);
- The furthest distance that a victim receiver can statistically be located – Emission point B - is simply determined through Pythagoras (7 x √2). At these points the victim receiver is subject to emissions at equal strength from the four nearest systems. This is the maximum distance a receiver can be located from a WPT device in this deployment density.

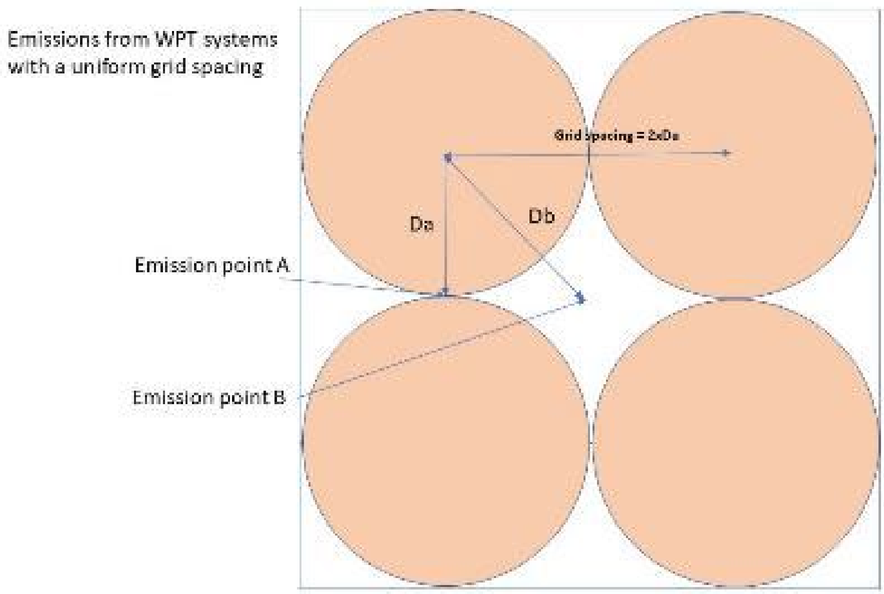


Figure 17: Azimuth plot - λ/2 dipole

In summary, the modelling shows that receivers in the residential environment at the projected deployment density of WPT may not expect separation distances which will reduce emissions much below those measured at 10 m from the WPT device. This result is based on the assumptions that the deployment of WPT devices is only in a single horizontal plane which is unlikely.

The probability of frequency coincidence can be calculated by considering the following factors:

- The operating frequency of the WPT and its stability;
- The presence of both even and uneven harmonics;
- The bandwidth of the amateur service receiver;
- The number of devices potentially affected.

In the case of J3E reception, the bandwidth is 2.7 kHz. The frequency of the WPT system is taken as 100-148.5 kHz for the purposes of this assessment.

The probability of interference of the fundamental, through frequency coincidence, is given by:

$$BW_{rx} * 100/F_{op} \quad (1)$$

Where:

- BW_{rx} is the receiver bandwidth;
- F_{op} is the operating frequency of the WPT. So, for a single-entry case, the probability of interference from a fixed frequency WPT device operating at 100 kHz is just under 3%.

Emission point A is affected by two devices at this level (Σ 6% probability) and emission point B is affected by four devices at a slightly lower level (Σ 12% probability) and by yet more devices at decreasing levels which are further away. In it is noted that most of the WPT devices tested had a variable frequency characteristic. Account needs to be taken of this variability of the operating frequency and for the purposes of this study a factor of 2x is taken to allow for this, resulting in a 24% probability of frequency coincidence. This assumes a degree of integration of interference over time – i.e. a time slice selected such that it encompasses the variability of frequency in some devices. But it ignores the interference of other devices further away from the reception point.

A1.3 THE CURRENT EMISSION LIMITS

A1.3.1 At the operating frequency

The SRD emission limits at the operating frequency, currently defined in ERC Recommendation 70-03, annex 9 (Frequency Band b) include a limit of +42 dBµA/m at 135-140 kHz. Modelling suggests that this will result in emissions some 50 dB above man-made background noise at those frequencies with 10 m separation.

This shows that proximity of a WPT device could represent harmful interference to the amateur service in the 136 kHz band. Although the man-made noise is significant at this frequency in residential environments, modelling suggest that this will still require a separation distance of some 50 m or more to avoid harmful interference.

The other amateur spectrum in the LF range, that might be impacted by emissions at the operating frequency, is the allocation at 472–479 kHz. Here, the emission level defined in ERC Recommendation 70-03 Annex 9 is -8 dBµA/m, which is 50 dB lower than that at 136 kHz. It is unlikely that this will cause harmful interference to amateur service stations operating in the 472 kHz band.

A1.3.2 At other frequencies

To assess the potential interference to amateur service communications at other frequencies, the typical level of amateur signals is determined first. Section 4.1 provides the statistical distribution of amateur signal-to-noise ratios with respect to background noise and A1.1 assesses the mean level of amateur signals. The median signal-noise ratio is around 15 dB and the median signal level some -40 to -45 dBuA/m. Recommendation

ITU-R F.240 [10] suggests a protection ratio of 13 dB for the amateur service (with some variations based on transmission mode and interferer characteristic). This implies a maximum level of interferer around 0 to +2 dB compared to background noise.

Figure 18 shows the current unwanted emission limits and the noise levels in Recommendation ITU-R P.372 [7]. Unwanted emissions at the current unwanted emission limits from a transmitting device operating at the ERC Recommendation 74-01 [11] limits at a distance of 10 m from the service antenna can exceed the noise level by 40-50 dB. The basis for the data in this graph is set out in ECC Report 289, annex 4 [6].

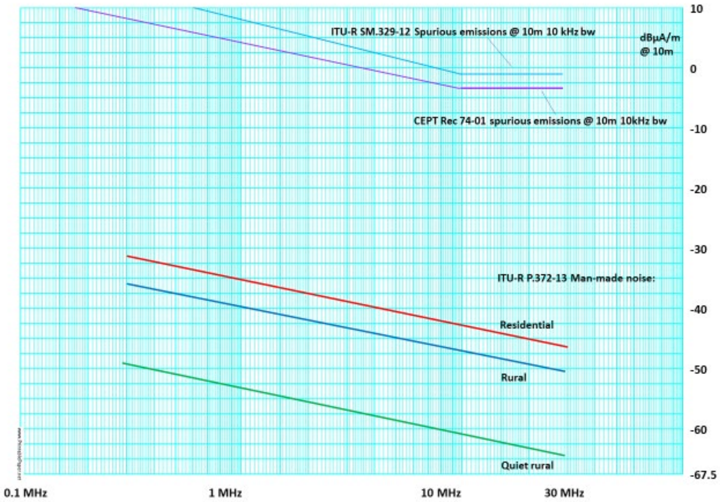


Figure 18: Graphical representation of the current unwanted emission limits compared with background noise levels in Recommendation ITU-R P.372

The man-made noise lines from Recommendation ITU-R P.372 [7] have been converted to H field units using the free space impedance of 377 Ω. At most frequencies, the noise sources will be far field. Even where it is not, at distances > 0.5 radians (λ/6π) modelling shows that the error can be assumed to be no more than 3 - 4 dB.

Decay rates of emissions from a WPT unit in the near field are 60 dB/distance decade. When transition takes place to the far field (at a distance of some λ/2π) the rate decreases to 20 dB/distance decade. This is shown in ETSI EN 300 330, annex I [12].

Using this data, the plots in Figure 19 shows the projected level of emissions at 5 MHz at increasing distance from a transmitting device operating at the current unwanted emission limits.

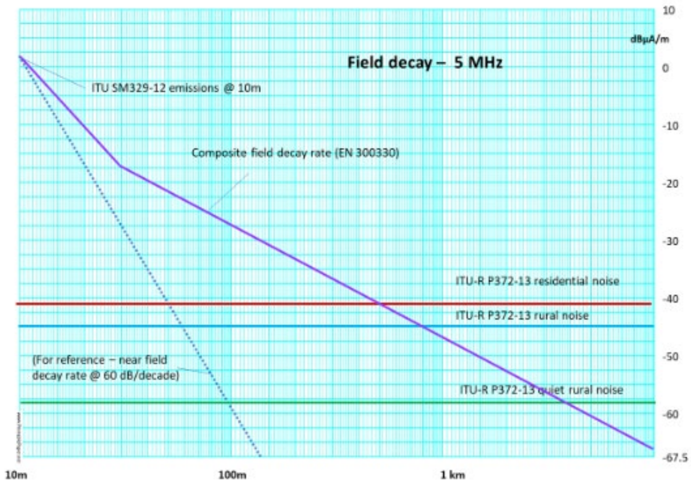


Figure 19: Decay rate of emissions with distance at 5 MHz

Figure 19 assumes a device operates with unwanted emission levels up to the current unwanted emission limits of Recommendation ITU-R SM.329 [40], almost identical to ERC Recommendation 74-01 [11]. If there were adequate protection distance between the device and the radio receiver, this may not be a problem. Modelling of the projected installed density based on data provided by WPT manufacturers enables an assessment to be made of the typical physical separation distance. Examination of the emissions of WPT systems enables an assessment to be made of the worst-case probability of frequency coincidence between unwanted emissions from the WPT system and the radiocommunications channel in use. Both these factors were considered earlier in this Annex.

A1.4 SYSTEM TESTS - LOW POWER GENERIC WPT

A1.4.1 The measurement process

Extensive measurements were carried out on a range of popular 5-15 W WPT devices to assess the pattern of emissions from the devices. The tests were carried out at an electrically quiet site in Buckinghamshire, UK, in June 2019. Representatives from the Wireless Power Consortium, IARU and Copsey Communications were present along with other organisations having an interest in the issue.

Measurements of spurious emissions were carried out at three distances from the equipment under test (EUT) – 1 m, 3 m and 10 m. Plots of spurious emissions were recorded, allowing comparisons to be made with the existing emission limits for inductive SRDs.

The tests were carried out both in a screened room and on an open area test site (OATS) using standard EMC test equipment. Tests were carried out using various designs of loop antennas and measurements of off-air broadcast signals were made using laboratory field strength measuring equipment.

The equipment used for the measurements was:

- Rohde and Schwarz FSH8 portable spectrum analyser operating from internal battery;
- Schaffner-Chase HLA6120 active loop antenna (600 mm diameter) with battery pack.

In the screened room, a mobile phone was placed on each charging pad with near optimum alignment, i.e. near the centre of the active area of the pad so that the WPT device was in power transfer mode. Each charging pad was then rotated about three axes to find the maximum emission at the fundamental frequency. The slant distance from the EUT to the centre of the measuring loop was 1 m.

For all tests the mobile phone was kept in an almost uncharged state, to ensure that the WPT devices were actively charging when powered up. This derived a frequency plot showing the unwanted emissions from each device. An example is shown Figure 20.

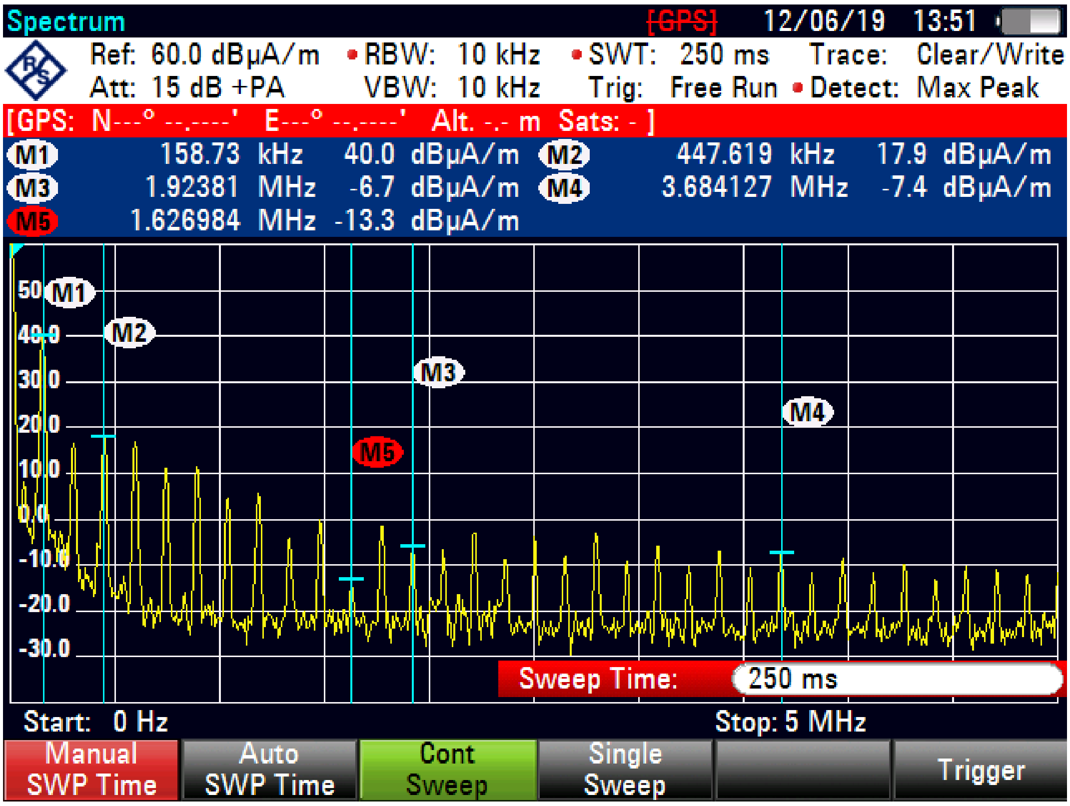


Figure 20: Illustrative frequency plot

In each case, the charging pad was horizontal on the bench and the mobile phone was deliberately misaligned in two directions on the charging pad to find the point just before the charger stops charging. The purpose of this test was to find the range of operating frequencies and determine by how much the emissions increased for each EUT due to variable alignment between the phone and the charging pad.

Measurements were then conducted in an open area test site (OATS). Measurements in such an environment are always complicated by the level of off-air broadcast and other radio services. However, the measurements were conducted in order to measure in a "real world" environment and also to check the decay rate of emissions with distance.

In terms of the latter, the 1 m to 3 m distance showed a reduction of emissions of around 30 dB which is consistent with the theoretical decay of 28.6 dB over this distance for an H-field point source under near field or induction field conditions.

A1.4.2 Tabular presentation of results

The accumulated results of measurements are shown in Table 14.

Table 14: Summary of measured results

EUT	Freq (kHz)	@ 1 m (dBµA/m)	@ 10 m derived (dBµA/m)		Freq (kHz)	@ 1 m (dBµA/m)	@ 10 m derived (dBµA/m)
A	134	47.9	-12.1	**A**	134	57.2	-2.8
aligned	400	29.2	-30.8	**misaligned**	400	31	-29
	670	21	-39		670	22.3	-37.7
	938	16	-44		938	13	-47

EUT	Freq (kHz)	@ 1 m (dBµA/m)	@ 10 m derived (dBµA/m)		Freq (kHz)	@ 1 m (dBµA/m)	@ 10 m derived (dBµA/m)
	1206	11	-49		1206	10	-50
	1474	7	-53		1474	4	-56
	1742	3	-57		1742	2	-58
	2010	-1	-61		2010	-3	-63
C	158	40	-20	**C**	110.8	58.4	-1.6
aligned	474	18	-42	**misaligned**	332.4	36.8	-23.2
	790	17	-43		554	29	-31
	1106	11	-49		776	22	-38
	1422	11	-49		997	18	-42
	1738	5	-55		1219	13	-47
	2054	6	-54		1440	11	-49
D	222	36.6	-23.4	**D**	116.5	57.4	-2.6
aligned	666	16	-44	**misaligned**	350	34.4	-25.6
	1110	7	-53		582	26	-34
	1554	-3	-63		816	20	-40
	1998	-12.1	-72.1		1049	18	-42
	2442	-10	-70		1281	16	-44
	2886	-1.4	-61.4		1514	14	-46
E	182	41	-19	**E**	116	58.5	-1.5
aligned	546	19.3	-40.7	**misaligned**	348	36.1	-23.9
	910	12	-48		580	28	-32
	1274	7.7	-52.3		812	21	-39
	1638	4	-56		1044	18	-42
	2002	0.4	-59.6		1276	13	-47
	2366	-2	-62		1508	10	-50

The derived field strengths at 10 m distance in Table 14 above assume that the EUT can be regarded as an H-field 'point source' where the dimensions of the coil are small compared to a 1 m measurement distance and that all significant radiation is from the coil not radiated or conducted via the power cable to the EUT. It is also assumed that 10 m is still in the near field or induction field region. This assumption is valid for frequencies below 5 MHz.

A1.4.3 Graphical presentation of results

The above results are presented below in graphical form. The data represents the worst-case misalignment of the mobile phone on the charger. It will be seen that at 1 MHz, the derived emission levels at 10 metres for all units tested are some 40 dB below the limit level specified in ERC Recommendation 74-01 [11]. More importantly, at frequencies above 1 MHz, the derived levels at 10 m are below the levels requested by the amateur and the fixed/mobile services for WPT unwanted emissions.

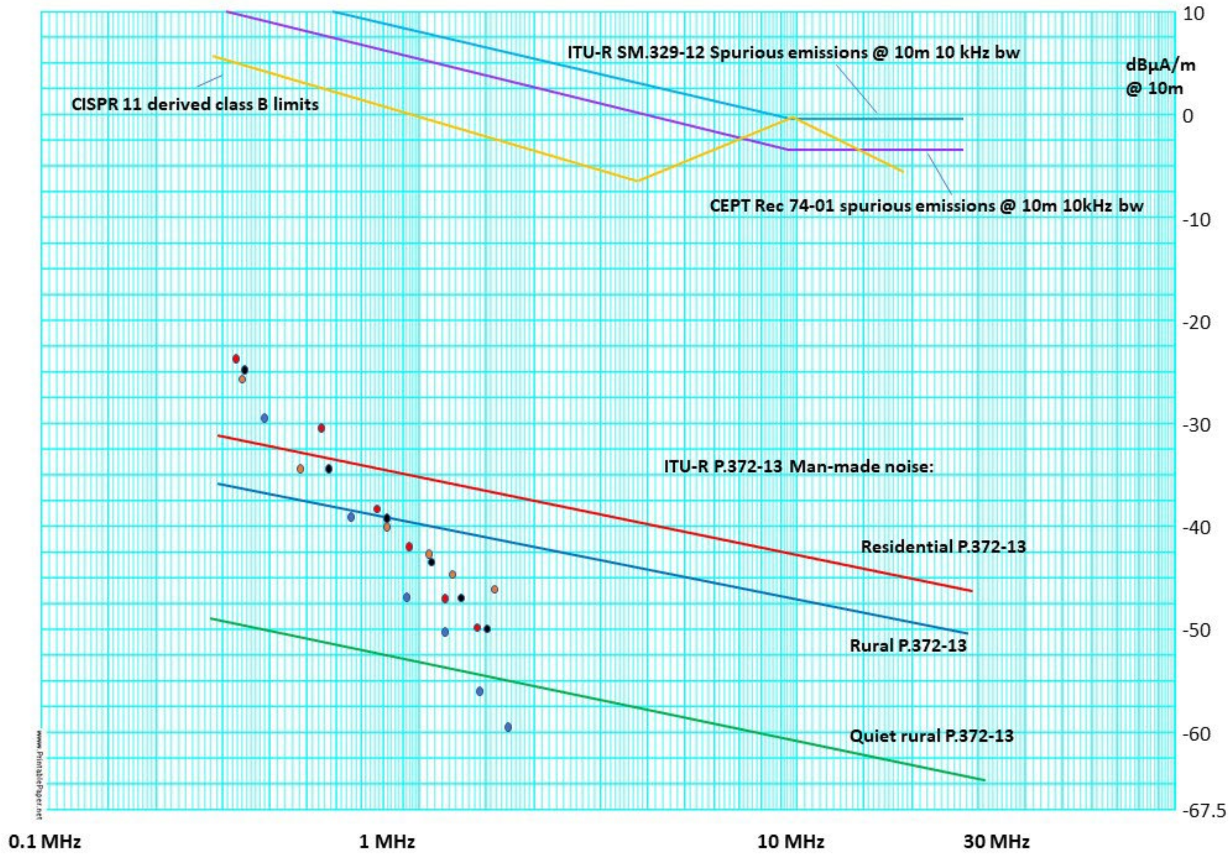


Figure 21: Graphical presentation of results

A1.4.4 Summary of findings of measurements

- Fundamental frequencies are in the range 113 -222 kHz with significant harmonics that extend up to over 2 MHz. In some cases, the harmonic levels continue to fall above 2 MHz but in other cases, they continue with relatively constant amplitude from 2 MHz up to 5 MHz or 10 MHz. No case was detected where the harmonic emissions rose again with increasing frequency;
- One EUT has a fixed operating frequency, but the others are variable. With variable frequency operation, the frequency varies with alignment of the phone on the charging pad;
- When the phone is misaligned on the charger, field strength measured at 1 m distance is up to 23 dB higher than with optimum alignment;
- When a variable frequency charging pad is idle, it repeatedly 'pings' to check whether a resonant load is within range. This involves generating a swept frequency whose harmonics will sweep across a wide range of frequencies causing a clicking sound on an AM receiver that is sufficiently close;
- Some EUTs also appear to conduct a regular frequency sweep while charging. This may be to check for changes in load alignment that would require a change in operating frequency;
- The use of variable frequency operation greatly increases the probability of interference to radio services, compared to fixed frequency operation;
- Tests on an open area test site have shown that the magnetic field strength reduces with distance at 60 dB per decade as would be expected;
- Some fundamental or harmonic levels at 1 m distance are significant in comparison with LF or MF broadcast signals. The test site was not a 'worst case' location in terms of broadcast field strength, which can be as low as 9 dB(µA/m) for MF or 2021 dB(µA/m) for LF at the edge of the service area. Under these conditions, if a fundamental or a harmonic of a WPT system is close to the frequency of a broadcast signal and if sufficient protection ration is not achieved, then interference may occur particularly if the broadcast receiver uses an H-field antenna such as a ferrite rod antenna (e.g. a portable) rather than a car radio which uses an E-field antenna;

- Harmonic levels in the 1.812.0 MHz and 3.53.8 MHz amateur bands may be significant at 3 metre distance and the use of variable frequency operation by the WPT system increases probability of interference;
- Figure 21 illustrates that the majority of spurious emissions measured at 1 MHz and above would be below the rural man-made noise floor (Recommendation ITU-R P.372 [7]) at 10 m distance.

A1.4.5 Conclusions of measurements

The tests conducted have shown the levels of harmonic emissions from the generic low power WPT device tested are reasonably low and for derived levels at 10 m distance, the majority of worst-case measurements are below the rural man made noise floor (Recommendation ITU-R P.372).

Levels increase with misalignment of the target device, and the emissions have a directional element to them, in that levels can be minimised or maximised in a particular direction by rotating the EUT and target device in three planes.

Whilst the devices all varied considerably in harmonic emissions, the levels are close to those needed to properly protect radiocommunication services at frequencies above 1 MHz. At lower frequencies, the potential for interference at distances less than 10 m increases.

A1.5 PROTECTION CONSIDERATIONS

Radiocommunications services protection ratios are suggested in Recommendation ITU-R F.240 [10]. Most HF radiocommunication services (including the amateur service) rely on operating with a relatively modest signal-to-noise ratio, implying that the received signal is as little as 10-15 dB above the background noise for effective communication.

In considering any impact of unwanted emissions, it should be noted that:

- WPT systems are high duty cycle, meaning the interference from such systems cannot be treated as “transient” or short-term;
- Some generic WPT systems are relatively high power (compared to a conventional SRD);
- As shown elsewhere in this report, generic WPT systems are projected for high density deployment, meaning that proximity to radio receivers is more likely;

A number of WPT systems adjust their operating frequency to achieve optimum coupling to the device being charged. WPT-EV systems are planned to use a relatively low operating frequency, but the higher order harmonics of the operating frequency can lie anywhere in the HF spectrum. ERC Recommendation 74-01 currently sets the limits for unwanted emissions from inductive SRDs as in Table 15.

Table 15: Limits for spurious emissions in ERC Recommendation 74-01

<table>
<tr><td rowspan="5">2.1.3</td><td rowspan="5">Short range inductive devices operating below 30 MHz
(in transmit mode)</td><td>27 dBμA/m, (at 9 kHz then decaying by 10 dB/decade) for 9 kHz ≤ f ≤ 10 MHz *</td></tr>
<tr><td>-3.5 dBμA/m, for 10 MHz < f ≤ 30 MHz *</td></tr>
<tr><td>-54 dBm, for f within the bands: 47-74 MHz, 87.5-118 MHz, 174-230 MHz, 470-862 MHz</td></tr>
<tr><td>-36 dBm, for 30 MHz < f ≤ 1 GHz (except above frequency bands)</td></tr>
<tr><td>-30 dBm, for 1 GHz < f ≤ f_{upper} (see recommend 3)
* H-field antenna at 10 m distance</td></tr>
</table>

The potential proximity of WPT systems to radio receivers/antennas, and assuming that WPT emissions are unstable in frequency or are not all exactly on a common frequency and/or with low levels of phase or sideband broadband noise, then this suggests that unwanted emissions below the following levels are unlikely to cause significant interference to amateur service signals:

-46 dBµA/m at 300 kHz reducing by 7 dB per frequency decade to -60.0 dBµA/m at 30 MHz.

This level has been derived taking into account the Recommendation ITU-R F.240 [10] protection ratio as applied to the median signals in the amateur spectrum and also the conventional measure of I/N as better than 6 dB. Both methods yield comparable results The measurements reported in A1.4 above suggest that the performance of those low power generic WPT devices tested is relatively close to the suggested protection level set out above at frequencies above 1 MHz.

A1.6 DERIVATION OF PROTECTION LEVEL

Although Recommendations ITU-R F.240 and ITU-R M.1044 point to suggested protection ratios for the amateur service, the service does not operate with minimum signal service levels. This makes it more challenging to assess the impact of interferers on traffic in the amateur service. A structured multi-dimensional approach to develop a means of assessing the interference potential from WPT devices has been adopted, which is described below.

A1.6.1 Protection ratio

Recommendation ITU-R M.1044 states:

5) that Recommendation ITU-R F.240 – Signal-to-interference protection ratios for various classes of emission in the fixed service below about 30 MHz, may be used for sharing studies involving the amateur services and other services unless more specific technical information is available.

Furthermore Table 1 of Recommendation ITU-R F.240 shows suggested protection ratios of various combinations of interferer and victim service. The ratios vary based on mode of transmission. For the purposes of defining the interferer, A1A has been used for both victim and interferer mode, the latter as there is no provision for continuous carrier mode in the Table 1 of ITU-R F.240.

Taking a mean of the various mode combinations relevant to the amateur service suggests a protection ratio of around 13 dB could be appropriate. RBW for A1A can be taken as 500 Hz.

A1.6.2 A noise level-based approach to determine signal and protection levels

This approach involved taking S/N ratio data of amateur service signals from a large global universe of automated monitoring stations in a 500 Hz bandwidth. This leads to a profile of amateur signal levels, with a 500 Hz RBW mean s/n ratio of around 17 dB.

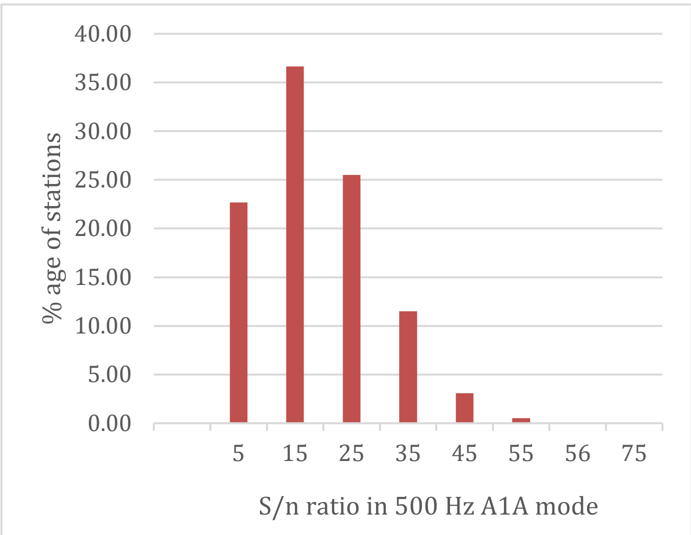


Figure 22: Distribution of typical S/N ratio in amateur service communications

Based on an assumption of Recommendation ITU-R P.372 residential noise levels at each automated receiver site (almost certainly a pessimistic view) it is possible to assess likely signal levels from the above data, using a 500 Hz RBW:

1.8 MHz:
- P.372 median residential noise level = -49.5 dBuA/m;
- This gives mean amateur signals of -32.5 dBuA/m;
- F.240 protection ratio (minimum) = 13 dB;
- Suggesting an interferer maximum level = -45.5 dBuA/m.

30 MHz:
- P.372 median residential noise level = -58.9 dBuA/m;
- This gives mean amateur signal levels of -41.9 dBuA/m;
- F.240 protection ratio (minimum) = 13 dB;
- Suggesting an interferer maximum level = -54.9 dBuA/m.

A1.6.3 A measurement basis to determine signal levels

Section A1.1.3 of this document includes a brief summary of measurements conducted using calibrated equipment to assess typical signal levels in the amateur service.

This confirmed that the median signal level is of the order of -40 to -45 dBuA/m in the lower HF range, suggesting a maximum interferer level to achieve the F.240 protection ratio, of -53 to -58 dBuA/m.

A1.6.4 The approach often adopted by ITU-R WP5A – I/N

ITU WP5A often assesses protection requirements on the basis of I/N better than -6 dB. Therefore, taking the noise medians at the limits of the whole range from 300 kHz to 30 MHz, and considering typical RBW for A1A and J3E reception, a residential noise profile as follows is seen:

Table 16: Noise profile

Frequency	500 Hz RBW	2700 Hz RBW
	P.372 median noise	P.372 median noise
300 kHz	-43.5 dBµA/m	-36.2 dBµA/m
30 MHz	-58.9 dBµA/m	-51.6 dBµA/m

Taking a mid-point between the two noise levels, this gives a suggested noise level of:
- 300 kHz: -39.86 dBuA/m;
- 30 MHz: -55.25 dBuA/m.

Applying the – 6 dB I/N figures gives maximum interferer of
- 300 kHz: -46 dBuA/m;
- 30 MHz: -61 dBuA/m.

Summarising these three triangulation points we get the following range of permissible interferer level:

Table 17: Permissible interferer level

Frequency	Noise-based	Measurement basis	WP5A basis	Proposal
300 kHz	-39.5 dBµA/m (Note 2)		-46 dBµA/m	-46 dBµA/m
30 MHz	-54.9 dBµA/m	-53 dBµA/m (Note 1)	-61 dBµA/m	-60 dBµA/m
Note 1: Varies by frequency Note 2: Interpolated back from 1.8 MHz				

It is recognised that there is some debate about the actual level of noise in the residential environment. The measurements submitted to the ITU for inclusion in the noise database suggest that median noise in the residential environment could be around 6 dB higher than the Recommendation ITU-R P.372 median levels suggest. The rural environment shows a similar or slightly larger level of degradation.

A1.6.5 Summary

The above paragraphs explain the three-pronged approach to determine appropriate protection requirements for the amateur service in MF and HF bands.

A1.7 SUMMARY OF STUDIES IN THIS ANNEX

The above analysis indicates that the projected installation density of WPT devices may not permit a separation distance much above 10 m in many environments. The co-existence of amateur service radio communications and WPT systems in the same environment could potentially cause harmful impact on amateur radio communications operating in the vicinity should unwanted emissions, measured at 10 m be above the suggested protection level suggested in section A1.5.

Those low power WPT systems which have been tested, however, appear to offer unwanted and harmonic emission levels which may allow satisfactory coexistence with radiocommunication services subject to all products matching the performance of the samples tested. As WPT power levels increase the potential for interference may become more significant.

ANNEX 2: PROTECTION OF RADIO SERVICES FROM INTERFERENCE CAUSED BY SHORT RANGE DEVICES - RELEVANT EXISTING DOCUMENTS

A2.1 RECOMMENDATION ITU-R BS.1895

Recommendation ITU-R BS.1895 “Protection Criteria for Terrestrial Broadcasting Systems” [32] recommends:

1 that the values in recommends 2 and 3 be used as guidelines, above which compatibility studies on the effect of radiations and emissions from other applications and services into the broadcasting service should be undertaken;

2 that the total interference at the receiver from all radiations and emissions without a corresponding frequency allocation in the Radio Regulations should not exceed 1% of the total receiving system noise power;

3 that the total interference at the receiver arising from all sources of radio-frequency emissions from radiocommunication services with a corresponding co-primary frequency allocation should not exceed 10% of the total receiving system noise power.

While this Recommendation is specific to the (sound) Broadcasting Service, similar Recommendations exist for other services.

A2.2 EU COMMISSION DECISION ON HARMONISATION OF THE RADIO SPECTRUM FOR USE BY SHORT-RANGE DEVICES

In the European context, setting standards for high power inductive power transfer units such as WPT systems under a regime designed for SRDs is at variance with EU Commission Decision 2017/1483 [36] which states in Article 2 that:

For the purpose of this Decision:

1. ”short-range device’ means radio transmitters which provide either unidirectional or bidirectional communication and which transmit over a short distance at low power”;

2. ”non-interference and non-protected basis’ means that no harmful interference may be caused to any radio communications service and that no claim may be made for protection of these devices against harmful interference originating from radio communications services”.

A2.3 ERC RECOMMENDATION 70-03

ERC Recommendation 70-03 “Relating to the use of Short Range Devices (SRD)” [31], similarly defines SRD as:

“The term ‘Short Range Device’ (SRD) is intended to cover the radio transmitters which provide either uni-directional or bi-directional communication which have low capability of causing interference to other radio equipment. SRDs use either integral, dedicated or external antennas and all modes of modulation can be permitted subject to relevant standards. SRDs are not considered a ‘Radio Service’ under the ITU Radio Regulations (Article 1).”

A2.4 REPORT ITU-R SM.2153

Report ITU-R SM.2153-7 “Technical and operating parameters and spectrum use for short-range radiocommunication devices” [37] is an ITU-R text on SRDs which enshrines the assumption that they do not cause interference to radio services and states as part of the definition of a Short Range Device that:

" ..... the term short-range radio device is intended to cover radio transmitters which provide either unidirectional or bidirectional communication and which have low capability of causing interference to other radio equipment.

Such devices are permitted to operate on a non-interference and non-protected basis."

It also states in the introduction:

"SRDs operate on a variety of frequencies. They must share these frequencies with other radio applications and are generally prohibited from causing harmful interference to or claiming protection from those radio applications. If an SRD does cause interference to authorised radiocommunications, even if the device complies with all of the technical standards and equipment authorisation requirements in the national rules, then its operator will be required to cease operation, at least until the interference problem is solved."

A2.5 EMC DIRECTIVE

The EMC Directive [38] is the legal instrument in the EU that provides protection to the radio spectrum and specifically to licensed radio services. The "essential requirements" of the EMC Directive require equipment to 'operate as intended' in its radio environment and to 'not prevent other devices from operating as intended' in this environment. These requirements are achieved through the application of standards that carry presumption of conformity with the Directive. Appropriate standards are under preparation in ETSI and CISPR and CISPR 11 in common with most CISPR publications will be an international standard that can be called up by any country or region (e.g. the EU) to provide protection to the radio spectrum.

A2.6 ECC REPORT 135

ECC Report 135 on "Inductive limits in the frequency range 9 kHz to 148.5 kHz" [41] was intended to review the limits applicable to inductive systems in order to address developments in technology since the publication of ERC Report 44 in 1997. In particular, several types of inductive RFIDs had been introduced since then, many subject to specifications set by ISO and other standards developing organisations, for use in the frequency range of 105.5 kHz to 148.5 kHz. The Report also addressed possible relaxations of the limits for the magnetic field strength required for inductive applications then set out in ERC Recommendation 70-03, annex 9, particularly in the frequency range 70 to 90 kHz.

A2.7 ECC REPORT 67

ECC Report 67 [44] "Compatibility study for generic limits for the emission levels if inductive SRDs" (2005) states that:

"3.2.1.6.3 Analogue broadcasting

For analogue broadcasting service, the protection distances from SRD to the victim broadcast receiver range from 8 to 238 m for the LF,MF and HF bands and a field strength in 10 kHz varying from -5 dBmA/m@10 m to -25 dBmA/m@10 m . In the frequency range 3.95–26.10 MHz (HF band), depending on SRD transmitter power and the considered field strength limit, the calculated protection distances are:

- for field strength -5 dBmA/m@10 m: 146-238 m
- for field strength -10 dBmA/m@10 m: 85-179 m
- for field strength -15 dBmA/m@10 m: 48-134 m
- for field strength -20 dBmA/m@10 m: 21-101 m
- for field strength -25 dBmA/m@10 m: 16-60 m

These distances are very large; consequently, they cannot guaranty the protection of analogue broadcast service operating below 30 MHz. An interfering field strength of -30 dBmA/m@10 m, which ensures a maximum protection distance of 34 m from SRD to the victim broadcast receiver, would be acceptable in case of "indoor to outdoor" or "outdoor to indoor" interference. However, an interfering filed strength of - 30 dBmA/m@10 m will still cause interference to analogue broadcast receiver if the latter operates in indoor in the vicinity of SRD (in the same room for example). As for the LF and MF broadcasting bands, an interfering SRD field strength of -15 dBmA/m@10 m in a 10 kHz bandwidth would be acceptable in case of “indoor to outdoor” or “outdoor to indoor” interference.”

A2.8 ECC REPORT 7

ECC Report 7 on "Compatibility between inductive LF RFID systems and radiocommunication systems in the frequency range 135 – 148.5 kHz" (2002) [45] was intended as a response to the rapidly increasing use of RFID systems operating in the frequency range 135–148.5 kHz and was developed to address concerns regarding compatibility with radio services having primary or secondary allocation in those bands. The objective was to determine a limit on the magnetic field strength that would result in a low probability additional interference cases. The limit of 42 dBμA/m @ 10m was recommended, considering that an 8 dB increase would result in an 85% increase in expected interference cases.

A2.9 ERC REPORT 44

ERC Report 44 “Sharing between inductive systems and radiocommunications systems in the band 9 – 135 kHz” (1997) [47] records that “SE24 collected information on existing primary services and also on inductive loop systems. The phenomena of magnetic fields were examined.”

It was concluded that “there is a risk of interference when:

- A receiver of a primary status service and an inductive system operating at the higher field strength level operate co-channel and within a distance of less than 100 m. This scenario also requires time coincidence and that the inductive system operates at the fringe reception area of the primary service;
- Inductive systems operating at the two field strength levels operate co-channel within a distance below 100 m.

PT SE24 therefore proposed to divide the band 9-135 kHz into sub-bands for the higher and lower field strength levels. This division provides more protection for certain primary services and also for inductive loop systems with the lower field strength level. The proposal leads to an increased availability of spectrum, because the band can be shared in an efficient way between various services, especially since the band is not heavily used in most European countries at present.

The division into sub-bands would not change the status of the current primary services in the whole 9135 kHz band. If an inductive system causes harmful interference to primary service users, the operator of the inductive system is responsible for removing the interference.”

ANNEX 3: DETAILED IN7FORMATION ON THE PROTECTION OF THE BROADCASTING SERVICE FROM GENERIC WPT

A3.1 BROADCAST TRANSMITTER COVERAGE AND PROTECTIONS

A3.1.1 Transmitter coverage noise and interference

The (geographical) extent of coverage from a given transmitter is limited either by background electrical noise (natural, man made and in the receiver itself) or interference from other transmitters. Despite being inexpensive and simple, the majority of AM radio receivers have quite good inherent noise performance and so coverage from a given transmitter can be extensive. The noise limited coverage boundary for a given service is governed by Recommendation ITU-R BS.703 "Characteristics of AM sound broadcasting reference receivers for planning purposes" [23]. This effectively sets the noise limited minimum usable field strength for an AM transmission as:

- Band 5 (LF): 66 dBµV/m; 14.5 dBµA/m;
- Band 6 (MF): 60 dBµV/m; 8.5 dBµA/m;
- Band 7 (HF): 40 dBµV/m; -11.5 dBµA/m.

Assuming that the coverage limit is in the far field, the well known '51.5 dB' (377 Ω) relationship between the electric and magnetic field can be applied. Nearly all AM receivers use ferrite antennas which are sensitive to the magnetic component of the incoming radio signal and so it is appropriate to consider the magnetic figure.

It must be borne in mind that these figures predominantly represent the strength of the carrier component of the wanted signal. Assuming speech modulation, the energy in the information carrying sidebands is typically only 4% of (14 dB lower than) that of the power in the carrier; see Report ITU-R BS-2433 "Assessment of modulation depth for AM sound broadcasting transmissions" [20]:

- Band 5 (LF): 52 dBµV/m; 0.5 dBµA/m;
- Band 6 (MF): 46 dBµV/m; -5.5 dBµA/m;
- Band 7 (HF): 26 dBµV/m; -25.5 dBµA/m.

It will be seen that the strength of this information carrying component for MF is 12.5 dB smaller than the level of interference prescribed in Annex 2 to ERC Recommendation 74-01 "Unwanted Emissions in the Spurious Domain" [11] at 900 kHz and 10 m from the source of interference (900 kHz is the approximate logarithmic centre of the MF broadcast band[9]); an interferer at this level would be 12.5 dB stronger than the wanted signal. However, the limits on unwanted emissions in ERC Recommendation 74-01, mirroring those of the base reference for unwanted emissions in the spurious domain set by Recommendation ITU-R SM.329 [40]," Unwanted emissions in the spurious domain", only represent practicably achievable limits for transmitters, and are not intended to protect radio services in all circumstances. The underlying assumption when planning a radio service, is that care will be taken so as to ensure that there is sufficient separation, in terms of frequency and distance, that receivers in the same or other radio services will not be adversely affected. The assumption in Recommendation ITU-R BS.703 is that the audio signal to noise ratio at the periphery of the service area should be at least 26 dB; not 'Hi-Fi' but a fairly high quality standard nevertheless. In a noise limited environment, quite good reception is still possible outside the minimum signal contours specified in the Recommendation.

The human ear/brain is far less tolerant of a single tone interferer than it is or random noise[10]. For this reason, Recommendation ITU-R BS.560 "Radio-frequency protection ratios in LF, MF and HF broadcasting" [22] suggests that the level for a background interferer should be significantly less than that of random noise where the interference is a single sinusoid. The LF, MF and HF broadcast bands are allocated to the Broadcasting Service on a primary basis and so it is reasonable to expect that any interference might come from another broadcast station where the single frequency carrier represents up to 96% of the energy. Recommendation

[9] The spurious magnetic field limit specified in ERC Recommendation 74-01 exhibits a linear decay with the logarithm of frequency.

[10] It is also less tolerant of another intelligible audio signal in the background and Recommendation ITU-R BS.560 [24] seeks a 40 dB wanted to unwanted signal ratio where the source of interference is, for example, another radio station.

ITU-R BS.560 is written with this in mind[11]. Where the interferer is (predominantly) a single sinusoid, a ‘beat’ or intermodulation is generated which manifests itself as an audible tone in the output of the receiver. This ‘beat’ will be at the difference frequency between the carrier and the interferer. The frequency response of the human ear is far from ‘flat’ and so the tolerable level of the beat varies with its frequency. Figure 1 in Recommendation ITU-R BS.560 (which is reproduced in A3.3.1, Figure 23) shows this variation with frequency which follows the average for human hearing acuity.

A3.1.2 Protection of the AM broadcasting service

Formulating and defining protection criteria for radiocommunication services is within the purview of ITU-R. Protection criteria are frequently enshrined within, or can be readily calculated from, ITU-R Reports and Recommendations. Traditionally, the protection criteria are based solely on radio service related factors such as receiver sensitivity and anticipated received signal strength. A receiver cannot distinguish between ‘wanted’ and ‘unwanted’ radiation. Self-evidently, a radiocommunication receiver will respond in some way to any RF energy of sufficient strength presented to it, irrespective of whether it is the wanted signal or anything else

At this stage it is worth considering what might constitute ‘harmful interference’. The extent to which such interference is ‘harmful’ depends on a number of psycho-acoustic factors and will vary from one listener to another. A WPT device (for example) is likely to generate some stray electromagnetic field with the potential to interfere with radio services. This can be at, or close to, the frequency(s) of operation of the WPT device or at some other, quite likely harmonically related, frequency; the presence of any such extraneous radiation falling within the passband of the receiver will degrade the ability of the system or receiver to defend itself against interference, there are a number of factors which will dictate whether or not the interference is harmful. The major influences, some of which are included for completeness as much as relevance to WPT, are:

- Power Output of the WPT device;
- Separation Distance;
- Intermittency;
- Antenna Directionality;
- Building Penetration Loss and;
- Polarisation Alignment.

A brief explanation of each of these is given in A3.2.

Looking at the specific case of an AM broadcast receiver (LF, MF or possibly even HF) suffering interference from a WPT device, the relevant factors are the strength of the extraneous WPT fields at the operating frequency of the receiver (fundamental or harmonic) and the physical separation between the receiver and the WPT device.

A WPT system is likely to operate continuously during the active operation or charging time which is likely to be at least several minutes and could be up to several hours. During the ‘active’ time, any LF and / or MF receiver in close proximity to the WPT system could be adversely affected if the WPT system is radiating RF energy at levels above those specified in section 4.4.

Some WPT systems have the potential to generate interference outside the ‘active’ time (with no ‘receiving; device taking power) depending on how and if they ‘poll’ to detect the presence of a power receiving device or an obstruction. It is therefore likely that in the case of these devices the major source of interference to broadcasting reception would be from this ‘polling’.

[11] In many instances the extent of coverage is limited more by interference from neighbouring stations than by noise.

A3.2 FACTORS EFFECTING THE IMPACT OF INTERFERENCE

A3.2.1 Power output of the WPT device

Obviously, this will have a significant impact on the propensity of the device to cause harmful interference. The higher the power output, the greater the potential for radiation from such devices causing interference, on harmonically related frequencies, as well as the nominal operating frequency. The mechanisms for radiating significant amounts of RF energy can be many and varied and there is no guarantee that the levels of interference are directly related to the level of the designed power transfer output.

A3.2.2 Separation distance

As shown in Figure 24 in the near field the magnetic field strength falls with the cube of the distance between the source of radiation and the measuring point. The potential for interference therefore increases markedly as the source of interference moves closer to the affected receiver. Conventionally, limits on radiated emissions from any SRDs are defined at a (convenient) measurement distance of 10 m from the device. This, of course, in no way implies that 10 m is a representative or expected separation distance between the SRD and the victim receiver; the stray field has to be specified somewhere.

A3.2.3 Intermittency

A short burst of radiation, even at quite a high level, with a small mark space ratio is much less likely to cause harmful interference to a radio service than a device which operates continuously. On a broadcast radio channel for example a short burst will be perceived as an occasional short click which will have a negligible psycho acoustic effect.

A3.2.4 Antenna directionality

This is probably only relevant in specific cases; if all the extraneous radiation is, for example, directed vertically upward and all the potential victim receivers are spread horizontally around the interfering device, harmful interference is likely to be minimised. The antenna systems in most radio receivers are to some extent directional but it is difficult to ensure that an uncontrolled WPT system will always, or even often, be in the direction of minimum sensitivity.

A3.2.5 Building penetration loss

At the frequencies under consideration, the magnetic permeability of most common building materials (brick, wood, glass, GRP, etc.) is small and so they will be transparent to any magnetic field. Extraneous magnetic fields from WPT devices will not be attenuated by typical walls. In metallic walls and metal framing eddy currents may be generated which will have an effect on magnetic transparency. Most buildings do not have metallic walls or metal framing and so building or wall penetration can’t be regarded as a factor when assessing interference from WPT devices.

A3.2.6 Polarisation alignment

With most radiocommunication systems an attempt is made to align the polarisation of the receiving antenna with that of the transmitter. For example, an LF or MF portable broadcast receiver typically has a horizontally mounted ferrite rod antenna which is most sensitive to the horizontally polarised magnetic component of the wanted signal. LF and MF broadcast transmitters nearly always generate a vertically polarised electric field component and a horizontally polarised magnetic field component thereby optimising the sensitivity of the receiver. If a WPT device could be designed and operated such that the polarisation of its own stray field was at right angles to that of the receiving antenna a little more interference might be tolerable. In practice this is likely to be very difficult to achieve. If the WPT device and the receiver are in close proximity (less than about a quarter of a wavelength at the operating or interfering harmonic frequency – the reactive field region) the actual polarisation of the magnetic (or electric) field is difficult to control or even ascertain. Adding to this the fact that any harmonic radiation from the WPT device might itself not be related to the intended polarisation of the ‘antenna’, it must be assumed that worst-case conditions apply and that the interference is maximised.

A3.3 DERIVATION OF THE MAXIMUM TOLERABLE LEVEL OF INTERFERENCE

A3.3.1 At the receiver

The first step in the derivation of tolerable field strength limits is to consider the wanted and interfering field strengths at the location of the broadcasting receiver itself, whatever the distance this happens to be from the interfering source.

Recommendation ITU-R BS.703 “Characteristics of AM sound broadcasting reference receivers for planning purposes” [21] sets the minimum sensitivity of an AM sound broadcasting sound receiver for planning purposes as:

- Band 5 (LF): 66 dBμV/m; 14.5 dBμA/m;
- Band 6 (MF): 60 dBμV/m; 8.5 dBμA/m;
- Band 7 (HF): 40 dBμV/m; -11.5 dBμA/m.

Recommendation ITU-R BS.560 “Radio-frequency protection ratios in LF, MF and HF broadcasting” [22] outlines applicable protection ratios for interference between AM broadcast signals. Although WPT is not a broadcast signal, it may take the form of a (mostly) un-modulated carrier and to that extent is actually very similar to a broadcast AM signal, during a pause or quiet passage as presented to the receiver. The protection ratios of Recommendation ITU-R BS.560 can therefore be considered a good starting point for deriving radiated emission limits from WPT.

Starting from the planning considerations and protection criteria given in Recommendation ITU-R BS.703 and Recommendation ITU-R BS.560 and noting that broadcast receivers used in and around the home commonly use ferrite rod antennas that respond to the magnetic-field component- H - of the wave, it is convenient to use the corresponding H-field strengths when considering emission limits from WPT equipment. Assuming far-field free-space conditions (which will apply to the received broadcast signal at the receiver antenna) the relationship between the electric and magnetic fields (from Maxwell’s equations) is:

$$\frac{E}{H} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\ \Omega \qquad (2)$$

Where:

- μ_0 is the permeability of free space;
- ε_0 is the permittivity of free space.

This means that the following conversion factors apply:

$$H_{(\frac{\mu A}{m})} = E_{(\frac{\mu V}{m})} \cdot \frac{1}{377} \qquad (3)$$

Which may be expressed as:

$$H_{dB(\frac{\mu A}{M})} = E_{dB(\frac{\mu V}{m})} - 51.5\ dB \qquad (4)$$

So the receiver sensitivities at LF and MF (above) can also be expressed as 14.5 and 8.5 dBμA/m respectively.

Recommendation ITU-R BS.560 is formulated for the protection of one AM radio service from another similar AM radio service[12]. Importantly, this means that both the wanted and interfering signals consist of a high power carrier and much lower power sidebands which carry the modulation. For a typical speech based programme with a 20% (rms) modulation depth the sideband/modulation power is 4% of the carrier power. A quantitative overview of AM radio is given in [25].

[12] It has been assumed that in a frequency band where only AM broadcasting has a primary allocation the principal sources of interference will be other AM broadcastings stations.

The protection ratios for AM broadcasting defined in Recommendation ITU-R BS.560 comprise two components:

a) The co-channel protection ratio (PR) needed when the interferer and wanted signal carrier are on essentially the same frequency so any beat between them is of a frequency below the audible range. In this case the modulation of the interferer is the dominant cause of audible disturbance.

b) If the interfering signal is another radio station on exactly (or close to) the same carrier frequency as the wanted signal, the carrier component, despite being very large can typically be ignored. It has an effect on the linearity of the AM detector which is not noticeable while the interfering carrier is 13 dB or more below the wanted carrier. The wanted signal only has to be defended against the sidebands of the unwanted signal. It is assumed that the ratio of the sideband power to the carrier power is comparable for both wanted and unwanted signals and so the ratio of the sideband powers is the same as the ratio of the carrier powers.

c) Recommendation ITU-R BS.560 calls for a co-channel protection ratio between the wanted and interfering signal (carrier levels) of 40 dB. The Geneva 1975 Regional Planning Agreement Plan for LF and MF radio in some circumstances tolerates a smaller co-channel protection ratio in an attempt to fit more channels into the available spectrum. This relaxation does not extend to any situation where there is an offset between the wanted and unwanted carrier frequencies; the Geneva 1975 plan [23] does not foresee there being any such offsets.

d) The additional relative PR that must be added when the wanted and interfering signals have a frequency difference which will give rise to a continual audible beat tone; this correction depends on the frequency offset, primarily because the frequency response of the human ear is far from 'flat'. If there is an offset between the carrier frequency of the wanted signal and the carrier frequency of the interferer, the unwanted carrier itself (or the interfering sine wave from the WPT system) starts to become psycho-acoustically dominant and, because the carrier is so large, greater protection is needed. Between zero and about +/-5 kHz offset, the protection curve is a similar shape to that for hearing acuity.

e) Note that Recommendation ITU-R BS.560 does not cover the situation where there is no offset between the wanted and the interfering carrier/WPT when and if the latter are un-modulated. As the frequency offset falls below the onset of hearing (or below the low frequency filtering in the receiver) the perturbation mechanism in the receiver is different (at least psycho acoustically). It has been established by the BBC through subjective tests reported in BBC Research and Development White Paper WHP322 [33] that if the interfering carrier/WPT is un-modulated and within a few tens of Hz (onset of hearing) a higher level of interference can be tolerated.

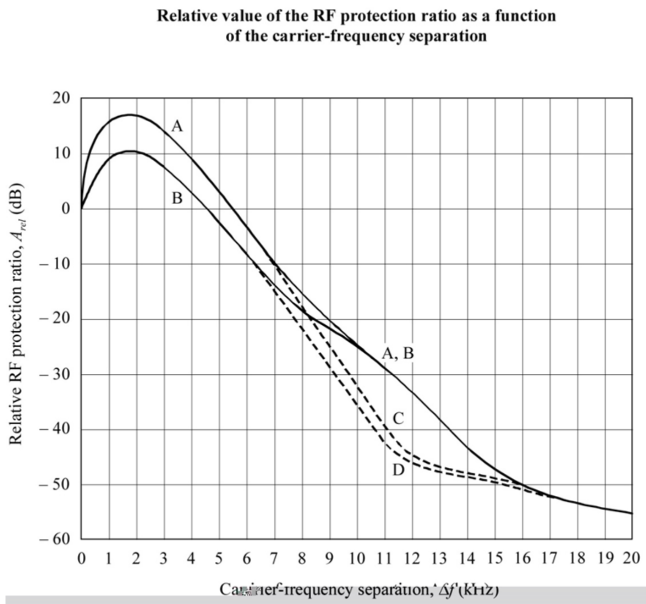


Figure 23: Extract from Recommendation ITU-R BS.560 [22]
Variation of relative protection ratio with offset frequency

The relevant curve is A blending into C. Curve B blending into D is relevant for highly compressed audio material with a high modulation depth while curves A and B above about 7 kHz are pertinent to transmissions with a 10 kHz audio bandwidth. A large proportion of AM transmission are speech based which, even when highly compressed does not result in a high modulation depth. Even though it is in a few instances allowed for in the frequency plan, very few AM transmissions have an audio bandwidth greater than 5 kHz. The frequency offset can be positive or negative.

In the case of an interferer generating single tone interference – for example a WPT device – unless the operating frequency and all of their significant harmonics are carefully aligned with the broadcast frequency (channelling) raster, the relative PR for non-co-channel operation will need to be added. Assuming the WPT frequency to be uncontrolled, it may be assumed that the worst case occurs. Recommendation ITU-R BS.560, figure 1 (reproduced above) shows that the greatest relative PR is approximately 16 dB, corresponding to a frequency offset of around 1.5–2.0 kHz.

For this worst case, the relative PR must be added to the co-channel PR of 40 dB to give an overall PR for WPT interference to AM broadcasting of (40 + 16) = 56 dB.

It therefore follows that the maximum acceptable WPT field strength, at the broadcast receiver location, is given by subtracting this PR from the receiver sensitivity. The maximum acceptable WPT H field at the broadcast receiver location is therefore:

- Band 5 (LF): (14.5 – 56) = -41.5 dBµA/m;
- Band 6 (MF): (8.5 – 56) = -47.5 dBµA/m;
- Band 7 (HF): (-11.5 – 56) = -67.5 dBµA/m.

The minimum field strengths quoted in Recommendation ITU-R BS.703 [21] are based on assumed modulation depth for the AM signal of 30%. Work carried out by the BBC in 2007 and detailed in Report ITU-R BS.2433 “Assessment of modulation depth for AM sound broadcasting transmissions” [35] suggests that a lower assumed modulation depth, 20%, is probably more appropriate. In the period, since Recommendation ITU-R BS.703 was last revised there has been a trend for AM radio to carry a lot more speech and a lot less (popular) music. Speech is characterised by generally lower modulation density and is interspersed with short periods of silence. To reflect the ‘real world’ situation where the most vulnerable AM signals are roundly 3.5 dB quieter than assumed in Recommendation ITU-R BS.703 (20% modulation depth compared with 30%) a further 3.5 dB should be subtracted from the figures derived from Recommendations ITU-R BS.703 and BS.560.

- Band 5 (LF): (-41.5 – 3.5) = -45.0 dBµA/m;
- Band 6 (MF): (-47.5 – 3.5) = -51.0 dBµA/m;
- Band 7 (HF): (-67.5 – 3.5) = -71.0 dBµA/m.

A3.3.2 Noise masking

Further studies carried out by the BBC and detailed in ANNEX 4: reveal that system noise - a combination of environmental (natural and man-made) noise and receiver noise - can mask the effect of a sinusoidal interferer. For a receiver with the performance predicated in Recommendation ITU-R BS.703 the masking effect of system noise would raise the tolerable level of any interfering magnetic field by 8 dB. The figures in A3.3.1 become:

- Band 5 (LF): (-45.0 +8.0) = -37.0 dBµA/m;
- Band 6 (MF): (-51.0 + 8.0) = -43.0 dBµA/m;
- Band 7 (HF): (-71.0 + 8.0) = -63.0 dBµA/m.

A3.3.3 Separation Between the Receiver and the Source of Interference

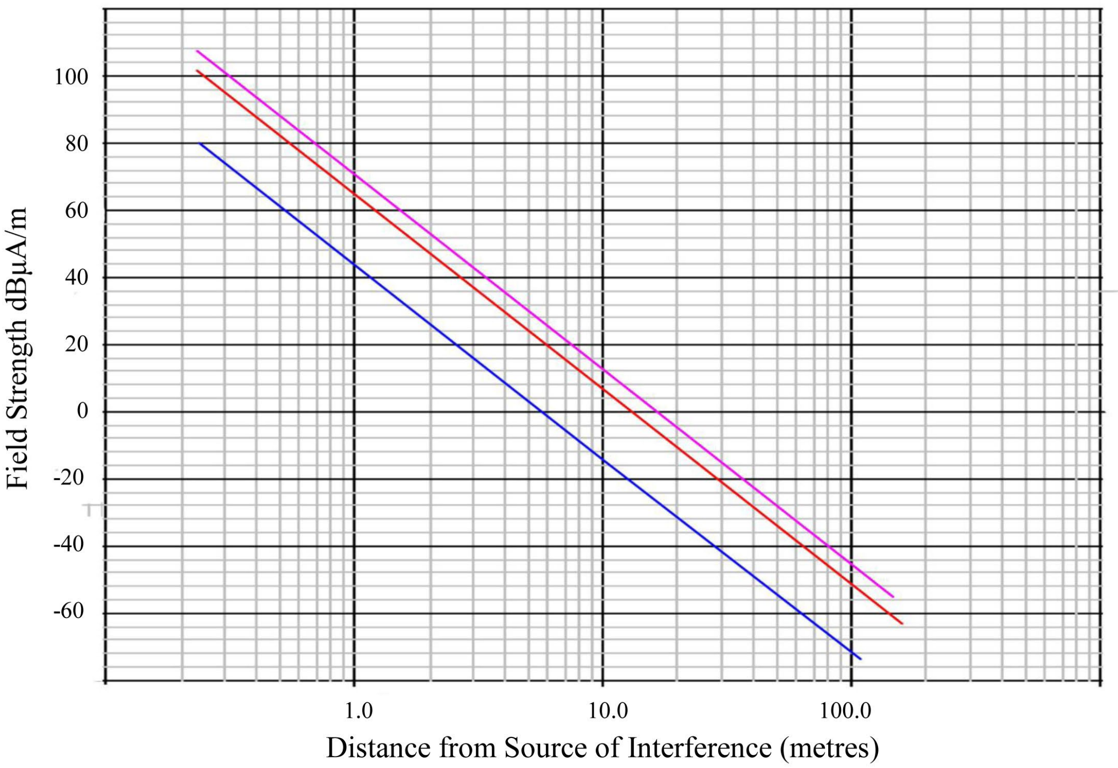
So far, the analysis has concentrated on the conditions pertaining at the receiver itself. Clearly, the separation between the receiver and the source of interference will have a major impact on the propensity for harmful interference actually to occur. The closer the interferer, the greater the effect. The next step in the process of determining whether co-existence is feasible is to consider:

- what assumptions are necessary about the separation distance used for defining an emission limit;
- the range of separation distances likely to be encountered in practice;

- the factors affecting the propagation between the interference source and the broadcasting receiver.

These will depend on the scenarios for WPT use.

The acceptable field strength limits at the location of the receiver can be assessed against the proposed emission limits at the reference distance from the interfering source.



ERC Recommendation 70-03 [31]	LF and MF	(blue line)
ERC Recommendation 74-01 [11]	LF	(pink line)
ERC Recommendation 74-01 [11]	MF[13]	(red line)

Figure 24: Variation of field strength with distance from source

Figure 24 shows that close[14] to the source of the interference the interfering field strength varies considerably with the distance away from the source; 18 dB for a doubling of the separation distance and 60 dB for a factor of ten-fold increase.

By convention, the magnetic field, strength from and SRD is specified at 10 metres reference distance; clearly, it cannot be expected that the separation between a broadcast receiver and a WPT device will actually be 10 metres. In practice, the realistic separation distance for, for example, a mobile telephone charger could be no more than 0.5 metres as a 'worst-case'. A WPT device placed close to a party wall in an apartment block could be separated from a broadcast receiver in a neighbouring apartment by no more than the thickness of a brick wall (the following two figures); at these frequencies bricks and most other traditional building materials are transparent to magnetic fields.

[13] For frequencies above about 500 kHz the gradient of this line flattens to 20 dB/decade beyond about 100 m. At the very highest frequency in the medium wave band this flattening occurs beyond about 30 m.

[14] Close means less than one sixth of a wavelength at the particular frequency (λ/2π). At greater separation distances the inverse square law applies.

Figure 25: Medium density urban housing in Southeast London

Figure 26: Apartment block in Southeast London

It is essential, therefore, that the limits derived earlier for the maximum tolerable interfering magnetic field strength at the receiver should prevail at the relevant minimum separation distance from the WPT device.

As an example, assuming the actual separation to be 1 m, the specified field strength has to be achieved at 1 m from the WPT device. At 10 m from the device (the standard measurement distance and 9 m further away than the victim receiver) the (measured) field strength would be 60 dB smaller than at 1 m. So if the interference performance of the WPT device is to be specified at a 10 m measuring distance, the required field strength would have to be 60 dB smaller than that called for at the victim receiver. Assuming that there are no other mitigating factors, the figures in section A3.3.2 above - normalised for a standard 10 m measurement distance - become:

- Band 5 (LF): (-37.0 – 60.0) = -97.0 dBµA/m;
- Band 6 (MF): (-43.0 - 60.0) = -103.0 dBµA/m;
- Band 7 (HF): (-71.0 - 60.0) = -123.0 dBµA/m.

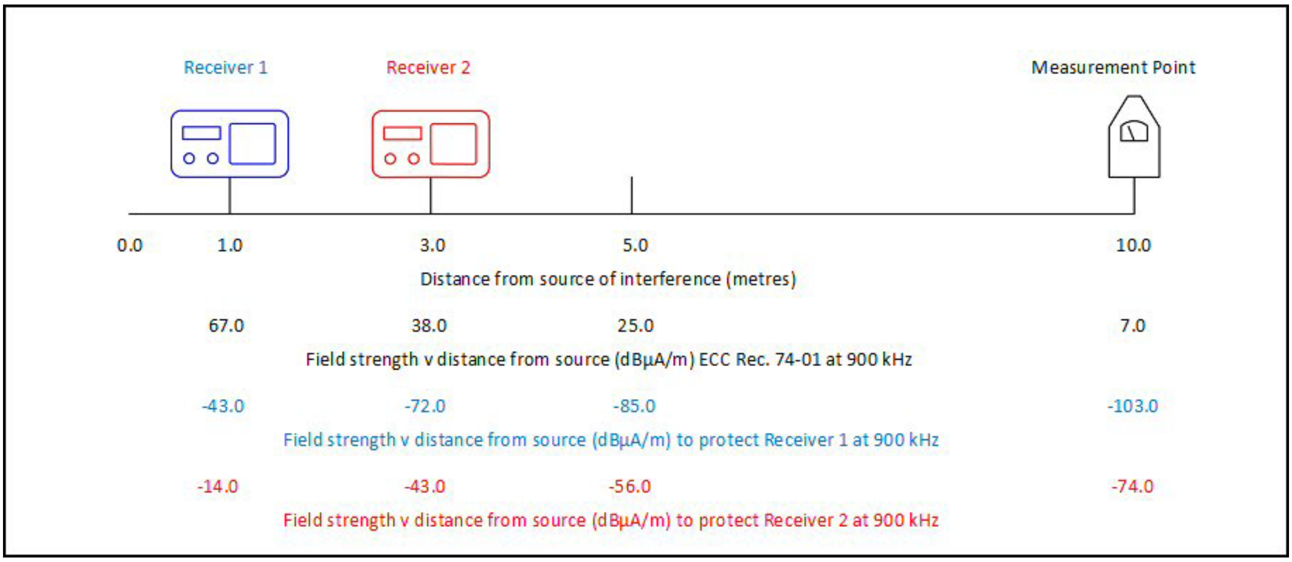


Figure 27: Variation of field strength with distance from source

The relationship between separation distance and tolerable interfering field strength levels is summarised in Figure 27, showing the unwanted emission limit at 10m, if the protection of -43 dBµA/m (as derived above) is provided at AM receivers spaced either 1m or 3m from the WPT device.

Importantly, the limits in ERC Recommendation 70-03 [31] and ERC Recommendation 74-01 [11] are only adequate to protect radiocommunication services under limited circumstances. As an example, the figure in Recommendation 70-03 covering the LF broadcast band (148.5–283.5 kHz) is given as -15 dBµA/m at 10 m. The level needed to protect an LF broadcast receiver from harmful interference at the edge of its protected coverage zone is -37 dBµA/m measured at the receiver itself. This means that an LF receiver would have to be located nearly 24 m from the source of interference in order not to be affected.

ERC Recommendation 74-01 allows much higher levels of spurious radiation, but this would be on the context of establishing a radio transmission system where care would be taken such that transmitters would be installed with the characteristics of nearby receiving equipment in mind. Looking again at the LF broadcast band (centre frequency 216 kHz) Annex 2 of ERC Recommendation 74-01 suggests that the allowable field strength at 10 m from the source is roundly 13 dBµA/m. This means that an LF broadcast receiver would have to be a little over 68 m from the source to avoid being affected. This is line with the conclusions of ECC Report 135 [41], ECC Report 67 [45] and ERC Report 44 [46] on the necessary separation distances from various types of inductive products to radiocommunication systems operating in the LF bands.

ANNEX 4: PERFORMANCE OF AN MF AM SOUND BROADCASTING RECEIVER IN THE PRESENCE OF INTERFERENCE FROM WPT

A4.1 GENERAL

A4.1.1 Introduction and background

This Annex describes studies carried out by the BBC which seek to define acceptable field-strength limits for interference from Wireless Power Transmission (WPT) devices. This work supplements an earlier study which is described in BBC White Paper WHP 332, published in November 2017 [33]. This further study uses a real, ‘off the shelf’, portable receiver with the wanted an unwanted signals injected using magnetic loop antennas to excite the inbuilt ferrite rod antenna in the receiver itself. This approach fulfils three objectives:

- to demonstrate that the reference receiver defined in Recommendation ITU-R BS.703 [21] is comparable with a real receiver;
- to offer a ‘reality check’ on the assumed interplay between Recommendations ITU-R BS.703 and ITU-R BS.560 [22] used when planning the LF and MF broadcast bands and used to set acceptable interference limits for WPT systems[15];
- to repeat some of the earlier measurements with a difference test arrangement.

The work for WHP 332 was carried out with an ‘ideal’ receiver – ‘ideal’ meaning that it did not introduce any noise of its own, and had a ‘flat’ frequency response with a modulation bandwidth of 4.5 kHz at –6 dB. In addition, the wanted signal and a single tone signal, simulating a WPT unit as an interferer, were combined before being fed into the ‘ideal’ receiver. This was a ‘hard wire’ connection and did not involve an antenna. This ‘purist’ approach was adopted to eliminate as many variables as possible. However, it is argued that a cross check to demonstrate that this approach corresponds with what happens in the ‘real world’ would be beneficial.

The principal conclusion of the earlier study was that for single tone signals, representing a source of interference, separated from the wanted transmission by more than 500 Hz, Recommendations ITU-R BS.560 and ITU-R BS.703 are a suitable basis for defining the required protection against interference levels. (‘Protection’ is defined as the ratio of wanted to unwanted signal levels presented to the receiver.) The ‘by more than 500 Hz’ qualification’ is important, as appreciably higher levels of interferer can be tolerated at lower frequency separations.

The work described here duplicates some of the earlier work, this time using a real but inexpensive radio, receiving signals off-air.

A4.1.2 Choice of receiver

At the time when the studies were carried out three representative commercial portable receivers of various ages were available:

- Panasonic GX500;
- Roberts RP26-B; and
- Sony ICF-700W.

A subjective assessment demonstrated that the Panasonic receiver had the lowest internal noise and so was chosen for the remainder of the tests. The receiver chosen was representative of the inexpensive end of the market. As the sensitivity and modulation bandwidth have an important bearing on the results, some details are given here.

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[15] To obtain the maximum allowable interferer level in absolute terms, the protection ratio (PR) as specified in Recommendation ITU-R BS.560 needs to be linked to the field-strength of the wanted signal at the receiver’s antenna. Recommendation ITU-R BS.703 gives the minimum sensitivity requirement for the ‘reference receiver’ as 60 dBμV/m, at which signal level the receiver should be capable of an audio signal-to-noise ratio (S/N) of 26 dB. The reference is 30% AM, with an un-weighted RMS detector being used for the noise measurement.

A number of portable radios had previously been tested in relation to ETSI specification EN 303 345 [49], ‘Broadcast Sound Receivers: Harmonised Standard’ covering the essential requirements of Article 3.2 of the Radio Equipment Directive (RED) 2014/53/EU’. A cumulative distribution function (CDF) of their sensitivities is shown in Figure 28. About two-thirds of the radios were more sensitive than the proposed ETSI requirement of 66 dBµV/m.

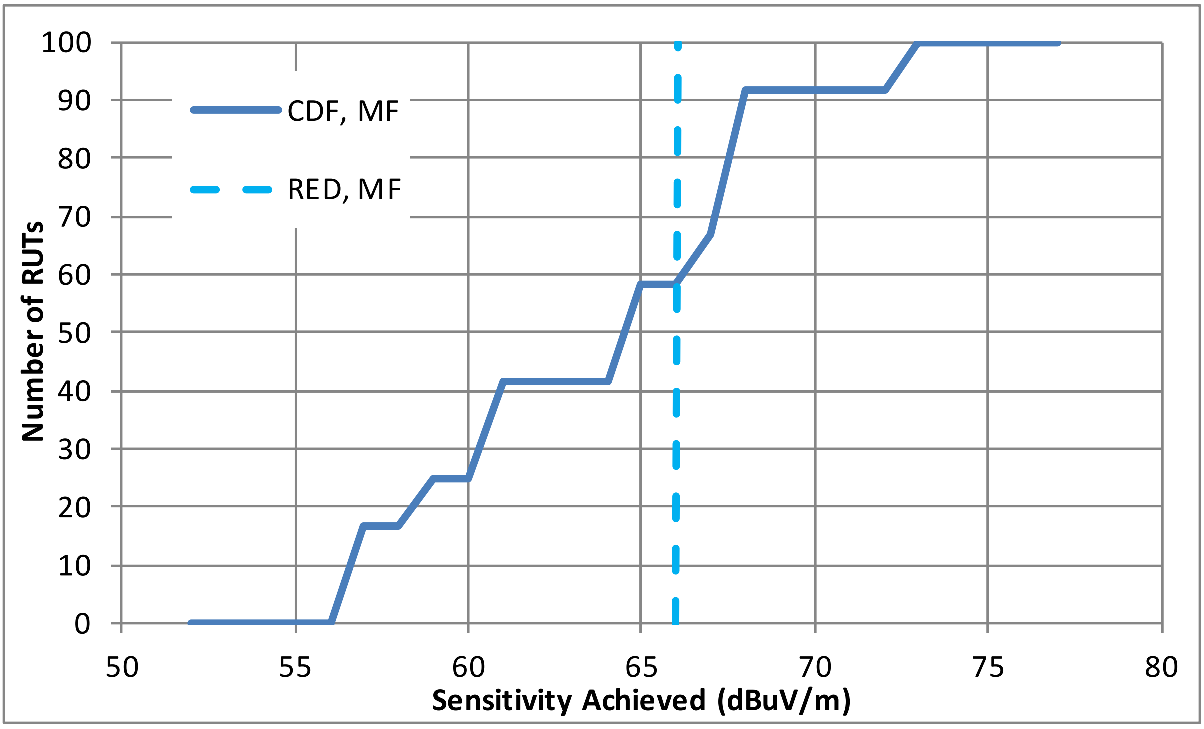

Figure 28: CDF of the Sensitivities of a Batch of Typical Portable Radios

The Panasonic GX500 achieved a sensitivity of 65 dBµV/m on the same scale; so it just met the ETSI requirements. Note that the sensitivity here is not defined in the same way as in Recommendation ITU-R BS.703. This is discussed below but for the moment, the requirements of Recommendation ITU-R BS.703 and EN 303 345 can be taken as approximately equivalent. The important point is that the Panasonic radio is typical and its noise performance is comparable with the ITU reference receiver.

Also important is the modulation frequency response of the receiver, as this will determine both the noise level at the output and the impact of the interfering WPT. A plot is shown in Figure 29.

Note that the response falls off sharply beyond 1.5 kHz, whereas that of the earlier ‘ideal’ receiver was essentially flat to 4 kHz. The narrow bandwidth implies greater tolerance to WPT and improves the measured sensitivity (although not the audio fidelity).

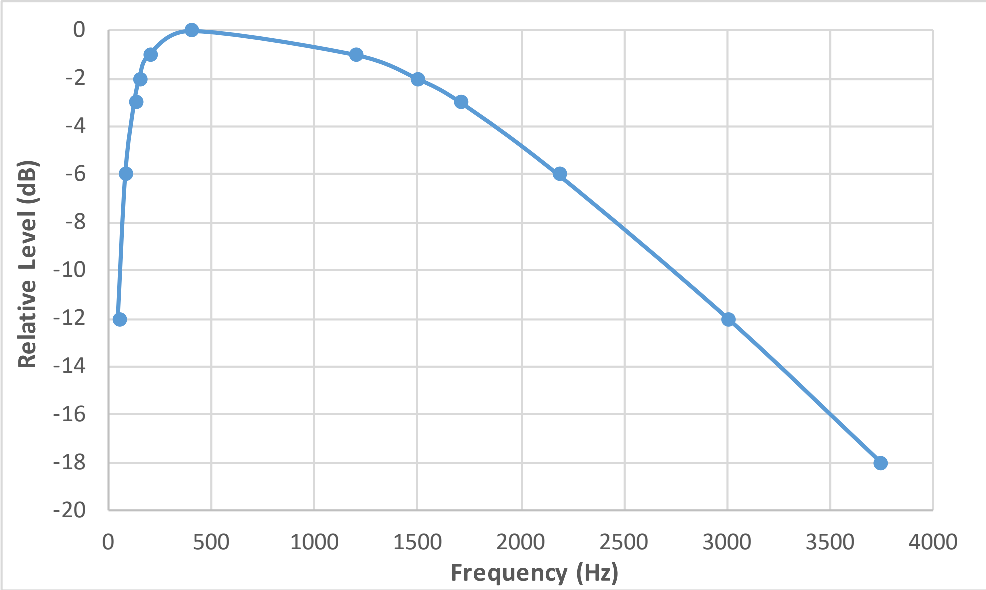

Figure 29: Modulation response of chosen portable radio

A4.1.3 The test set-up

The test set-up was essentially similar to that described in WHP 332 [33], with two RF signal generators: one set to 999 kHz and used to provide the wanted transmission; the second set to 1001 kHz and providing the (un-modulated) interferer with a 2 kHz offset. The two signals were 'transmitted' from separate calibrated loop antennas. To eliminate other sources of interference, the generators, loops and receiver were placed in an RF screened room, with the PC providing the programme material for listening tests (itself an appreciable source of radio noise) outside the screened test area. The audio analyser was connected to the receiver with a fibre-optic link. All incoming mains supplies were filtered and any un-necessary equipment was turned off.

A picture of the test set-up is shown in Figure 30.

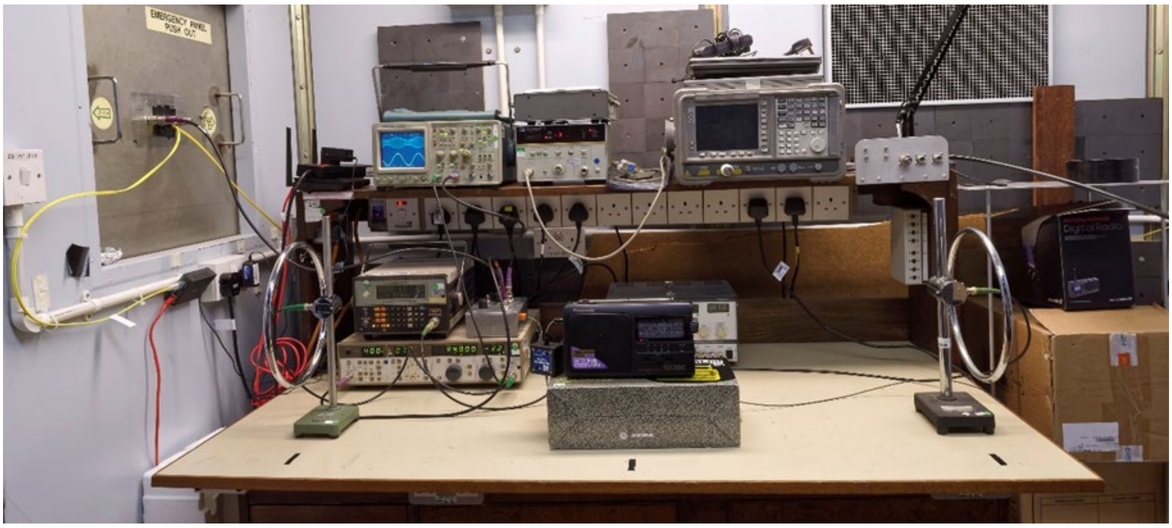

Figure 30: The test set-up in the BBC R&D screened room

In Figure 30, the portable radio is centre-stage, supported on a cardboard box to allow its ferrite antenna to be aligned with the axis of the loop antennas. The two loops are shown either side and are spaced from the radio by 600 mm – the magnetic field strength bore a simple relationship with the measured output of the signal generators which made setting up easier and more accurate. Alongside the radio (but not clearly visible) is the transmitter for the fibre-optic link. Out of frame is a measurement meter for double-checking the field-strength generated by the loops. The two RF signal generators are behind the left-hand loop.

Block diagrams of the original (Figure 31) and present test arrangements (Figure 32) are given here.

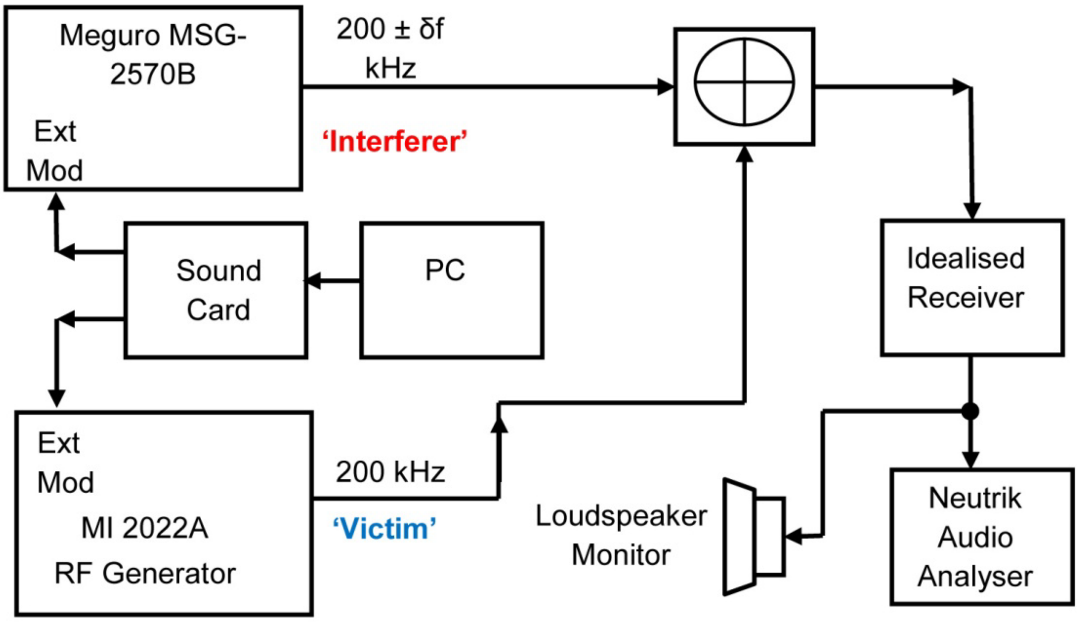

Figure 31: The test set-up as originally used for WHP 332

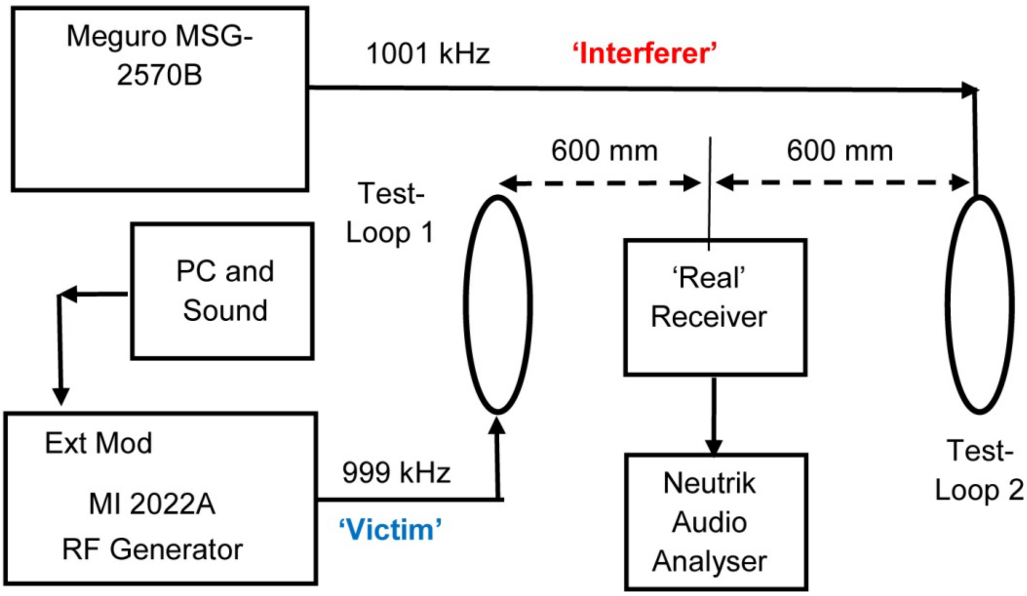

Figure 32: Modified set-up as used for the present work

Essentially, the two set-ups are the same, except that the interferer and the wanted transmission are combined in the ether, rather than electronically. The use of test-loops and an internal loudspeaker mean that the 'real' receiver has no electrical connections to it.

The same audio 'clip' was used for all the relevant tests. This consisted of 16 seconds of speech followed by 2 seconds of silence and 12 seconds of music. It was taken from the BBC's Radio Five Live MF network and recorded 'downstream' of the transmission processor. A large amount of AM radio is now speech based.

Speech is characterised by lower modulation depths and frequent short silences as the speaker comes to the end of a sentence, stops for breath etc. Low levels of interference can be masked by the audio signal but equally can be intrusive during the frequent silences and it is these that tend to dominate from the listener's perspective.

A4.1.4 Calibration

Calibration was carefully carried out. A thermal power meter was used to check the output power of the generators at an indicated level of 0 dBm (1 mW into a 50 Ω termination). When set to -33 dBm, the generator should give rise to a signal level of 8.5 dBuA/m at the receiver, a figure which was verified with the field-strength meter. The calculation of field-strength is carried out as follows:

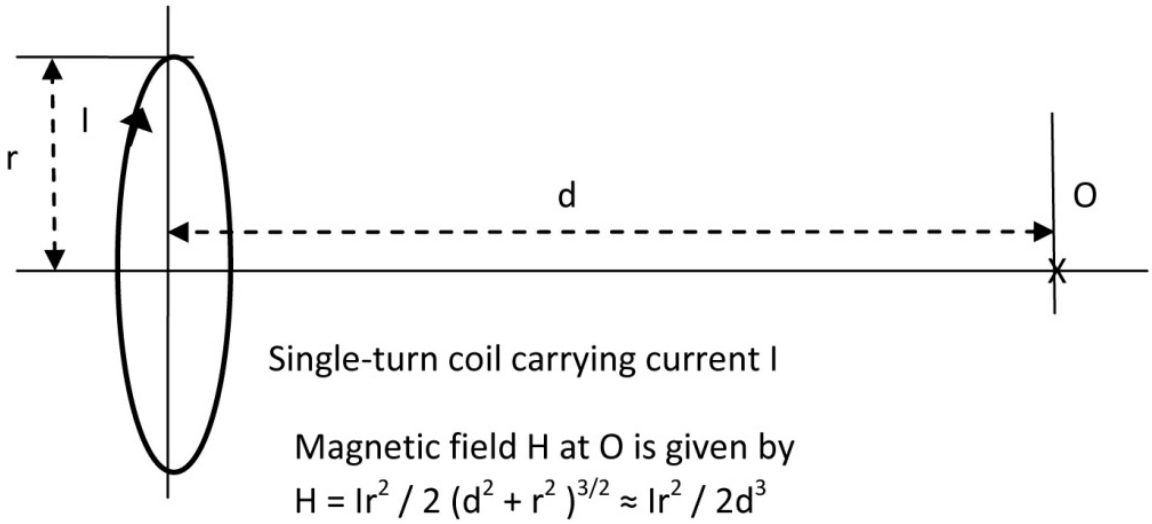

Figure 33: Magnetic field generated by a current-carrying loop

Figure 33 gives the magnetic field H arising from a current I through the coil. The current is defined by the generator EMF V and the source resistance R, so that I = V/R. The radius of the coil r is 125 mm and the distance d is 600 mm.

The equation can be re-arranged to find the current necessary to generate a given field at O.

$$I = H\,.\,(2d^3/r^2) \tag{5}$$

For the field strength to be $8.5\ dB\mu A/m$

$$H = 10^{\left(\frac{8.5}{20}\right)}\ \mu A/m \tag{6}$$
$$= 2.66\ \mu A/m$$

The necessary current is therefore:

$$I = 2.66\ \mu A/m\ .\ (2\,.\,0.6^3/\,0.125^2) \tag{7}$$
$$= 73.54\ \mu A$$

The necessary generator EMF is therefore:

$$V = 73.54\ \mu A\,.\,136\ \Omega \tag{8}$$
$$= 10\ mV$$

The 136 Ω source resistance includes 50 Ω within the RF generator itself, and 86 Ω forming part of the loop. For H to be 2.66 µA/m (or 8.5 dBµA/m), V must be 10 mV. The generator output (EMF) is calibrated in dBm, 0 dBm corresponding to a generator EMF of 448 mV, and 10 mV is therefore equivalent to 20 log (10/448), or –33 dBm.

The response of the receiver has already been mentioned. A further measurement confirms that the response is –4 dB at 2 kHz (the offset frequency of the interferer) relative to 1 kHz (the line-up tone for the system). Hence, to obtain a true comparison of what can be expected with 'good' receiver having a flat response, the interferer needs to be increased in level by 4 dB.

A4.1.5 Performance of the receiver used for the present tests

To ensure that the tests carried out with the portable radio are 'fair', it has to be checked how the sensitivity compares with that of the reference receiver in Recommendation ITU-R BS.703. The measured results are best summarised in the form of Table 18.

Table 18: Signal-to-noise ratios achieved by portable radio

Field-Strength	S/N, Ref 40% AM		S/N, Ref 30% AM
dBµV/m	Unweighted (dB)	Weighted (dBq)	Unweighted (dB)
60	26	18	23.5 (26)
65 (66)	30	22	28

The Table above shows that the noise performance of the Panasonic receiver is 2.5 dB worse than the Recommendation ITU-R BS.703 reference receiver (shaded pink), but exceeds the ETSI requirement of 66 dBµV/m (shaded blue) with 1 dB in hand. For this particular radio, the weighted noise is 8 dB greater than the unweighted noise. There is no 'universal' difference between the weighted and unweighted noise figures, since the bandwidth of the receiver is an important factor. In the work carried out for EN 303 345 [49], the figure was taken as 10 dB: 4 dB to convert between rms and quasi-peak, and 6 dB for the rising response of the weighting filter. With the Panasonic receiver the figure is slightly less because of the poor modulation response.

An important point is that it is possible to make the radio appear to match the performance of the reference receiver by increasing the incoming field-strength by 2.5 dB – where external noise is negligible, S/N increases with signal level pro rata. In other words, the radio will achieve 26 dB S/N reference 30% AM with a field-strength of 11 dBµA/m / 62.5 dBµV/m. Of course, when carrying out listening tests etc. it is necessary to increase the interferer by the same amount to keep the relative levels correct.

No comprehensive survey of environmental noise has been carried out, but walking around with the radio indicates that, at least in some locations, reception is limited by the radio's internal noise. The requirements laid down by ITU-R BS.703 and EN 303 345 hence seem reasonable.

A4.1.6 Interference thresholds

The earlier work on interference thresholds was carried out with a noiseless receiver. It might be expected that the noise present at the output of a 'real world' receiver would have a masking effect. If so, there could be a case for relaxing the limits for WPT interferers suggested in WHP 332 [33]. To find out in a rigorous manner would mean repeating the listening tests described in WHP 332. These tests involved playing out samples of programme material on the wanted 'transmitter', and asking a listening panel to determine at what level the interferer became audible. The tests had to be repeated over a wide range of offset frequencies. Although straightforward in principle, such listening tests need organisation, and such an approach was not possible with the resources available.

Rather than repeat all the previous work, a more pragmatic approach was adopted. A single listener judged the point at which the interference became audible at two different wanted signal levels. Level 1 was chosen to give 26 dB S/N (ref. 30% AM), to mimic the performance of the reference receiver working at 60 dBµV/m, Level 2 was 20 dB greater, when the noise was 10 dB lower and much less obtrusive. In that way, a small difference could be established, which could then be used to 'correct' the original 'noiseless' figures. Provided the difference really was small, any experimental uncertainties would have negligible effect.

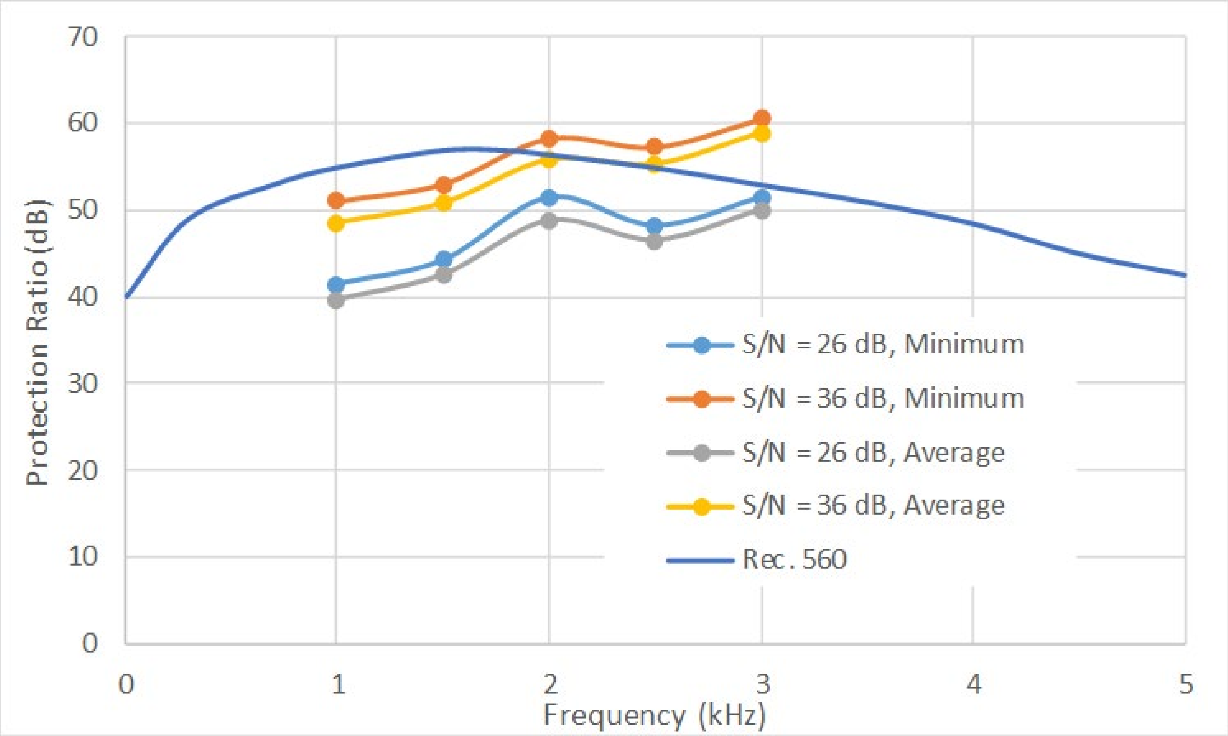

Figure 34: Single tone interference thresholds with a 'real world' receiver "Frequency" is the frequency offset from the AM carrier

For each frequency offset, in the range 1-3 kHz, and wanted signal level, the interfering signal level was slowly increased, and the level recorded at which the interference became just audible. A second level was recorded, at which the interference became unnoticeable as it was decreased. The process was repeated four times and averages taken. In Figure 34, the 'Minimum' figures correspond to the second level, whilst the 'Average' figures are the mean of the first and second levels. This allows a comparison to be made with WHP 332, figure 3.1. In plotting the results, allowance was made for the sideband response of the receiver; the curves would fall away at the high-frequency end if that were not done.

It is concluded that the presence of noise masks the interference and allows the interferer to be about 8 dB greater than would be the case in the absence of noise[16].

A further test was carried out in an attempt to quantify the psycho-acoustic difference between random (white) noise and a single tone interferer. The reference receiver proposed in Recommendation ITU-R BS.703 assumes an audio signal to random, system noise ratio of 26 dB, reference 30% AM modulation depth, at the limit of sensitivity. At the limit, the total system noise will be a mixture of receiver noise and environmental noise. Moving away from the limit of sensitivity into areas where the environmental noise is likely to be higher, the receiver noise will become less significant and the total system noise will be dominated by the environmental noise.

At the limit of sensitivity, the total system noise would be

$$-28\frac{dB\mu A}{m} = 8.5\frac{dB\mu A}{m} - 10.5\,dB - 26\,dB \qquad (9)$$

Where:

[16] This applies to single tone interferers at frequencies away from the broadcast carrier and does not affect the conclusions of [33]..

- $8.5\frac{dB\mu A}{m}$ $is\ the\ magnetic\ sensitivity\ limit\ (from$ Recommendation ITU – R BS. 703 [21];
- $-10.5\ dB\ is\ the\ ratio\ of\ the\ audio\ modulation\ (30\%\ modulation)\ to\ the\ carrier$[17];
- $-\ 26\ dB\ is\ the\ specified\ audio\ signal\ to\ random\ noise\ ratio;$

Note:

$$8.5\frac{dB\mu A}{m}\ is\ the\ level\ of\ the\ carrier.$$

A single tone interferer was injected at the same level as the total system noise[18] , as measured at the audio output of the receiver with an RMS detector, and progressively reduced in 2 dB steps until it became inaudible; masked by the system noise. The effect of the interferer had ceased to be objectionable (although it was still audible) when the level had been reduced by 8 dB and had disappeared when it was reduced by 10 dB. These levels correspond to -36 dBμA/m and -38 dBμA/m respectively for the Recommendation ITU-R BS.703 reference receiver. These results correlate well with the 8 dB masking effect of the system noise reported above. In higher noise environments, the absolute levels would be higher but the ratio of the interferer to the total system noise would always be the same – -8 dB to -10 dB if audible interference was to be avoided. In environments where the receiver noise itself is insignificant, the interferer would have to be 8 to 10 dB below the environmental noise level to be inaudible.

A4.2 CONCLUSIONS

Measurements made with the Panasonic GX500 receiver were in general agreement with the earlier measurements made with an idealised system to quantify the level of tolerable interference when a single tone interferer is aligned with the broadcast channel raster. The assumptions made when calculating the tolerable field strength from Recommendations ITU-R BS.703 [21] and ITU-R BS.560 [22] are basically correct. However, a number of things did come out of the tests.

A4.2.1 Validity of Recommendation ITU-R BS.703 reference receiver as a datum

The Panasonic GX500 receiver did not perform as well as the assumed performance of the reference receiver. Its audio frequency response was not flat and the receiver noise was a slightly greater. This is a relatively inexpensive portable receiver and work carried out previously by the BBC indicates that better quality receivers are available. This in turn means that the specification for the reference receiver is, as it should be, representative of a good quality commercial receiver and so earlier studies based on the reference receiver are perfectly valid. Recommendation ITU-R BS.703 effectively specifies the total system noise level at the fringe of reception by assuming a peak modulation depth of 30% (21.2% rms) and a modulation to random (system) noise of 26 dB. The total system noise is, therefore 60 dBμV/m (minimum carrier level from Recommendation ITU-R BS.703) minus 13.5 dB (level of modulation below carrier) minus 26 dB (wanted signal to noise ratio) which equals 20.5 dBμV/m or –31 dBμA/m (magnetic). In practice this will be a combination of internal receiver noise and environmental noise. Assuming both noise sources contribute equally to the system noise each will be -34 dBμA/m; a figure that will increase by 3 dB when they are added together. According to calculations made by Japan from Recommendation ITU-R P.372 this is, unsurprisingly, the environmental noise level to be expected in a rural situation.

A4.2.2 Masking effect of system noise

When the interference is at a low level, it can be masked by the presence of audio modulation. With the tendency for broadcasters to use AM radio for speech broadcasting, there are frequent gaps and silences in the programme and it is in these gaps that the interference is noticeable or annoying because it is not masked. A single tone interferer is more disturbing than random noise. The earlier, subjective tests described in BBC

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[17] This includes a correction for the correlation between the upper and lower modulation sidebands.

[18] For this test an idealised receiver was used with random noise deliberately injected at the equivalent of minus 31 dBμA/m to simulate the performance of Recommendation ITU-R BS.703 reference receiver.

White paper WHP 332 were performed using an idealised, noise free receiver. The presence of background, random noise in the gaps in speech was found itself to have the effect of masking the interference. A subjective test involving one listener but repeated several times suggests that the masking effect of system noise could offer an 8 dB relaxation in the tolerable noise level at frequencies away from the broadcast carrier. This does not have any effect on the levels suggested in WHP 332.

A4.2.3 Level of interferer relative to system noise

Because of the more intrusive psycho-acoustical effect, a single tone interferer must be at least 8 dB below the total system noise in any location to be inaudible. The total system noise itself will be location dependent. In the electrically quietest environments, internal receiver noise will play a large part but in more noisy environments (suburbs and cities perhaps) the environmental noise will dominate. Statistical guidance on anticipated environmental noise levels in various environments can be found in Recommendation ITU-R P.372, however, it must be stressed that these levels are for guidance and should not be used as targets. This does not address the general principle that electrical noise should always be minimised.

ANNEX 5: H-FIELD MEASUREMENTS DURING THE BATTERY RECHARGING OF THE HEARING IMPLANT SYSTEM AT 5 MHZ AND 6.78 MHZ

A5.1 MEASUREMENT METHOD

Typical in-band WPT emission levels together with spurious emissions during implant battery charging of hearing implant systems were measured for various scenarios at 5 MHz and 6.78 MHz operation.

The magnetic field strengths and disturbances were measured at 3 meters range due to the low inductive field levels and the use of a non-resonant shielded active loop antennas (broadband antennas) as recommended in ERC Recommendation 74-01 [11].

The centre of the loop antenna was placed 1.5 m above the floor of an indoor area test site (part of an office building, non-anechoic). The H-field was captured by the loop antenna at maximum magnetic coupling with the implant charger system (parallel vertical planes).

The magnetic field strengths of the wanted WPT emissions and spurious emissions were recorded below 30 MHz.

A5.2 MEASUREMENT RESULTS

The results from measurements are summarised in Table 19 and Table 20.

Table 19: H-field (peak/max hold) measurement results @3 m during charging of the implant battery at 5 MHz with load modulation at 10 kbps

Frequency of measurement	H-field WPT at 100% duty cycle (continuous)	H-field WPT at 50% duty cycle (time interleaved)
5 MHz (Fundamental)	14.4 dBµA/m at 3 m	19.6 dBµA/m at 3 m
10 MHz	0.5 dBµA/m at 3 m	-4.2 dBµA/m at 3 m
15 MHz	-8.8 dBµA/m at 3 m	-3.1 dBµA/m at 3 m
20 MHz	3.7 dBµA/m at 3 m	6.5 dBµA/m at 3 m
25 MHz	-1.2 dBµA/m at 3 m	0 dBµA/m at 3 m
30 MHz	-11.6 dBµA/m at 3 m	-4.3 dBµA/m at 3 m

Table 20: H-field (peak/max hold) measurement results @3 m during charging of the implant battery at 6.78 MHz with load modulation at 10 kbps

Frequency	H-field WPT at 100% duty cycle (continuous)	H-field WPT at 50% duty cycle (time interleaved)
6.78 MHz (Fundamental)	13.2 dBµA/m at 3 m	20.0 dBµA/m at 3 m
13.56 MHz	-5.2 dBµA/m at 3 m	5.2 dBµA/m at 3 m
20.34 MHz	-5.4 dBµA/m at 3 m	6.9 dBµA/m at 3 m
27.12 MHz	0.4 dBµA/m at 3 m	-9.2 dBµA/m at 3 m

A5.3 SUMMARY OF FINDINGS

Previous measured values were compared to the limits of ERC Recommendation 70-03 [31] and ERC Recommendation 74-01 [11] as illustrated in Figure 35 and Figure 36.

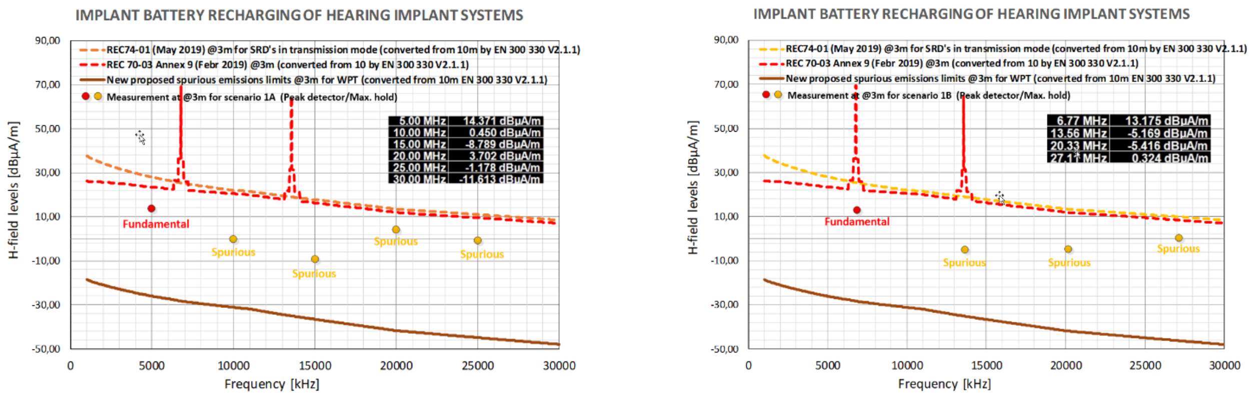


Figure 35: LEFT: H-field measurement results @3 m during charging of the implant battery at 5 MHz CW with load modulation at 10 kbps. RIGHT: H-field measurement results @3 m during charging of the implant battery at 6.78 MHz CW with load modulation at 10 kbps

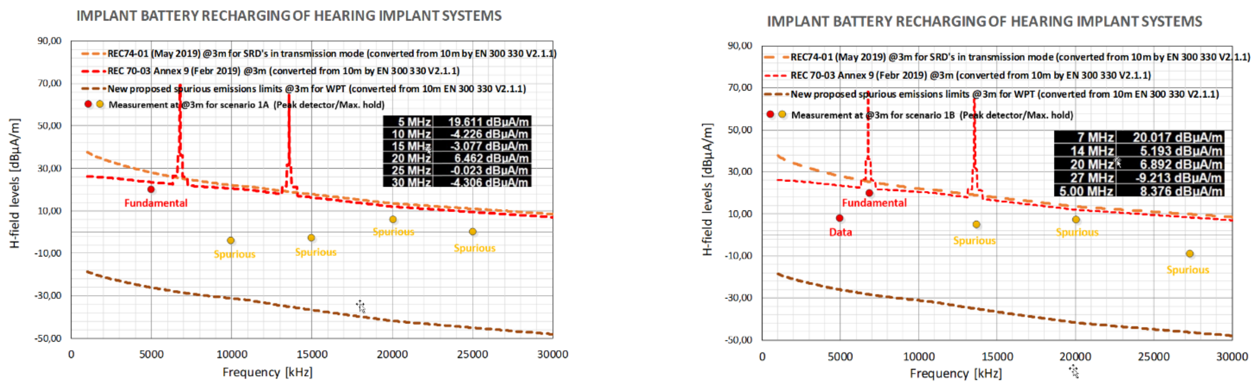


Figure 36: LEFT: H-field measurement results @3 m during charging of the implant battery at 5 MHz with a time interleaved (ratio 1:2) communication at 5 MHz . RIGHT: Emission mask measurements @1 m of the power carrier and interleaved communications at 5 MHz. RIGHT: H-field measurement results @3 m during charging of the implant battery at 6.78 MHz with a time interleaved (ratio 1:2) communication at 5 MHz

Typical measurements at 3 meters distance from the implant battery charger system reveal that the fundamental emission levels and spurious emission levels of the medical implant charger system are within the limits of ERC Recommendation 70-03 and ERC Recommendation 74-01 as of today.

The current implant technology already applied for first human trials today shows it would become unrealistic for the implant charger system to comply to the limits of e.g. -46 dBµA/m at 300 kHz reducing by 7 dB per frequency decade to -60.0 dBµA/m at 30 MHz at 10 m. The implant current rectification at higher frequencies is a non-linear process (diodes) and secondary harmonic currents are generated inside the implant coil. Separation distances and probability of close-proximity occurrence to incumbent services should be an important aspect in the assessment for new WPT regulations.

ANNEX 6: RESULTS OF THE STUDY ON IMPACT FROM WPT (300-400 KHZ, 1610 - 1800 KHZ AND 1950-2150 KHZ) ON RADIO SERVICES

A6.1 PARAMETERS

A6.1.1 WPT devices

The charging of portable and mobile devices takes place indoors. Most people charge their devices at night where the probability of being outdoors is very small.

A6.1.1.1 WPT Emissions

The emissions of WPT used in this study are provided in Table 21.

Table 21: WPT emissions

Parameter	Value
WPT Max emissions (worst alignment)	-15 dBµA/m at 10 m
WPT Min emissions (best alignment)	-30 dBµA/m at 10 m
WPT operating frequency 1	350-400 kHz
WPT operating frequency 2	1750–1800 kHz
WPT operating frequency 3	1950–2000 kHz
WPT bandwidth	< 1 kHz

Each WPT device is constructed so that it only emits the maximum allowed level in the worst alignment position of the two coils while for many alignments positions the actual radiated level is much lower. This is considered by randomly picking an emissions level between best and worst alignment. More information on the effect of alignment can also be found in section A1.4.

Emissions from WPT devices are generally very narrowband, i.e. much smaller than radio service receiver bandwidth. The charging signal is very similar to a CW signal and adjacent channel impact was therefore not considered.

A6.1.1.2 WPT height distribution

The WPT devices are evenly distributed over all floors of a building. The height of each floor is assumed to be 3 m. Devices on the lowest floor are assumed to be 1.5 m above ground. The height distribution is given in Table 22.

Table 22: WPT devices height distribution

Environment	Number of floors
City area (Dense Urban: 20k pop/km^2)	6
City area (Urban: 5k pop/km^2)	4
Residential Area (2k pop/km^2)	2

Density/Deployment

Table 23 and Table 24 provide an assumption of the density of WPT devices for the radio services used in the analyses based on Table 21.

Table 23: Density of WPT operating frequency 1 (400 kHz)

Parameter	Value
Device Density in City areas (Dense Urban: 20k pop/km^2)	1500/km^2
Device Density in City areas (Urban: 5k pop/km^2)	375/km^2
Density in Residential Area (2k pop/km^2)	150/km^2
Typical charging duration	1-2 hours
Devices charged during busy hours (Night: 0:00–07:00)	100%
Devices charged during non-busy hours (Day: 09:00–21:30)	25%

Table 24: Density of WPT operating frequency 2 (1800 kHz)

Parameter	Value
Density in City areas (Dense Urban: 20k pop / km2)	500 / km^2
Density in City areas (Urban: 5k pop / km2)	125/km^2
Density in Residential Area (2k pop /km2)	50 / km^2
Typical charging duration	1-2 hours
Devices charged during busy hours (Night: 23:30 – 07:00)	100%
Devices charged during non - busy hours (Day: 11:00–20:00)	1/3

Table 25: Density of WPT operating frequency 3 (2000 kHz)

Parameter	Value
Density in City areas (Dense Urban: 20k pop/km^2)	500/km^2
Density in City areas (Urban: 5k pop/km^2)	125/km^2
Density in Residential Area (2k pop/km^2)	50 / km^2
Typical charging duration	1-2 hours
Devices charged during busy hours (Night: 23:30–07:00)	100%
Devices charged during non - busy hours (Day: 11:00–20:00)	1/3

This study assumes that all installed WPT devices are charged concurrently during peak hours. That is not the case in reality. The level of impact is therefore overestimated.

There is correlation between man-made-noise levels and population density [58], therefore different WPT densities are considered linked to corresponding noise levels.

A6.1.2 Radio service parameters

Table 26 provides the parameters for the radio services used in the analyses.

Table 26: Parameters of the Radio Services

Parameter	Value
Rx Bandwidth	2.7 kHz (1)
Rx Frequency	400 kHz, 1800 kHz, 2000 kHz
RX Noise	Man-made noise (see section A6.1.3)
Antenna	Omni-directional
Height a.g.l.	1.5 m
(1) adjacent channel was not considered, overlapping channels were considered as fully co-channel	

A minimum distance between the WPT device and the radio service receiver is assumed. In city areas this distance is 5 m and in residential areas it is set to 10 m. These distances are either the typical minimum distance between the radio services or represent the operational reach of the operator of the radio service receiver [54]. used a distance of at least 10 m projected distance from the closest outside building wall as a typical distance between buildings and radio amateur antenna receive locations for MF and HF bands. The effect of interference is analysed by the increase in noise level.

That increase in noise level represents the level of interference which arrives within the 2.7 kHz bandwidth is summed up and is added it to MMN within that bandwidth. This treats the WPT interference only as a contribution to noise power not as a very narrow single carrier it is. Therefore, the result only applies to systems where assuming that interference can be treated as noise is applicable, i.e. for digital communications systems.

A6.1.3 Propagation

A6.1.3.1 Propagation Model

The propagation loss is based on description in ECC Report 6, section 5.9 [44] which is based on the propagation model as given in ERC Report 69 [52]. It is combining the magnetic coupling effect at close distances (60 dB per decade) with free space loss (20 dB per decade) in the far field. The transition between near and far field is modelled as 40 dB per decade. The model was programmed to output dBµA/m directly. Where the level at 10 m was different from -15 dBµA/m the difference was subtracted.

Two Breakpoints BP_1 and BP_2 are defined:

$$BP_1 = \frac{\lambda}{2 * \pi}$$

$$BP_2 = \frac{2.354 * \lambda}{2 * \pi}$$

$d <= BP_1$

$$level\ (dB\mu \frac{A}{m}) = 45 - 60 * log10\ (d) \qquad \text{(equivalent to } -15 \text{ dB}\mu\text{A/m at 10 m distance)} \tag{10}$$

$BP_1 < d <= BP_2$

$$level\left(dB\mu\frac{A}{m}\right) = level(at\ BP_1) - 40 * log10\left(\frac{d}{BP_1}\right) \quad (11)$$

d > BP_2

$$level\left(dB\mu\frac{A}{m}\right) = level(at\ BP_2) - 20 * log10\ (d/BP_2) \quad (12)$$

Where:

- d distance in m.

A6.1.3.2 Additional Propagation Losses

Two cases are considered:

- The first considers no building entry and no building exit losses, which results in very similar attenuation values as obtained when using the propagation model for urban environments of the ITU-R groundwave propagation handbook [55];
- The second considers two effects. First a loss from the building in which the WPT device is located and second the surroundings of the radio service receiver. However, it should be noted, that the results suggest underestimated interference, because attenuation due to built up structures is assumed, where there is very limited material that provides guidance on that effect.

Losses caused by the building in which the WPT device is located

In cities 30% of the paths are assumed to have a metal object between the interferer and the radio service receiver (metallized windows, steel reinforced concrete walls/floors, doors/gates, fences) while in residential areas, this is unlikely to appear. These values can also be understood as the percentage of buildings that are thermally efficient according to the definition of Recommendation ITU-R P.2109 [53] (i.e. metallised glass, foil-backed panels) assuming an extension of the applicable domain of this Recommendation. 30% was taken from previous studies carried out in ECC, such as ECC Report 302 and ECC Report 244. The parameters used for the calculation are shown in Table 27. These losses are only applicable to distances at which magnetic coupling is the dominant propagation mechanism.

Propagation through wood or bricks does not lead to additional loss.

Table 27: Additional Propagation Losses assumptions

Parameter	Applicable %	Value (dB)
City propagation loss	30%	10

Where the loss was not applicable (e.g. in residential environment) no loss i.e. 0 dB was applied.

Losses in the far field

Additional losses due to the buildings can only be assumed at distances in the far field. Using the definition of ERC Report 69 of where the far field starts, this loss was used in this study at distances that are greater than 2.354*λ/2π to represent the effect of built-up structures on the electric field received by the radio service receiver. However, magnetic coupling does not suddenly disappear, it is therefore used as a lower boundary after calculating this loss.

Base on the "Handbook on Ground Wave Propagation" [56] the building entry loss in the far field was used. Section 17 of the Handbook on indoor propagation provides the following formula assuming extension of the applicable domain of this formula to the propagation model of this Annex:

$$\mathrm{BEL}\ [dB] = -42.1 + 20.5.log_{10}(f\ [kHz]) \quad (13)$$

The standard deviation of the building entry loss is 11.8 dB. In case the BEL calculation predicts a gain, it is set to 0 dB.

The radio service receiver always likely to be surrounded by built-up structures.

A6.1.3.3 Noise Environment

The frequency range under consideration is often dominated by man-made noise. The analysis uses Recommendation ITU-R P.372 [7] as a baseline. In addition, man-made noise measurements carried out in the Netherlands (MN) are also used for analysis([54] and [56]). These measurements were carried out at a distance of at least 10 m from the nearest building wall. Those measurements aim at describing the man-made noise experience by radio service users, such as radio amateurs [56].

Table 28 and Table 29 below show the median noise levels from Recommendation ITU-R P.372 [7] and from man-mad noise measurements in the Netherlands (MN) converted into magnetic field using 51.5 dB correction factor.

Table 28: ITU-R P.372 [7] Noise levels

Parameter	Level	Std Dev
400 kHz		
City Noise	- 32.82 dBμA/m	8.4 dB
Residential Noise	- 37.12 dBμA/m	5.8 dB
1800 kHz		
City Noise	-37.85 dBμA/m	8.4 dB
Residential Noise	-42.15 dBμA/m	5.8 dB
2000 kHz		
City Noise	-38.20 dBμA/m	8.4 dB
Residential Noise	-42.50 dBμA/m	5.8 dB

Table 29: Noise levels from Measurements in the Netherlands (MN) [55]

Parameter	Level (from Table V [54])	Std Dev (from Table III [54])
400 kHz		
City Noise	-18.47 dBμA/m	5.6 dB
Residential Noise	-23.97 dBμA/m	9.5 dB
1800 kHz		
City Noise	-26.7 dBμA/m	6.4 dB
Residential Noise	-32.86 dBμA/m	5.5 dB
2000 kHz		
City Noise	-27.28 dBμA/m	6.4 dB
Residential Noise	-33.84 dBμA/m	5.5 dB

Only the variation of noise over location (spatial distribution) is analysed. However, as Recommendation ITU-R P.372 [7] clearly states noise also varies over time and such variations may be even larger

Table 30: Values of decile deviations of man-made noise, from Recommendation ITU-P.372 [7]

Category	Decile	Variation with time (dB)	Variation with location (dB)
City	Upper Lower	11.0 6.7	8.4 8.4
Residential	Upper Lower	10.6 5.3	5.8 5.8
Rural	Upper Lower	9.2 4.6	6.8 6.8

A6.1.4 Discrimination loss

The alignment of the antenna of the radio service receivers with the field generated by the WPT charger is not fixed. A random discrimination loss is generated by first generating a random mismatch angle, θ, that is uniformly distributed from 0 to 360 degrees. The polarisation loss in dB is then given by:

$$Discrimination\ Loss = \min\left(-10\log_{10}(\cos^2\theta), 35\right) \qquad (14)$$

The loss is capped at 35 dB at the boresight to account for imperfections in antenna design.

A6.2 METHODOLOGY

A Monte Carlo simulation is carried out in order to analyse the statistical impact of WPT charging in 300 - 400 kHz, in 1610-1800 kHz as well as in 1950-2150 kHz. The interference situation in these bands is dominated by man-made noise which is characterised by a mean and a standard deviation (spatial distribution). Any radio service that operates in these bands will face this level of man-made noise. Given its statistical nature the analysis was carried out to analyse the difference with and without WPT devices on the median.

The simulation Setup is as follows:

- Place a single radio service receiver at the centre of the simulation;
- Loop with 10000 events:
  - About 700 WPT devices are randomly scattered across an area as interferers (Note 1);
  - Each WPT device is assigned an emission level (randomly between best and worst alignment);
  - Assign a noise level corresponding to the distribution of man-made noise to the radio service receiver;
  - Assign a random operating frequency to each WPT device;
  - Calculate the received interference level (sum) from all WPT devices that are co-channel (i.e. propagation loss, polarisation discrimination, additional attenuation) (Note 2) (Note 3);
  - Store noise + interference level;
- Create CDF of Noise Levels and Noise + Interference Levels;
- Calculate increase of median noise levels.

Note 1: The simulation area needs to be large enough so that sufficient statistical samples (power levels and spatial configurations) are reflected in the simulation.

Note 2: Field strength levels are summed up not power levels.

Note 3: The radio service receiver bandwidth used is 2.7 kHz. However, to consider that the radio service receiver and the WPT might not be perfect the actual bandwidth considered was increased by 1 kHz to 3.7 kHz which leads to a higher amount of noise estimated in the receiver bandwidth. Thus, the presented results are to be taken as worst case.

Figure 37 shows an example for the frequency band 1800 kHz or 2000 kHz, the layout of a single simulation snapshot with an assumed WPT density of 500 devices per km^2.

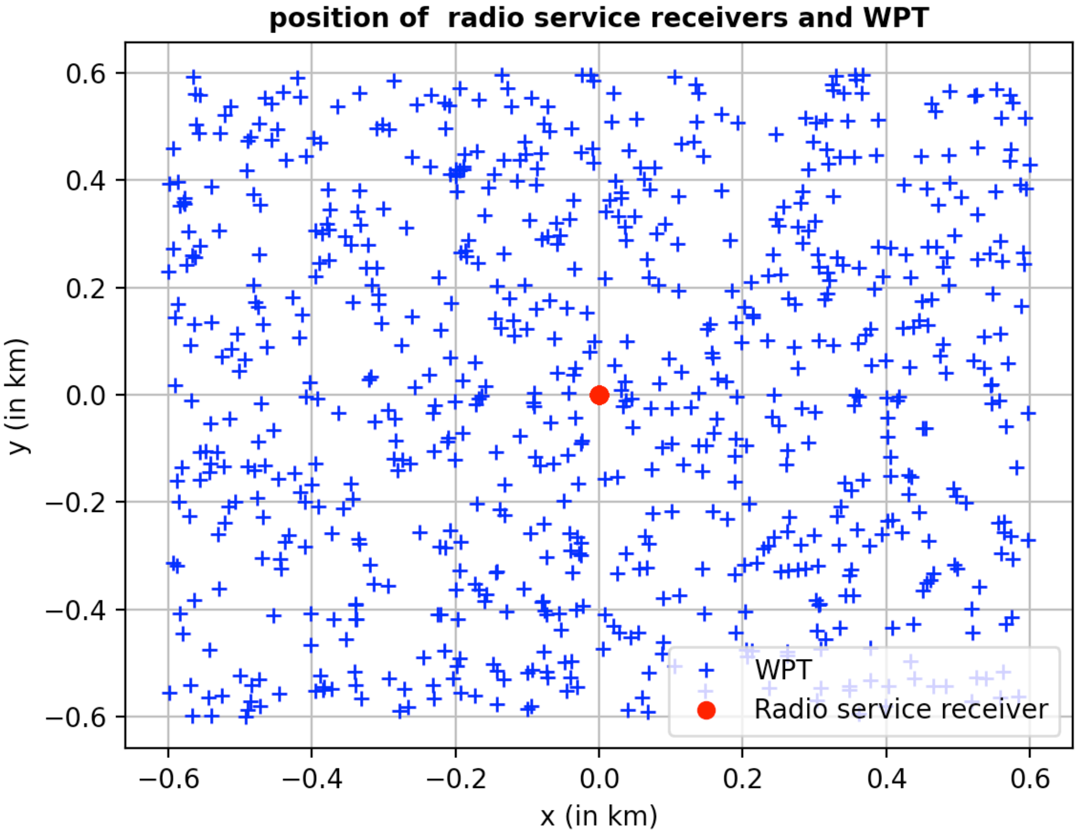


Figure 37: Example Layout of the Simulation

A6.3 RESULTS

A6.3.1 Interpretation of the results

Radio Services operating in the frequency ranges 300-400 kHz, 1610-1800 kHz as well as 1950-2150 kHz face a noisy environment in indoor locations. Other than in UHF frequency bands or above, the noise can be dominated by man-made noise external to the receiver, rather than thermal noise or natural noise.

Figure 38 shows the current noise environments of radio service receivers in the analysed frequency bands. Both sources for noise levels, Recommendation ITU-R P.372 and man-made noise measurements from the Netherlands (MN) are shown based on median levels and associated standard deviations.

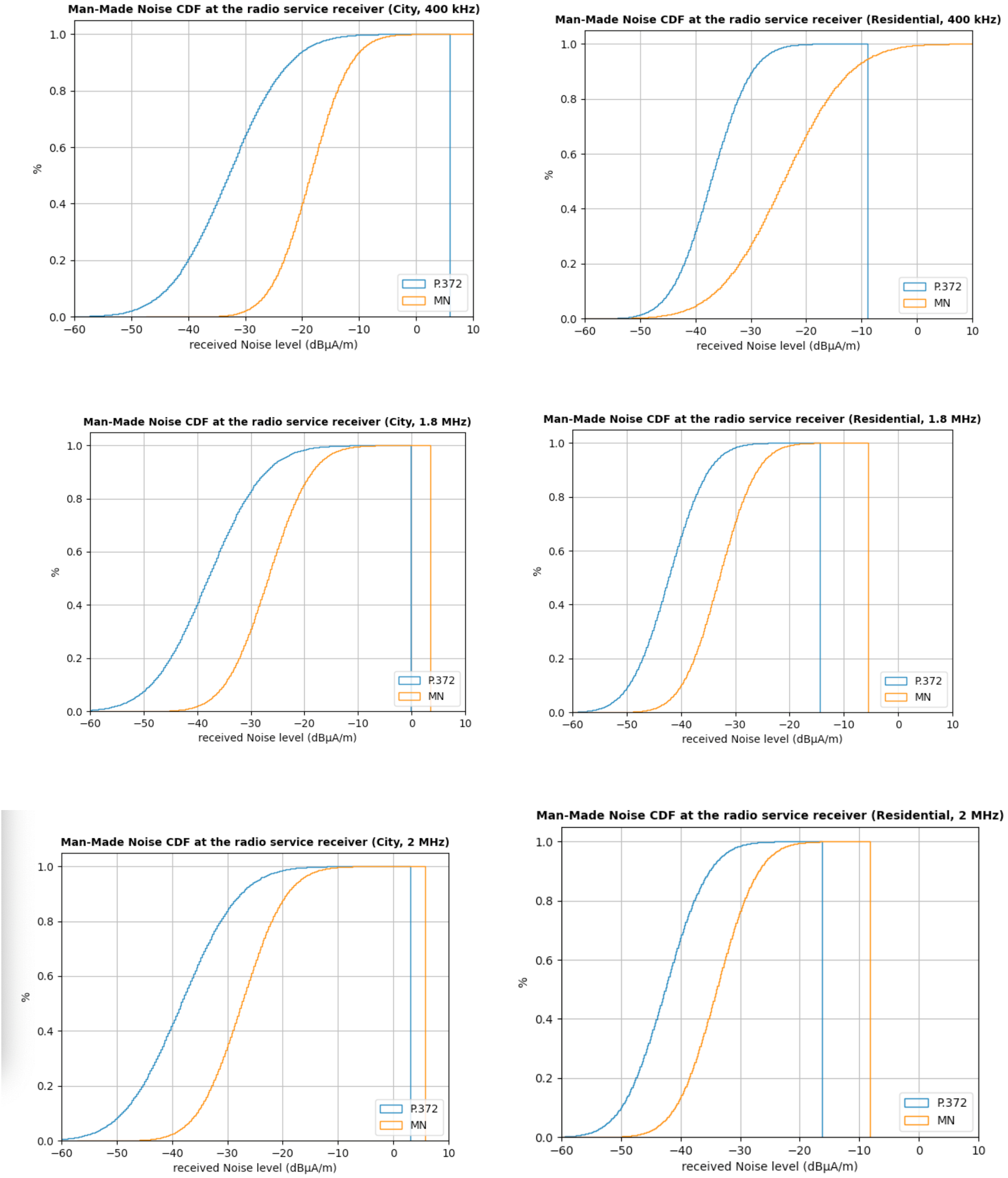


Figure 38: Example Man-made noise levels at the radio service receiver

The reception of a radio service in these bands depends heavily on ensuring that the receiver has a location that is closer to the left side of the curves. This can be either due to movement of the receiver in space and/or in some cases frequency.

For example, some receivers of the mobile service apply a frequency hopping scheme, so that a difference in noise levels lead to a more reliable connection.

A6.3.2 Results for 400 kHz

Table 31: Increase in noise level (WPT frequency at 400 kHz)

Environment	Day/Night	Density (/km²)	Noise Level	Increase of median noise (dB)	
				No additional attenuation	With additional attenuation
City (Dense Urban)	Night	1500	Recommendation ITU-R P.372	1.6	1.3
			MN	0.4	0.3
	Day	375	Recommendation ITU-R P.372	0.7	0.4
			MN	0.1	0.1
City (Urban)	Night	375	Recommendation ITU-R P.372	0.5	0.4
			MN	0.1	0.1
	Day	94	Recommendation ITU-R P.372	0.2	0.1
			MN	0	0
Residential	Night	150	Recommendation ITU-R P.372	0.3	0.2
			MN	0.1	0.1
	Day	38	Recommendation ITU-R P.372	0.1	0.1
			MN	0	0.0

A6.3.3 Results for 1800 kHz

Table 32: Increase in noise level (WPT frequency at 1750-1800 kHz)

Environment	Day/Night	Density (/km2)	Noise Level	Increase of median Noise (dB)	
				No additional attenuation	With additional attenuation
City (Dense Urban)	Night	500	Recommendation ITU-R P.372	3.9	1.2
			MN	1.3	0.4
	Day	167	Recommendation ITU-R P.372	2.5	0.6
			MN	0.7	0.2
City (Urban)	Night	125	Recommendation ITU-R P.372	2.2	0.5
			MN	0.6	0.1
	Day	42	Recommendation ITU-R P.372	1.4	0.3
			MN	0.4	0.1
Residential	Night	50	Recommendation ITU-R P.372	1.9	0.4
			MN	0.7	0.1
	Day	17	Recommendation ITU-R P.372	1.2	0.2
			MN	0.4	0.1

A6.3.4 Results for 2000 kHz

Table 33: Increase in noise level (WPT frequency at 2000 kHz)

Environment	Day/Night	Density (/km^2)	Noise Level	Noise Increase (dB)	
				No additional attenuation	With additional attenuation
City (Dense Urban)	Night	500	Recommendation ITU-R P.372	4.6	1.3
			MN	1.5	0.4
	Day	167	Recommendation ITU-R P.372	2.5	0.7
			MN	0.8	0.2
City (Urban)	Night	125	Recommendation ITU-R P.372	2.1	0.6
			MN	0.6	0.2
	Day	42	Recommendation ITU-R P.372	1.0	0.3
			MN	0.3	0.1
Residential	Night	50	Recommendation ITU-R P.372	1.5	0.4
			MN	0.6	0.2
	Day	17	Recommendation ITU-R P.372	0.6	0.2
			MN	0.2	0.1

A6.3.5 Summary of the results

This study considered interference from a density of 1500 WPT devices per km² deployed in 300-400 kHz and 500 WPT devices per km² in 1610-1800 kHz and 1950-2150 kHz with a maximum transmit level of -15 dBµA/m at 10 m, to radio services receiving at exactly 400 kHz, 1800 kHz and 2000 kHz, respectively (only one receiver at a time is considered).

Building entry losses (BEL) in the far field are modelled according to the ITU-R handbook on ground wave propagation [55]. The model is used on top of propagation model of ERC Report 69 [52], although it is supposed to be used with propagation curves of Recommendation ITU-R P.368 [61]. At distances where magnetic coupling is dominant, 10 dB attenuation of attenuation for 30% of cases has been assumed in urban scenario.

Potential in-band interference to radio services with a reception bandwidth of 2.7 kHz were considered, taking into account that a WPT device randomly choose its transmitted frequency within its operating band.

For WPT emissions at -15 dbµA/m at 10 m distance, two sets of results have been derived. For the first set including the effect of build-up structures like buildings it was found that in very dense urban areas, a 1.2 to 1.3 dB noise increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.3 or 0.4 dB, respectively for the two frequency ranges. For all other environments (urban and residential) the increase of the median noise is less than 0.4 dB or 0.6 dB, depending on the frequency.

For the second set without the effect of build-up structures like buildings it was found that in in very dense urban areas, a 1.5 dB noise at 400 kHz, 3.9 dB at 1800 kHz and 4.6 dB at 2000 kHz increase above the median level predicted in Recommendation ITU-R P.372 depending on the frequency, respectively. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.4 dB at 400 kHz, 1.3 dB at 1800 kHz and 1.5 dB at 2000 kHz, respectively. For all other environments (urban and residential) the increase of the median noise was lower than in the high density urban case.

However, it should be noted, that the in the absence of any reference/recommendation describing the effect of “building exit losses” and losses for built up structures, the first set of results may be underestimating the interference while for the second set of results may be overestimating it. The exact effect of interference impact is somewhere in the presented range.

These levels represent peak charging times that occur at night. During daytime, the median increase in noise was found to be lower.

The actual noise environment at less than 10 m distance from the WPT device can be higher or lower than the noise levels that were used as a reference; i.e., Recommendation ITU-R P.372 median levels and man-made noise measurements carried out in the Netherlands. The actual impact of WPT on the noise environment at such close distances to buildings or inside buildings could not be evaluated because of a lack of sources on man-made noise levels for that case.

This study analyses the amount of interference that falls inside a receiver's bandwidth by comparing it to the man-made noise level. This is relevant to cases where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, which are more susceptible to single tone interference (see A3.3.1).

It is noted that, the study does not consider emissions at other frequencies (i.e. spurious/harmonics) nor does it consider the situation of indoor reception, both of which are more relevant for AM broadcasting.

ANNEX 7: EXAMINATION OF MEASURED LEVELS AND ANALYSIS FOR IMPLANTABLE WIRELESS POWER TRANSMISSION (WPT) OPERATING IN 260-320 KHZ RANGE

A7.1 PURPOSE

This study was conducted to better understand Abbott’s use of the 260-320 kHz operating range and to contribute to studies for Active Implantable Medical WPT.

A7.1.1 Theory of Impact Study

Studies provided in this Annex are an extension of the information found in the section 2.2.1 on technical requirements and use cases for Active Implantable Medical WPT and in conclusions section 5.2 for AIMD neuromodulators.

Measurements cover the range of 150 kHz to 30 MHz to address the fundamental charging frequencies within 260-320 kHz and any spurious frequencies up to the 100th harmonic. Both magnetic and electric field measurements were studied, and where applicable, at multiple test distances from the device under test to help understand energy propagation. Comparison to published standards or limits are used as a reference. Some studies within this Report include reference measurements not outlined by a specific test method, however these tests are to help understand the impact of implantable Wireless Power Transmission devices to support conclusions or recommendations. Some images have been partially redacted since the devices in this study are not for public release at this stage.

Based on the theory of operation and the documented design, the expectation is that the system will operate efficiently in the magnetic near field and inefficiently at the electric near field.

Also, at any distance less than 10 m it will extrapolate close to 60 dB/decade at the fundamental frequency and harmonics below 5 MHz and at least 20 dB/decade from 5-30 MHz.

In the far field, (2D2/λ, where D is the largest physical dimension of the radiating structure). Electric fields and magnetic fields are expected to behave as typical plane waves with a consistent decay.

A7.2 SCOPE

The scope of the studies is to use hardware/firmware from Orion RC/Gemini design verification candidate and perform measurements using published test methods and experiments outlined within this document.

A7.3 TEST AND MEASUREMENT

A7.3.1 Test Sites

Accredited Test Lab (ATL)

Testing performed by ISO 17025 Accredited Test Lab in 10m Semi-Anechoic Chamber (Element 3801 E. Plano Pkwy Suite 150 Plano, TX 75074, United States)

Secondary Site for Open Area Test (3901 Preston, Plano, TX, United States).

A7.3.2 Test Equipment and Process

Table 34: Abbott Equipment

Item
Charger Operating and producing 260-320 kHz charging frequency (Design Freeze Candidate)
Rechargeable IPG (Design Freeze Candidate)
Lead for EL 1-8 ID (60 cm)
Lead for EL 9-16 ID (60 cm)
Lead Extension for EL 1-8 ID (30 cm)
Lead Extension for EL 9-16 ID (30 cm)

Table 35: Accredited Test Lab Equipment

Item	Identifier
CISPR Compliant Loop Antenna 60cm "9 kHz-30 MHz"	ETS Model 6502 S/N 00166071
CISPR Compliance Measurement Receiver	Gauss Model 30M S/N 1908002
Semi Anechoic Chamber (test site)	ETS 10 m Chamber
Isotropic Magnetic and Electric Field Probe Analyzer "9 kHz-30 MHz"	NARDA Model EHP-200A
LW, MW, SW international receiver	Sangean ATS-909X
Spectrum Analyzer	Agilent E4446A S/N US44300970
Oscilloscope	Tektronix MDO410B-3 C010828
Signal Generator	Tektronix AFG3252 S/N C021992
Transmitting 12inch Loop Antenna	A.H. Systems Part 2195 from SAS-563B
Electrically Non conductive support (polypropylene table with polyethylene foam adjustable from 80 to 120 cm height.)	N/A

Table 36: Procedure

Basic Process	
Step	Action
1	Setup WPT Charger and IPG with appropriate alignment distances
2	Accredited Test Lab (ATB) setup receive antenna in SAC Chamber or OATS along with measurement receiver
3	Measure WPT Charger at multiple angles and test distances to determine the mode that produces the highest levels using published test methods.
4	Perform additional measurements using modes that created highest levels
5	Coexistence with commercial off the shelf international receiver with LW, MW and SW frequency selection
6	Perform applicable distance extrapolation and analysis

Cables to connect the receiver and antenna were double shield RG223 and/or LMR400, and any insertion losses were measured prior to testing by the ATL and were factored into the final measurements.

For SAC measurements, a 1-4 metres capable antenna mast was used to raise and lower the antenna when necessary. For OATS, an electrically non-conductive tripod was used to adjust the antenna height. Angular rotation of Abbott equipment was performed using the 360 degrees ground turntable in the SAC, or manually rotating the devices for major angular positions such as going for 0 to 90 degrees. In addition, a 3 axis field probe analyser designed to measure electric (0.02-1000 V/m) and magnetic (6-300 A/m) fields was also used as a supplemental test. The magnetic sensor system is composed by three orthogonal magnetic loops. The electric sensor system is composed by three orthogonal parallel capacitors installed on opposite side of the magnetic loops.

For OATS measurements, an FCC listed site could not be found within Abbott's travel restricted zone caused by the Covid-19 pandemic. Due to the time limitation of when this impact study needed to be completed, it was decided some outdoor measurements were better than none, so a limited amount of measurements were taken using the configurations that produced the highest measurements during SAC measurements. In this Report, OATS should be translated to the open field next to Abbott's Plano, TX location in the United States of America which is approximately 18000 square meters.

At all sites, measurements were taken using the receivers Peak, Quasi Peak, and Average settings for historical reference. Any data referenced within this Report, unless otherwise specified, will be using the quasi peak data as it is the common measurement detector for currently published standards in the 150 kHz-30 MHz range for European SRD standards.

Abbott, with the help of the Accredited Test Lab, took over 220 separate test case measurements across several configurations. Each measurement included thousands or millions of individual acquisition points and would be overwhelming in the context of this report. A summary of the most relevant data is included in this study.

Figure 39 is an oscilloscope capture using a reference near field RF probe into the 50 Ohm input of a calibrated oscilloscope while the charger was charging the implantable pulse generator.

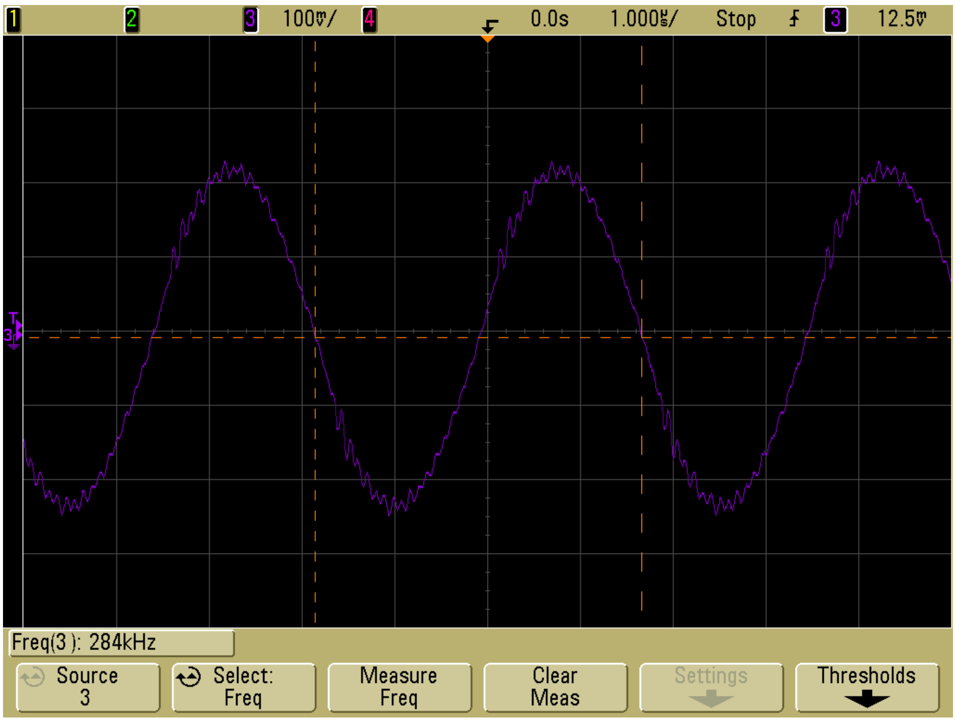


Figure 39: WPT Charging Signal

A7.3.3 Semi Anechoic Chamber (SAC) and Open Area Test Site ("OATS") Measurements

As a starting point, the measurement system noise floor was measured. Note that CISPR 16-1-4 based loop antennas contain a pre-amplifier. System noise floor is largely determined by the pre-amplifier in the 6502 active loop. Frequency steps for this data is 400 Hz when using the receiver mode of the FFT based receiver which provides great accuracy.

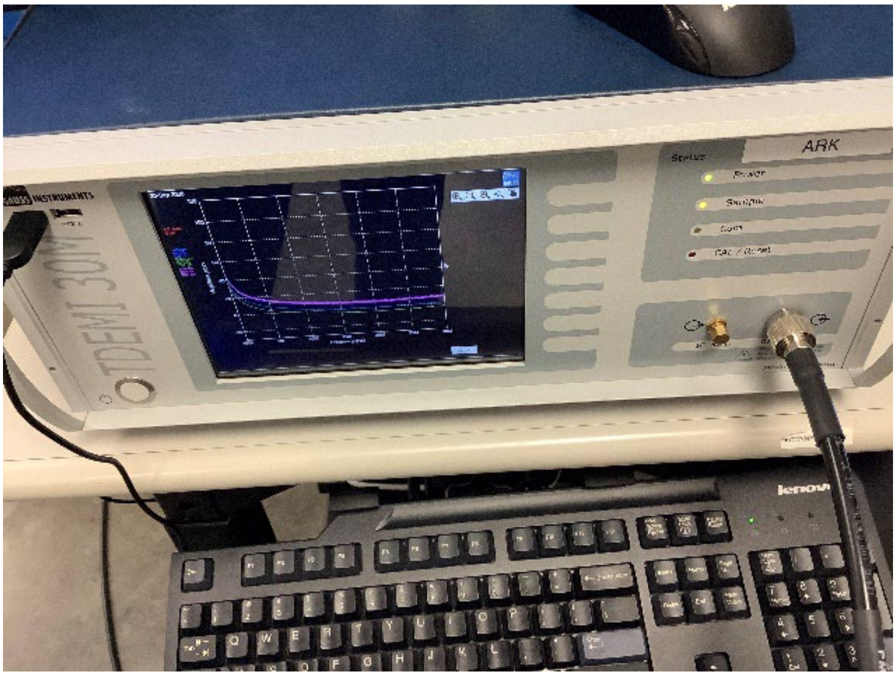


Figure 40: Measurement Receiver outside of SAC

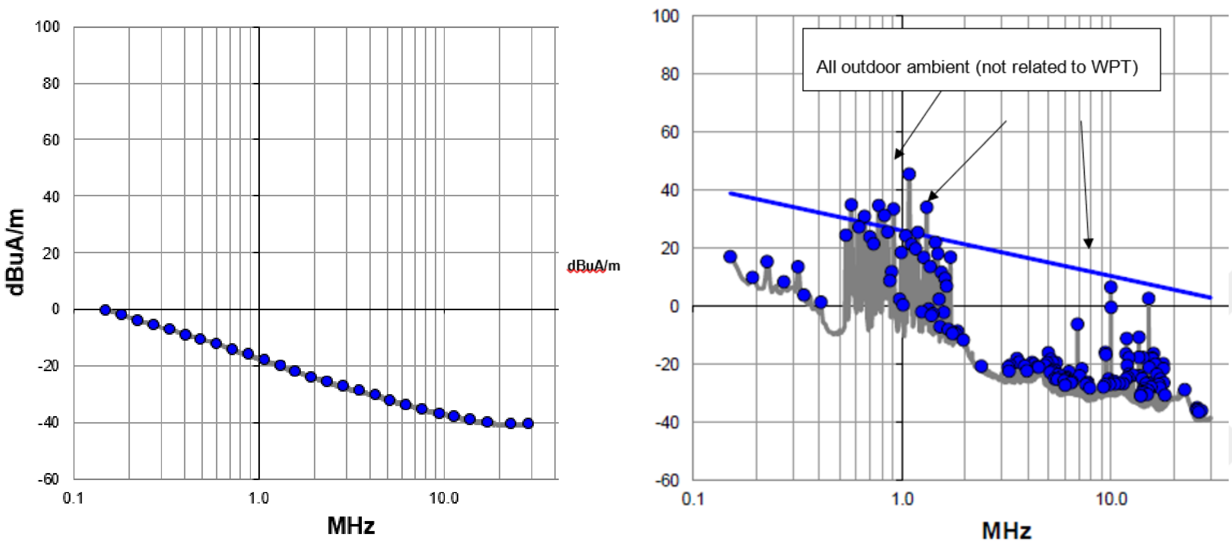


Figure 41: (LEFT) Baseline Noise Floor of SAC 150 kHz-30 MHz

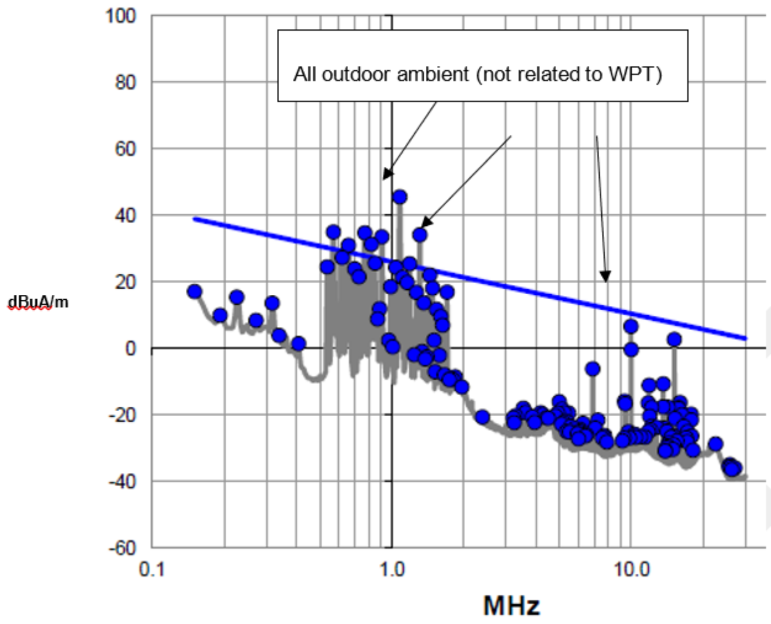


Figure 42: (RIGHT) Baseline Noise Floor of “OATS” 150 kHz-30 MHz

The IPG’s rechargeable battery was kept in an appropriate range so the WPT Charger would produce the maximum charging level. The IPG’s lower limit is 2.78 volts and its fully charged level is 4.1. 2.78 Volts – 3.9 volts created a maximum charge current. The battery status was checked periodically during testing to make sure this range was maintained. When the battery approached the upper limit, a second IPG of the same model was swapped in.

90 cm IPG leads were attached and terminated into a 500 Ohm load board to increase battery drain. In addition, if any WPT signals propagated into the leads, any additional emissions were represented in the setup.

Also note, the WPT charger cannot charge the IPG when powered by a USB to AC charger. This is an inherent system requirement since the device is medical. By design, it cannot charge the patients IPG while being connected to AC mains. Propagation of the WPT signal through additional USB cables or via AC grid is not possible. Based on this design, tests in this mode were not performed.

Orientation References for Antenna and WPT Charger:

Figure 43: 0 Degrees EUT, Measurement Antenna Parallel to EUT (parallel to reference)

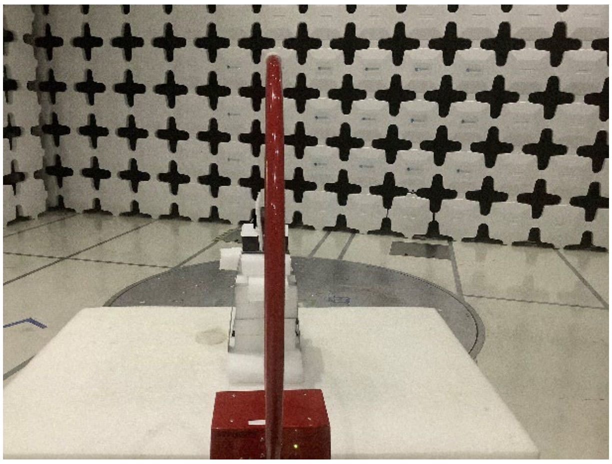


Figure 44: 90 Degrees EUT, Measurement Antenna Coplanar to EUT (Perpendicular to reference

Note: Not all orientations are represented in Figure 43 and Figure 44.

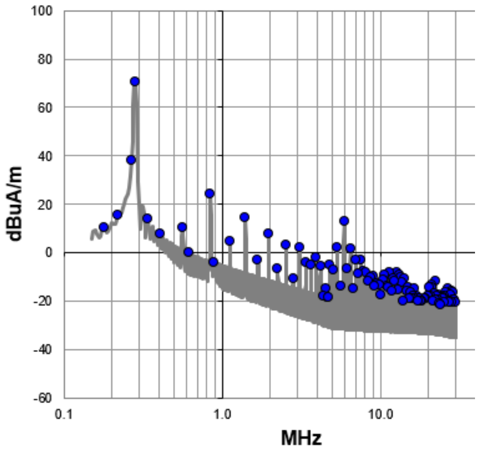


Figure 45: 1 m Test Distance, SAC, 0 degrees, Receive Antenna Parallel to Charger

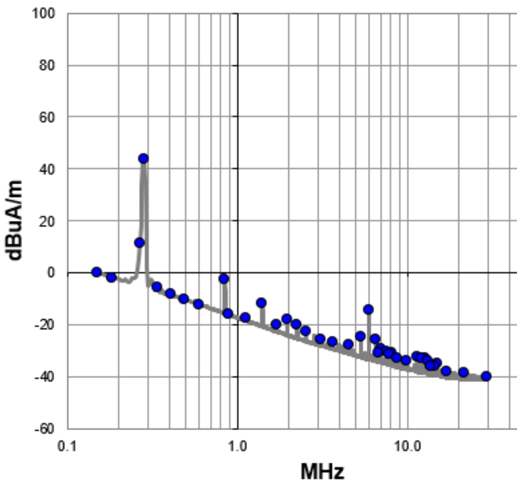


Figure 46: 3 m Test Distance, SAC, 0 degrees, Receive Antenna Parallel to Charger

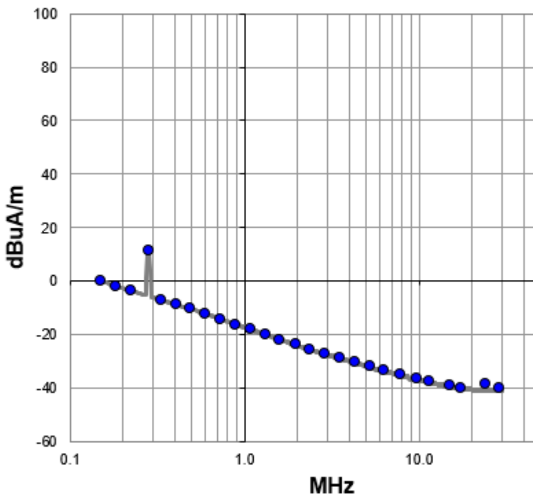


Figure 47: 10 m Test Distance, SAC, 0 degrees, Receive Antenna Parallel to Charger

Figure 48: OATS Setup 1

Table 37: Summary of Highest Measurements in SAC

Point	Charger Orientation	Receive Antenna Orientation	Angle	1 m Test Distance (dBuA/m)	3 m Test Distance (dBuA/m)	10 m Test Distance (dBuA/m)	Test distance where signal meets proposed limits in ECC Report 289 (metres)
Highest 284 kHz Fundamental	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	70.5	43.7	11.3	~70

Point	Charger Orientation	Receive Antenna Orientation	Angle	1 m Test Distance (dBuA/m)	3 m Test Distance (dBuA/m)	10 m Test Distance (dBuA/m)	Test distance where signal meets proposed limits in ECC Report 289 (metres)
Highest 2nd harmonic	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	10.4	-12.1	-36.8	~25
Highest 3rd harmonic	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	24.5	-2.2	-31.5	~25
Highest 4th harmonic	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	5.0	-17.1	-41.3	~20
Highest 5th harmonic	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	14.6	-11.6	-40.3	~20
Highest Spurious 1.5-10 MHz (20th harmonic)	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	13.0	-14.5	-44.6	~20
Highest Spurious (10-20 MHz)	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	-8.1	-32.5	-59.2	~10
Highest Spurious (20-30 MHz)	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	-11.7	-39.7	-70.4	~10

Derived from distance extrapolation using ARRL's definition of point sources found in "Rationale for the Abandonment of the Use of a Single 40 dB/decade Extrapolation Factor for Radiated Emissions Measurements Made Below 30 MHz"

Table 38: Summary of Highest Measurements in OATS

Point	Charger Orientation	Receive Antenna Orientation	Angle	1 m Test Distance (dBuA/m)	3 m Test Distance (dBuA/m)	10 m Test Distance (dBuA/m)
Highest Fundamental 284 kHz	Parallel to Receive Antenna Loop	Parallel to Charger Coil	0	68.4	44.2	NF
NF = Noise Floor of Open Area Test site. Background noise was too high to measure signals from WPT						

A7.3.4 Near field Electric vs Magnetic Field comparison

In case the unit is operated in close proximity to equipment that is sensitive to the produced frequencies, near field measurements were taken using a measurement probe often used for electromagnetic Human Exposure measurements. The table below provides the measurements at a 20 cm distance at its maximised position (angle and antenna orientation).

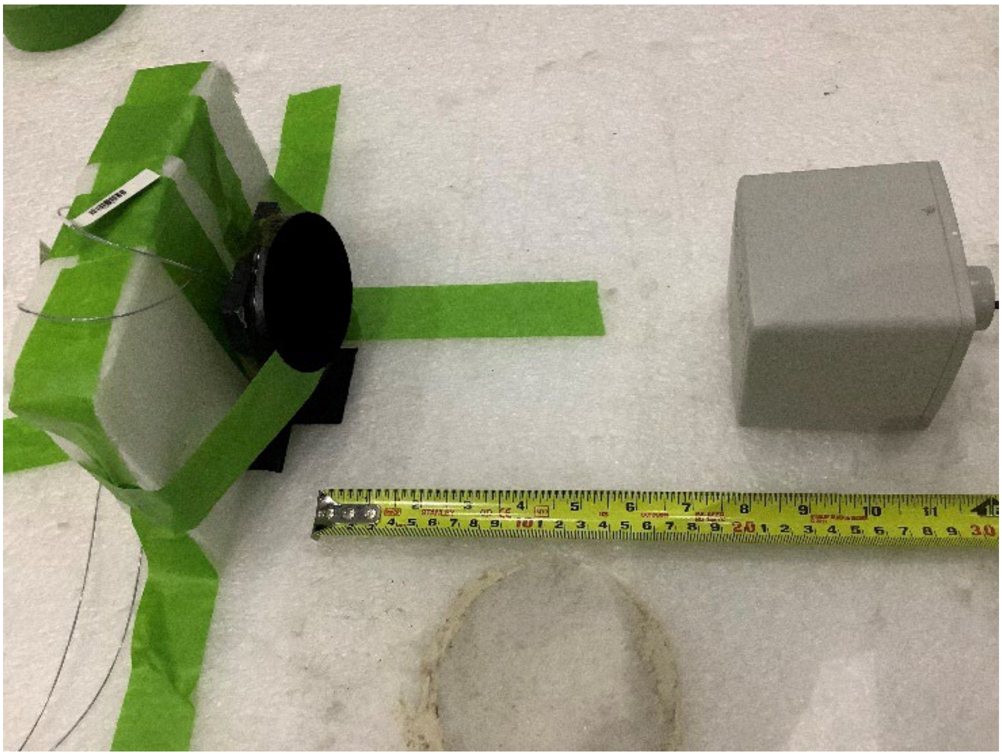


Figure 49: Isotropic Magnetic and Electric Field Probe Analyser setup

Table 39: Summary Comparison of Highest Measured E/H Field

Point	Frequency (kHz)	Measured Amplitude 20 cm Test Distance (A/m)	Measured Amplitude 20 cm Test Distance (V/m)
Highest Fundamental	288	0.2	1.65
Highest 2nd harmonic	576	0.02	0.7
Highest 3rd harmonic	864	0.015	0.5
Highest 4th harmonic	1152	0.01	0.5
Highest 5th harmonic	1440	0.01	0.5
Highest harmonic 1.5-10 MHz	5760 (20th harmonic)	0.02	0.7

A7.3.5 Coexistence with LW/MW/SW receiver

Understanding the impact WPT devices have on established AM receivers is one of the goals of this Annex. In this section a more direct approach was taken using a commercially available radio receiver in proximity to the WPT source. While this is not an expansive study of various receivers on the market, this data is a representative quantitative data point for a typical receiver that could be used in an urban/suburban residential or commercial environment. This receiver was chosen because more sophisticated or experienced operators of AM receivers may use more advanced receivers with improved gain and/or filtering circuitry. These users may also travel to areas with less near field interference and be more cognisant of operating interferers, such as WPT devices, in close proximity while in operation.

Summary of Data: an off the shelf AM receiver operating/receiving at the WPT fundamental shows an impact at close proximities near 1 metre but not at 5 metres and beyond. WPT harmonics show little to no impact even when at close proximities near 1 metre when operating as described within this section. This includes the commonly used 526 and 1606 kHz bands.

A7.3.5.1 Method and Data

The basic setup diagram is outlined in Figure 50 and shown in Figure 51. A loop antenna connected to a signal generator capable of 260 kHz-10 MHz Carrier and 1 kHz AM/50% modulation depth signal was used. The AM Receiver was set to its max AM RF Gain. Further details are here below:

- Transmit Loop Antenna: A.H Systems Part 2195 – 12 in Loop
- AM Signal Generator: Tektronix AFG 3252
- AM Receiver: Sangean 909x
- Time Domain Oscilloscope output of AM Receiver: Tektronix MDO4104B-3
- Frequency Domain Spectrum Analyzer output of AM Receiver: Agilent/Keysight E4446A

An attempt was made to adjust the transmitting AM signal to approximately 8.5 dBuA/m at the location of the Sangrean ATS 909X radio receiver. This particular receiver showed a signal strength on its display of approximately 1 on its signal strength scale of 10. The transmitting AM signal was increase to 3 on this scale and both the audible signal from the speaker and signal on the measurement oscilloscope were still highly unintelligible. For comparison, the receiver was moved to an area outside the chamber and tuned to various public broadcast channels. It was found that anything below 5 on the scale of 10 was highly unintelligible from a subjective listener perspective. Due to this performance, all testing was performed at a signal strength of 5 on the receiver. This value correlated to approximately 29.3 dBuA/m (transmitting loop 2.5 meters from receiving antenna). At this level, the audio signal could be clearly heard and the signal on the oscilloscope was stable for measurement purposes prior to introducing the WPT device. Note, the permanently attached receive antenna was used for the LW and MW measurements. An external SW antenna (long wire) was used for SW measurements.

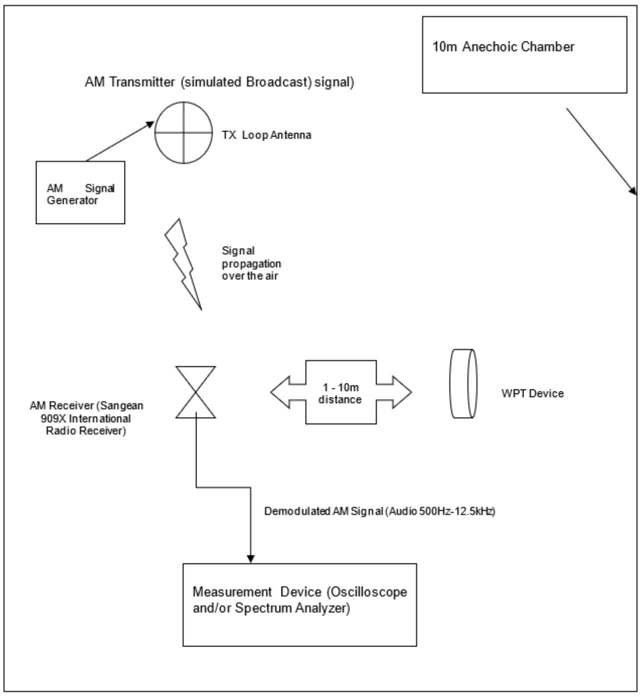


Figure 50: Basic setup diagram

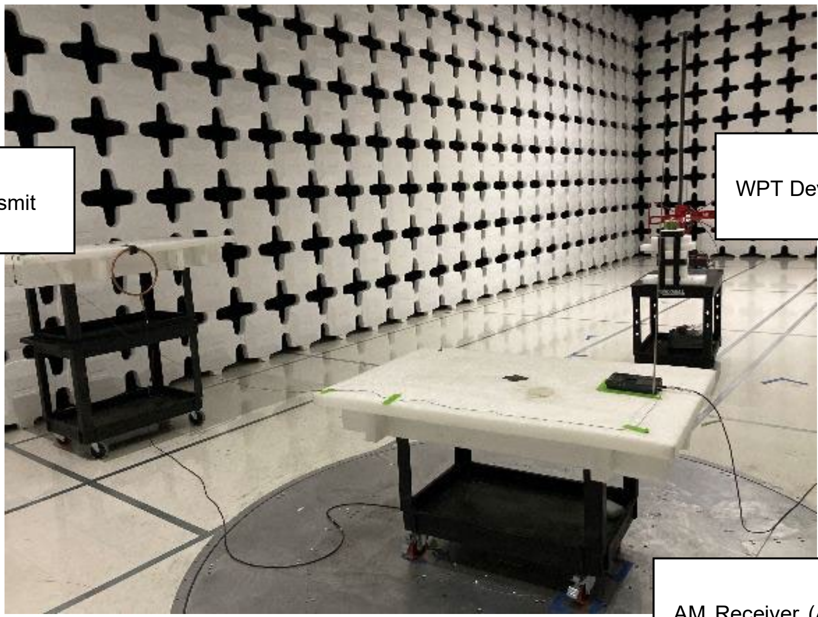


Figure 51: Measurement setup

Transmit Carrier frequencies were chosen by common broadcast channels and by the highest harmonics from the WPT charger as seen during radiated spurious measurements taken in section A7.3.3. This was done to increase the chance that the AM Receiver would be impacted by the WPT device.

Measurements were taken in the time domain and frequency domain to help analyse audio fidelity and to show unwanted individual harmonic content. The time domain signals were measured using a 5 giga-sample/second oscilloscope. The Envelope Acquisition mode with 100 samples was used to capture variations in signal content caused by poor demodulation or reception interference. An overall RMS value was also taken to gauge signal level.

For frequency domain measurements, a spectrum analyser was used to capture 500 Hz-12.5 kHz range which covers the most sensitive range of human hearing. Peak readings were taken at the 1 kHz demodulated signal and any key spurious or interference signals so relative level comparisons could be made. Once baselines were taken for reference, the WPT device was introduced in the range of 1 metre and 10 metre distances from the AM Receiver and data was recorded again. This was repeated with the AM Transmitter and AM receiver tuned to match the WPT devices fundamental signal and its harmonics in the LW, MW, and SW bands.

Table 40 is a summary of all the measurements of the demodulated 1 kHz signal output from the AM Receiver. Time Domain mV RMS taken with oscilloscope high impedance. Frequency domain dBm Values taken with 50 Ohm Spectrum Analyser.

Table 40: Measurements of the demodulated 1 kHz signal output from the AM Receiver

Description of AM Tuned Frequency	1 kHz signal performance Baseline (no WPT)	1 kHz signal performance when WPT 1 m Away	1 kHz signal performance when WPT 3 m Away	1 kHz signal performance when WPT 5 m Away	1 kHz signal performance when WPT 10 m Away	Disruption of AM Reception	Unwanted Frequency Content in Audible Range
Baseline Reference	1.72 mV RMS / -47.88 dBm	N/A	N/A	N/A	N/A	N/A	N/A
Coexistence Fundamental	1.72 mV RMS/-47.88 dBm	338 mV RMS/-82.2 dBm	0.841 mV RMS/-72.1 dBm	1.76 mV RMS/-47.85 dBm	1.73 mV RMS/-47.9 dBm	Only at 1 m	<20 dB delta from 1 kHz in 1-

Description of AM Tuned Frequency	1 kHz signal performance Baseline (no WPT)	1 kHz signal performance when WPT 1 m Away	1 kHz signal performance when WPT 3 m Away	1 kHz signal performance when WPT 5 m Away	1 kHz signal performance when WPT 10 m Away	Disruption of AM Reception	Unwanted Frequency Content in Audible Range
(289 kHz LW w/ 1kHz AM)							5 m Distance, >30 dB at 10 m distance
Coexistence (289 kHz offset +30 kHz LW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.72 mV RMS/-47.9 dBm	N/A	N/A	N/A	No	>30 dB delta from 1 kHz
Coexistence common broadcast frequency (526 kHz MW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.72 mV RMS/-47.9 dBm	N/A	N/A	1.72 mV RMS/-47.9 dBm	No	>30 dB delta from 1 kHz
Coexistence 3rd harmonic (840 kHz MW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.73 mV RMS/-47.86 dBm	N/A	N/A	1.72 mV RMS/-47.87 dBm	No	>30 dB delta from 1 kHz
Coexistence 5th harmonic (1400 kHz MW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.73 mV RMS/-47.84 dBm	N/A	N/A	1.72 mV RMS/-47.85 dBm	No	>30 dB delta from 1 kHz
Coexistence common broadcast frequency (1606 kHz MW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.74 mV RMS/-47.79 dBm	N/A	N/A	1.73 mV RMS/-47.83 dBm	No	>30 dB delta from 1 kHz
Coexistence 11th harmonic (3080 kHz SW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.74 mV RMS/-47.75 dBm	N/A	N/A	1.74 mV RMS/-47.73 dBm	No	>30 dB delta from 1 kHz
Coexistence 21st harmonic (5900 kHz SW w/1 kHz AM)	1.72 mV RMS/-47.88 dBm	1.77 mV RMS/-47.7 dBm	N/A	N/A	1.76 mV RMS/-47.72 dBm	No	>30 dB delta from 1 kHz

Based on the data, the largest coexistence impact is at the WPT devices fundamental frequency Near 280-290 kHz at 1 m distance. At 1 m there is an impact on reception as expected. At 3 metres and 5 metres, there is some audible impact, but the reception and demodulation process show little impact. At 10 metres there was no noticeable impact.

For all the other tuned frequencies tested related to the WPT’s harmonics, there was no noticeable impact on reception or demodulation at 1 m distance. This helps support the case the spurious readings from WPT devices in this Annex will not have detrimental impact on AM Broadcast receivers or similar reception devices in a similar context.

A7.3.5.2 Transmitted AM Signal References

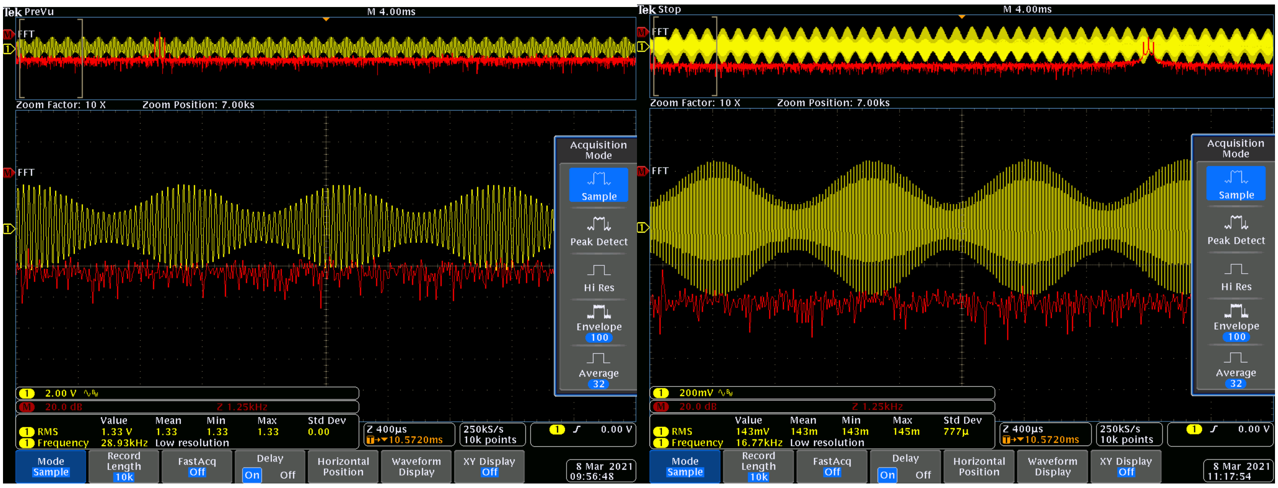


Figure 52: Left Figure: LW signal with 1 kHz/AM 50% depth). Right Figure: SW carrier with 1 kHz/AM 50% depth)

In all test cases, tuned frequencies were matched to WPT operating frequencies where possible. For example:

- WPT fundamental ~ 289 kHz. AM Transmitter and AM Receiver Tuned to AM frequency 289 kHz.
- WPT Harmonic ~867 kHz. AM Transmitter and AM Receiver Tuned to AM frequency 867 kHz.

If AM transmitter and AM receiver was offset/tuned away from the WPT fundamental frequency, the impact started to reduce the AM reception interference and audible noise. Once there was at least a 30 kHz offset from the fundamental at a 1 m distance, there was no impact on the received signal so further study was not performed as matching the frequencies had the largest impact for the purposes of this characterisation.

A7.3.5.3 Baseline Received Demodulated signal of 1 kHz (No WPT Present)

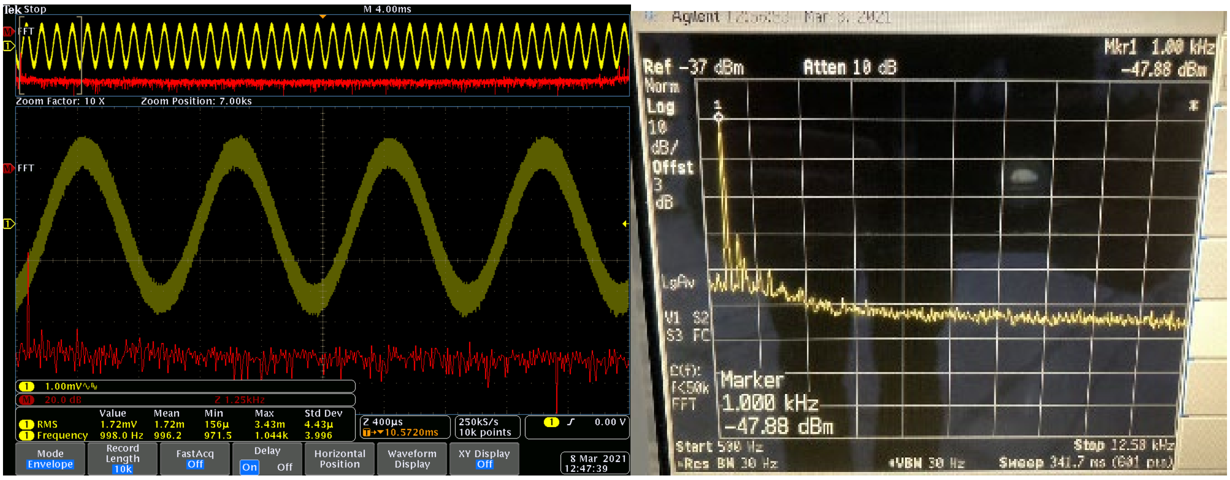


**Figure 53: (LEFT) Time Domain = 1.72 mV RMS into High Impedance)
(RIGHT) Frequency Domain (500 Hz-12.5 kHz) = -47.9 dBm into 50 Ohm**

Interpretation of Results

Figure 54 and Figure 55 are the measurements for spurious and fundamental values.

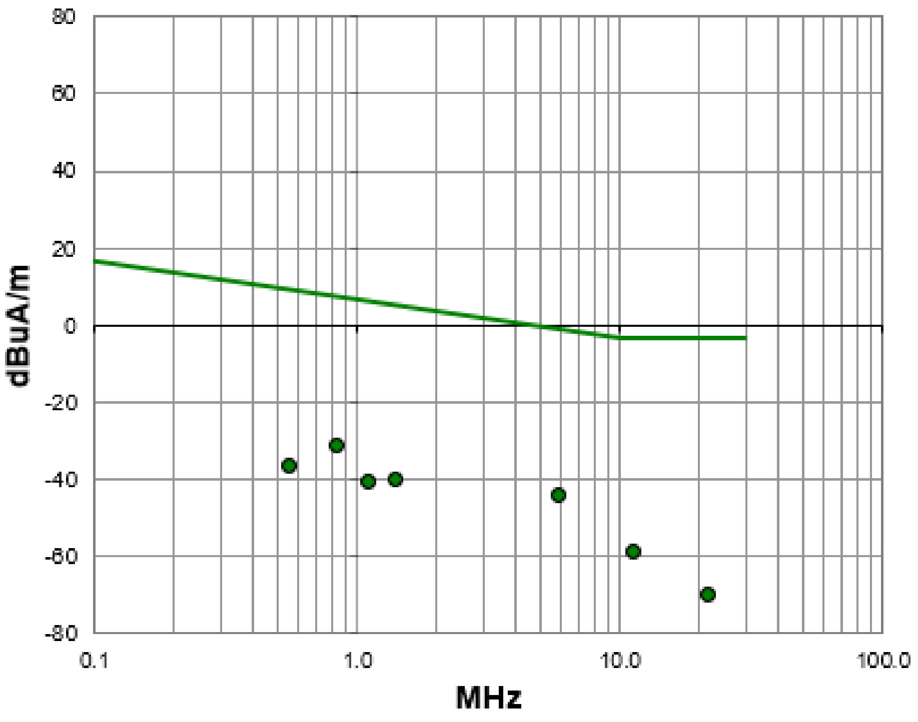


Figure 54: Spurious harmonics plotted with ERC Recommendation 74-01 2.1.3 10 m Spurious Limits

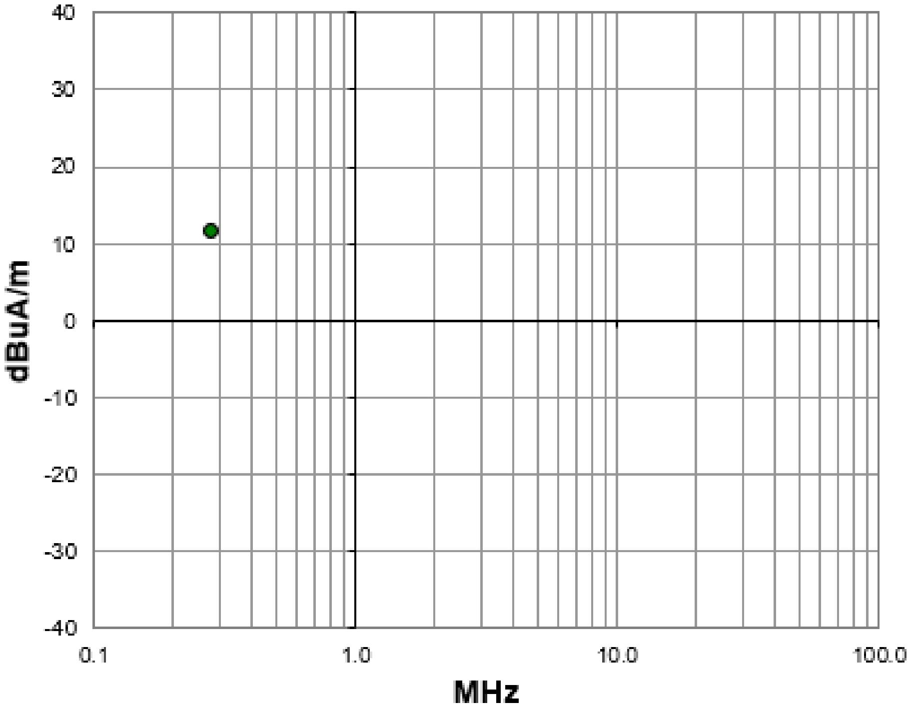


Figure 55 Fundamental at 10 m

The test results graph for the 284 kHz fundamental is 11.3 dBµA/m at 10 m.

A7.4 CONCLUSIONS

Based on the data, inductive WPT sources produce the maximum field when directly parallel or perpendicular to a loop receiving source when measured at 1, 3 or 10 meter distances and the source is relatively small compared to the receiving loop.

Taking OATS measurements of the WPT charger at an uncontrolled site provided little value outside the fundament frequency at 3 m or less test distance. It is clear operating measurement systems at certain frequency requires pre-site investigation if measurements are taken with the frequency bands used for public or private use. Most relevant frequencies (i.e. harmonics of the 260-320 kHz charger) have unwanted high ambient signals.

The coexistence test cases of the WPT charger in proximity to a commercially available AM receiver also showed limited impact on LW, MW, and SW radio bands. No significant impact from WPT harmonics were identified. Unless the AM receiver is tuned within 30kHz of the WPT's fundamental frequency and also operating at a very close distance of 1-3 meters, there was not detrimental impact to AM receiver performance based on the test cases.

A7.4.1 Spurious and Harmonics

Extrapolation from 1, 3, and 10 m shows consistent roll off the predicted 60 dB per decade. Also, spurious harmonics were compared to ERC Recommendation 74-01 which showed margin under the limit as seen in the section A7.4.

A7.4.2 Fundamental 260-320 kHz

There is an inconsistency in the current ERC Recommendation 70-03, annex 9 band k1 and ERC Recommendation 74-01, annex 2.1.3. The former has a fundamental requirement of -15.5 dBuA/m at 10 m where the latter has a requirement of 12 dBuA/m at the frequency 284 kHz for spurious. It is inconsistent to have the fundamental H-Field limited by such a restrictive level in the 148.5-300 kHz range, while the spurious harmonics of other SRDs can operate at nearly 20 dB higher levels in the same frequency band. Evidence that the existing limit in ERC Recommendation 70-03 of the -15.5 dBuA/m limit in the 148.5300 kHz has not been shown to be necessary and a more appropriate limit should be considered.

ANNEX 8: RESULTS OF SINGLE ENTRY CO-CHANNEL MONTE CARLO STUDY ON IMPACT FROM WPT (300-400 KHZ, 1610-1800 KHZ AND 1950-2150 KHZ) ON RADIO SERVICES

A8.1 PARAMETERS

A8.1.1 WPT Devices

A8.1.1.1 WPT Emissions

The emissions of WPT used in this study are provided in Table 41.

Table 41: WPT Emissions

Parameter	Value
WPT max. emissions (worst alignment)	-15 dBμA/m at 10 m
WPT min. emissions (best alignment)	-30 dBμA/m at 10 m
WPT operating frequency 1	400 kHz
WPT operating frequency 2	1650 kHz
WPT operating frequency 3	2000 kHz
WPT height above ground level (a.g.l.)	1.5 m

Each WPT device is constructed so that it only emits the maximum allowed level in the worst alignment position of the two coils while for many alignments positions the actual radiated level is much lower. The effect of alignment is considered by randomly picking an emissions level between best and worst alignment. More information on the effect of alignment can also be found in section A1.4.

For this study the co-channel impact of a WPT device is analysed.

A8.1.2 Generic Radio service parameters

Table 42 provides the parameters for the radio services used in the analyses.

Table 42: Parameters of the Radio Services

Parameter	Value
Rx Bandwidth	2.7 kHz (note 1)
Rx Frequency	400 kHz, 1650 kHz, 2000 kHz
RX Noise	Man-made noise (see section A8.1.3)
Antenna	Omni-directional
Height a.g.l.	1.5 m
Note 1: adjacent channel was not considered, overlapping channels were considered as fully co-channel	

The effect of interference is analysed by calculating the median interference level versus distance.

A8.1.3 Propagation

A8.1.3.1 Propagation Model

The propagation loss is based on description in ECC Report 6, section 5.9 [44] which is based on the propagation model as given in ERC Report 69 [52]. It is combining the magnetic coupling effect at close distances (60 dB per decade) with free space loss (20 dB per decade) in the far field. The transition between near and far field is modelled as 40 dB per decade. The model was programmed to output dBµA/m directly. Where the level at 10 m was different from -15 dBµA/m the difference was subtracted.

Two Breakpoints BP_1 and BP_2 are defined:

$$BP_1 = \frac{\lambda}{2 * \pi}$$

$$BP_2 = \frac{2.354 * \lambda}{2 * \pi}$$

d <= BP_1

$$level\ (dB\mu\frac{A}{m}) = 45 - 60 * log10\ (d)$$ (equivalent to -15 dBµA/m at 10 m distance)

BP_1 < d <= BP_2

$$level\ \left(dB\mu\frac{A}{m}\right) = level(at\ BP_1) - 40 * log10\ (d/BP_1)$$

d > BP_2

$$level\ \left(dB\mu\frac{A}{m}\right) = level(at\ BP_2) - 20 * log10\ (d/BP_2)$$

Where:

d distance in m

A8.1.3.2 Additional Propagation Losses

In cities, 30% of the paths are assumed to have a metal object between the interferer and the radio service receiver (i.e. metallized windows, steel reinforced concrete walls/floors, doors/gates, fences) while in residential areas, this is unlikely to appear. These values can also be understood as the percentage of buildings that are thermally efficient according to the definition of Recommendation ITU-R P. 2109 (i.e. metallised glass, foil-backed panels) [53] assuming an extension of the applicable domain of this Recommendation. 30% was taken from previous studies carried out in ECC, such as ECC Report 302 and ECC Report 244. The parameters used for the calculation are shown in Table 43. These losses are only applicable to distances at which magnetic coupling is the dominant propagation mechanism.

Propagation through wood or bricks does not lead to additional loss.

Table 43: Additional propagation losses assumptions

Parameter	Applicable %	Value (dB)
City propagation loss	30%	10

Where the loss was not applicable no loss i.e. 0 dB was applied.

A8.1.3.3 Noise Environment

The frequency range under consideration is often dominated by man-made noise. The analysis uses Recommendation ITU-R P.372 [7] as a baseline. In addition, man-made noise measurements carried out in the Netherlands (MN) are also used for analysis ([52]). These measurements were carried out at a distance of at least 10 m from the nearest building wall. In [52], it is clarified that the measurements aim at describing the man-made noise experience by radio service users, such as radio amateurs.

Table 44 and Table 45 show the median noise levels from ITU-R P.372 and from man-mad noise measurements in the Netherlands (MN) converted into magnetic field using 51.5 dB correction factor.

Table 44: Recommendation ITU-R P.372 Noise levels

Parameter	Level	Std Dev
400 kHz		
City Noise	- 32.82 dBµA/m	8.4 dB
Residential Noise	- 37.12 dBµA/m	5.8 dB
1650 kHz		
City Noise	- 37.56 dBµA/m	8.4 dB
Residential Noise	- 41.86 dBµA/m	5.8 dB
2000 kHz		
City Noise	-38.20 dBµA/m	8.4 dB
Residential Noise	-42.50 dBµA/m	5.8 dB

Table 45: Noise levels from measurements in the Netherlands (MN)

Parameter	Level (from Table V)	Std Dev (from Table III)
400 kHz		
City Noise	-18.47 dBµA/m	5.6 dB
Residential Noise	-23.97 dBµA/m	9.5 dB
1650 kHz		
City Noise	- 26.23 dBµA/m	6.4 dB
Residential Noise	- 32.34 dBµA/m	5.5 dB
2000 kHz		
City Noise	-27.28 dBµA/m	6.4 dB
Residential Noise	-33.84 dBµA/m	5.5 dB

A8.1.4 Discrimination loss

The alignment of the antenna of the radio service receivers to the field generated by the WPT charger is not fixed. A random discrimination loss is generated by first generating a random mismatch angle, θ, that is uniformly distributed from 0 to 360 degrees. The discrimination loss in dB is then given by:

$$Discrimination\ Loss = \min\left(-10\log_{10}(\cos^2\theta), 35\right) \quad (15)$$

The loss is capped at 35 dB at the boresight to account for imperfections in antenna and coil design.

A8.2 METHODOLOGY

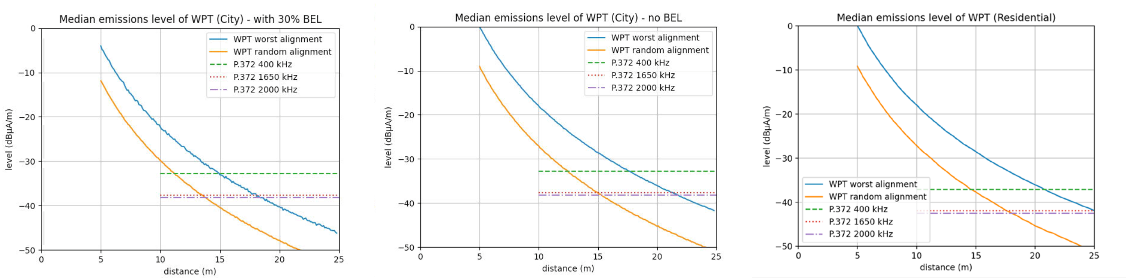
A single-entry Monte Carlo simulation is carried out in order to analyse the statistical impact of WPT charging at 400 kHz at 1650 kHz as well as at 2000 kHz. The interference situation in these bands is mostly dominated by man-made noise which is characterised by a mean and a standard deviation (spatial distribution). Any radio service that operates in these bands will face this level of man-made noise. Given its statistical nature the analysis was carried out to analyse the difference with and without WPT devices on the median.

The simulation setup is as follows:

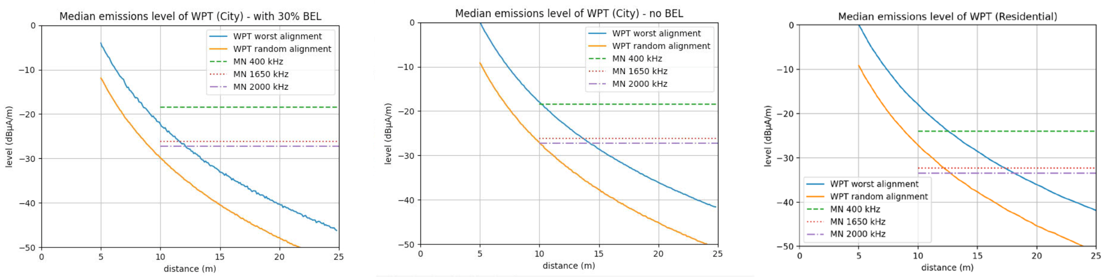
- Place a single radio service receiver at a distance of 5 m from the radio WPT device;
- Loop with 20000 events;
- WPT device is assigned an emission level (randomly varying from best to worst alignment);
- calculate the received interference level (sum) from the WPT (including propagation loss, discrimination);
- Store interference level;
- Calculate Median of the interference levels;
- Increase the distance between the single radio service receiver and the WPT device by 0.1 m;
- Show how the median emission level from a WPT device change with distance from the radio service receiver.

A8.3 SUMMARY OF RESULTS

Figure 56 shows the detailed results. The blue curve is based on the WPT device always having the worst alignment between the WPT charger and receiver coils only (hence being the upper bound), while the orange curve is based on random alignment between the coils (i.e. varying from best to worst alignment hence emissions). The horizontal lines represent the median man-made noise levels at 400 kHz, 1650 kHz and 2000 kHz.



(a) for Recommendation ITU-R P.372 as a reference



(b) for Measured Netherlands

Figure 56: Detailed results

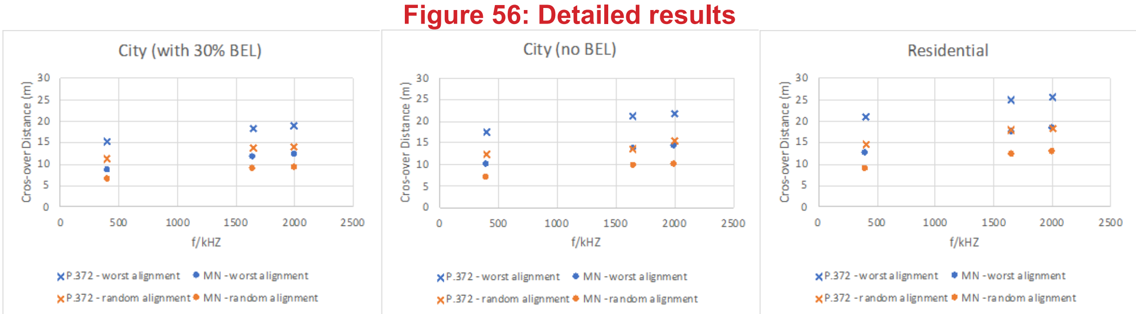


Figure 57 shows the distance at which the median interference level from a WPT device drops below the median noise floor.

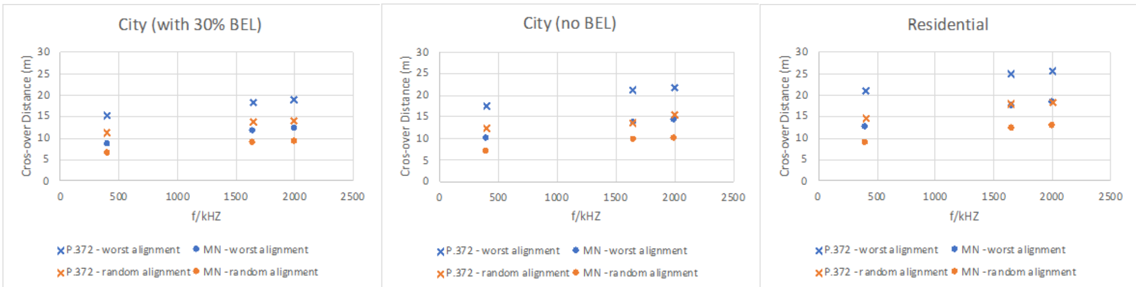


Figure 57: Detailed results

Table 46 shows a summary of the distance for which the emissions from the WPT charger drop below the median man-made noise level of a single-entry study.

Table 46: Distances in m for which the emissions from the WPT charger drop below the median man-made noise level of a single-entry study

	Noise Level	Worst alignment	Random alignment
Cities (30% BEL)	Recommendation ITU-R P.372 [7]	15 to 19 m	11 to 14 m
	Measured Netherlands	9 to 13 m	7 to 9 m
Cities (no BEL)	Recommendation ITU-R P.372 [7]	18 to 21 m	12 to 15 m
	Measured Netherlands	10 to 14 m	7 to 10 m
Residential areas	Recommendation ITU-R P.372 [7]	21 to 26 m	15 to 18 m
	Measured Netherlands	13 to 18 m	9 to 13 m

This single-entry study is a worst-case analysis, since it assumes that the WPT emissions are always co-channel to the radio service receiver.

This study compares the median Interference level to a median man-made Noise level and identifies the point below which the interference exceeds the man-made noise level. This is relevant to cases where protection can be expressed in terms of I/N, such as for the protection of digital systems. However, it is not applicable to analogue systems, including AM broadcasting, which are more susceptible to single tone interference (see A3.3.1).

It is noted that, the study does not consider emissions at other frequencies (i.e. spurious / harmonics) nor does it consider the situation of indoor reception, both of which are more relevant for AM broadcasting.

ANNEX 9: PRACTICAL COEXISTENCE MEASUREMENTS OF WPT AND AM RECEIVER

A9.1 GENERAL

A9.1.1 Introduction and background

A wide range of WPT devices are available on the market. In this study basic laboratory measurements were conducted on a selection of 14 different types of low power WPT devices to understand the potential impact they may have on an AM broadcasting receiver when operating in charging or idle mode.

A9.1.2 Selection of AM radio receiver

Three receivers were available for the study:

- Portable broadcast receiver 1;
- Portable broadcast receiver 2;
- Hi-Fi stereo receiver.

The Hi-Fi stereo receiver had the lowest noise performance and was used for most of the audio testing, although the portable receivers were used in testing with WPT devices which had the highest level of harmonic emissions.

A9.1.3 Selection of WPT devices

The WPT devices purchased for the testing included the following types :

- Multi-phone chargers;
- Basic desk mobile phone chargers;
- Multi-device chargers;
- Computer mouse pads;
- Car cradle mobile phone chargers;
- Electric toothbrushes;
- Power tool battery chargers;
- One of the phone chargers was also supplied with a cup for keeping liquids warm when placed onto the base-station and this was tested in both configurations.

Most of the WPT devices used for testing were Qi devices with a nominal fundamental frequency in the 100-148.5 kHz band and 5, 10 and 15 W of power transfer.

A9.1.4 WPT operating modes

The performance of the WPT device will vary depending on the operational mode. ETSI EN 303 417, table 2 [5] provides a description of the different charging modes:

- Mode 1: base-station in standby, idle mode;
- Mode 2: communication before charging, adjustment charging mode / position;
- Mode 3: communication;
- Mode 4: energy transmission

Testing is based on Mode 1 and Mode 4, which is referred to as base station idle and base station charging throughout this Report.

A9.1.5 Harmonic emission measurements

The harmonic emission levels for all 15 WPT devices were first measured.

A9.1.6 Test Arrangement

The test arrangement was based on the requirements given in ETSI EN 300 330, annex C [12]. Radiated measurements were made in a semi-anechoic chamber (SAC) using a loop antenna placed at 3 metres from the WPT device. The device was placed on a turntable and rotated through 360° to find the direction of highest radiation.

The WPT device was placed in its expected plane of operation, e.g. a desktop charger was placed flat on the turntable, while a car charger was mounted upright as it would be when installed in a vehicle. For devices placed flat on the turntable, arguably the highest emissions occur in the plane directly above the device. However, it is considered unlikely that a radio would be suspended a few metres above the WPT device in a normal domestic environment.

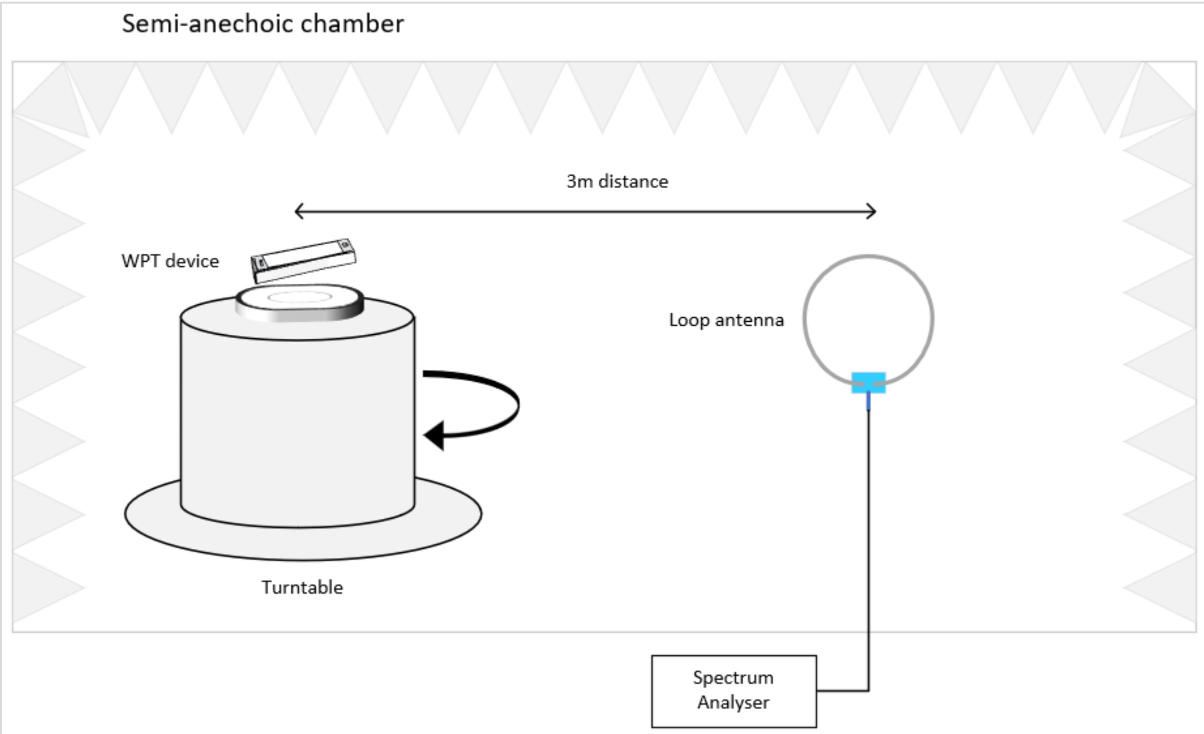


Figure 58: Test arrangement for Harmonic emission measurements

A9.1.7 Measurement Units

In practice, an AM radio will be in the far field (more than $\lambda/2\pi$) from the broadcast transmitter so the free-space relationship between electric and magnetic field components applies and field strength is specified in dBµV/m. In contrast, the radio will be in the near field from a WPT device and so will be susceptible to the magnetic field strength.

The magnetic field strength by measuring the voltage (in dBµV) using a loop antenna at 3 m distance is determined, and the magnetic antenna factor (dBS/m) is applied. All found from the calibration data sheet:

$$H\ (dB\mu A/m) = V\ (dB\mu V) + K\ (dBS/m)$$

Measurements were made with a spectrum analyser using a peak detector and MAX HOLD function. Resolution bandwidth was set to 1 kHz to reduce the analyser noise floor and allow low level signals to be measured.

A9.1.8 Results of harmonic emission measurements

The harmonic levels for the devices when idle and charging are shown in Figure 59 and Figure 60, measured at 3 metres distance. The tabulated results are presented in section A1.4.

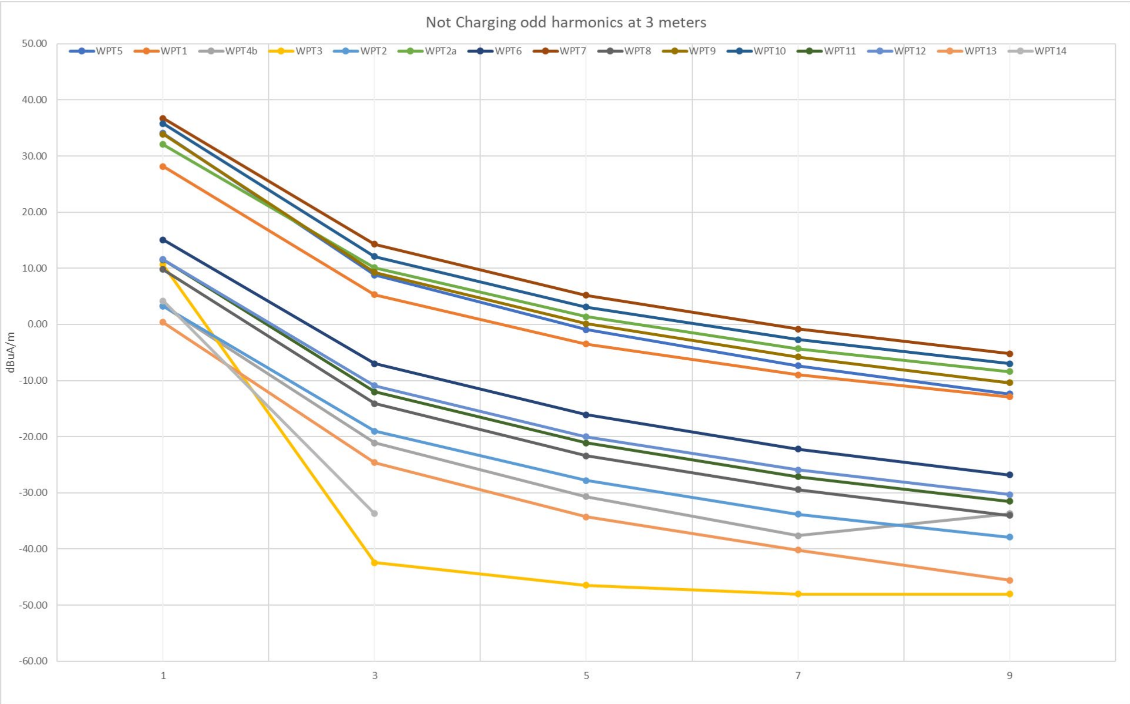


Figure 59: Harmonic emission levels of WPT devices when idle

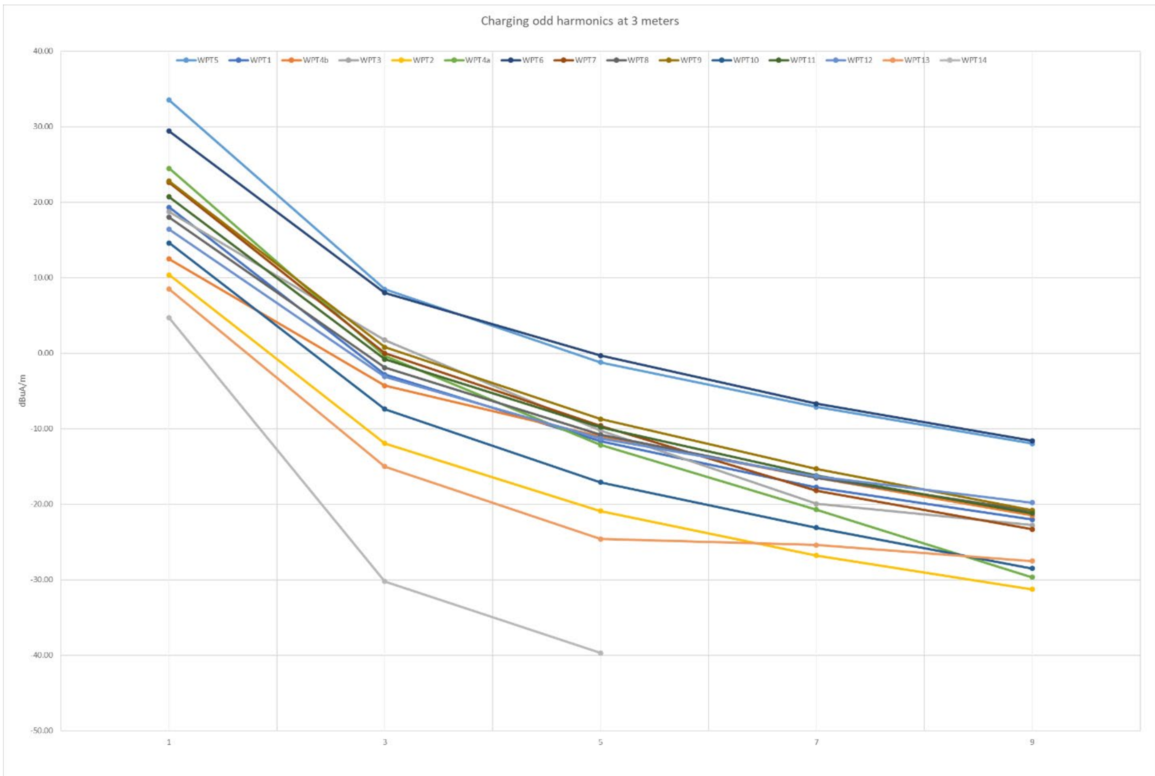


Figure 60: Harmonic emission levels of WPT devices when charging

Figure 59 and Figure 60 show that the rate of decline of the harmonics for each device is relatively constant, the 3rd harmonic falls within the broadcast MW band.

To measure the higher order harmonics on some devices, due to their low levels, it was necessary to reduce the distance of the receiving loop to the WPT device to 1 meter and use the cubed law to calculate the level at 3 metres.

Figure 61 shows where the 5th harmonic falls within the AM radio band and the measured field strength in both idle and charging modes. There is a larger spread in both frequency and signal strength when the devices are in idle mode. The emissions are focussed at the lower end of the MW band, with none of the 5th harmonics occurring above 900 kHz.

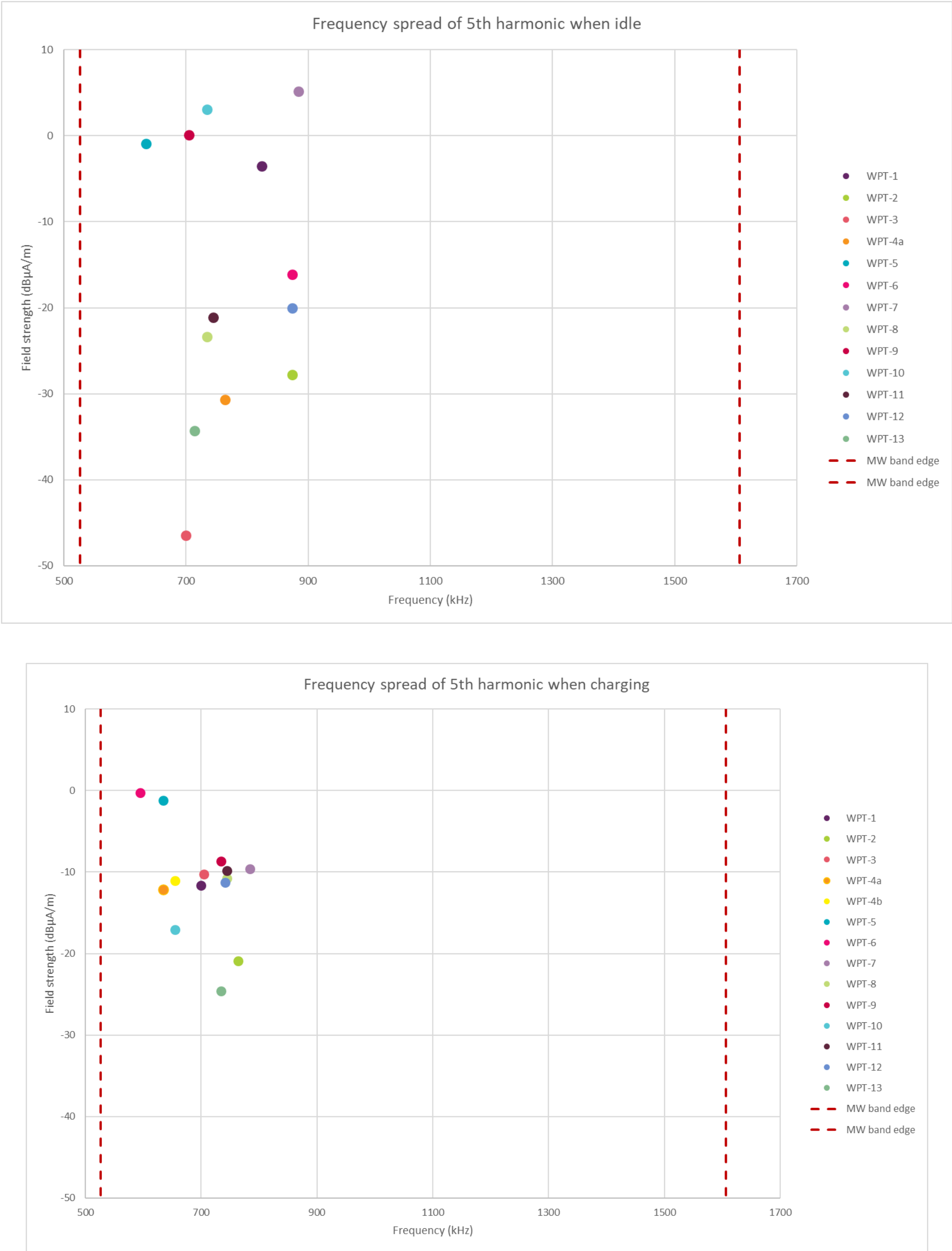


Figure 61: Frequency and field strength of 5th harmonic in idle (above) and charging (below) modes

A9.2 IMPACT ANALYSIS ON AM BROADCASTING

The harmonic emission results is used to inform selection of five WPT devices for use in further testing to determine the impact on AM broadcast services operating in the band 526.5–1606.5 kHz. 5 devices from a possible 15 were selected.

A9.2.1 Subjective impairment scale

The analysis is based on subjective assessment of audio quality using the ITU 5-point scale given in Recommendation ITU-R BS.1284 [59].

Table 47: Subjective audio quality impairment scale

Quality		Impairment
5	Excellent	Imperceptible
4	Good	Perceptible, but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

The initial testing suggested interference is either just audible or very significant. Therefore, for each test is graded the audio quality as either level 5 (excellent), level 4 (good) or level 1 (bad).

A9.2.2 Test arrangement

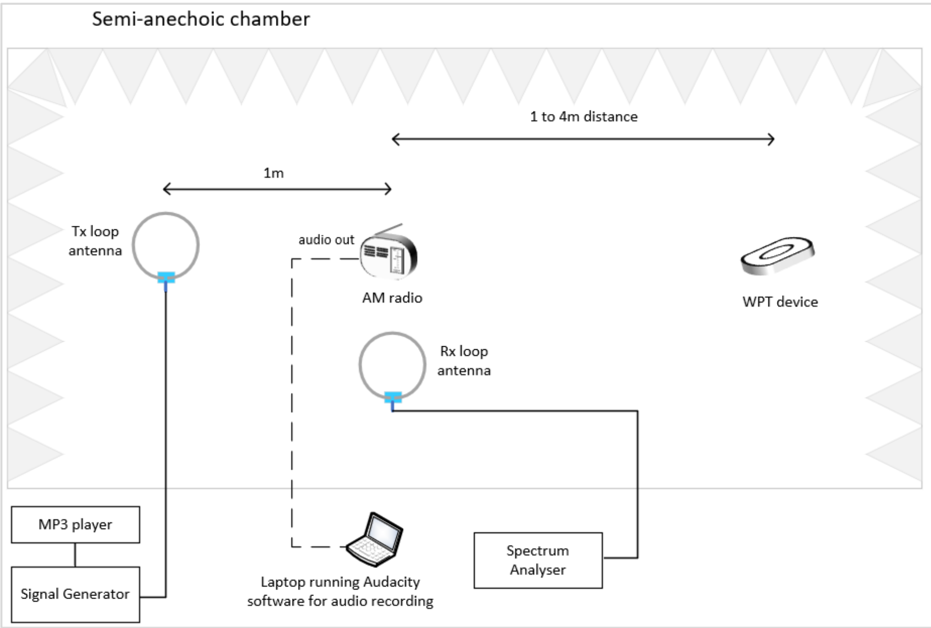


Figure 62: Test arrangement for subjective audio impact analysis

A9.2.3 Testing methodology

For the impact analysis, a 30 second speech recording provided from the BBC Radio 5 Live studios, with the normal audio processing and compression applied, ready for transmission over the AM network. This audio file was played through a broadcast quality MP3 player and used this to modulate an RF carrier generated by the signal generator. A loop antenna was used to generate a wanted field strength of 66 dBμV/m[19], which was verified using a second loop antenna located adjacent to the AM broadcast receiver.

The WPT device was orientated to give the highest measured emission levels and the receiver was tuned to a frequency that overlapped with the 5th harmonic. The separation distance between the radio and WPT device was then varied from 1 to 4 metres, and at each step the audio output from the receiver's headphone jack was monitored and recorded. These recordings were saved as audio files.

For each test it was subjectively assessed whether the audio content was excellent (grade 5), good (grade 4) or bad (grade 1) using the ITU impairment scale.

In practice it is found that the frequency of the WPT device varied by a few kHz during the test, as the level of charge in the battery varied. In most cases the audio degradation was more noticeable when the WPT frequency was slightly offset from the channel the radio was tuned to.

A9.2.4 Subjective Audio Quality Results

The results of our impact analysis are shown in Table 48. The results are shown as the subjective audio impairment recorded for each separation distance, for the WPT device in both idle and charging modes.

Table 48: Results of subjective audio quality impairment tests

Device ID	1 m separation		2 m separation		3 m separation		4 m separation		5.9 m separation (see note 1)	
	Idle	Charge	Idle	Charge	Idle	Charge	Idle	Charge	Idle	Charge
WPT1	1	1	1	1	4	4	5	5	-	-
WPT2	1	1	4	4	5	5	5	5	-	-
WPT3	-	1	-	4	-	4	-	5	-	-
WPT4a	1	1	5	1	5	5	5	5	-	-
WPT4b	1	1	5	1	5	5	5	5	-	-
WPT5	1	1	1	1	4	4	4	4	5	5
Note 1: The 5.9 m separation distance is equivalent to increasing the broadcasting signal level by 10 dB										

The results show that at separation distances of less than 2 metres, the audio quality impairment is generally intolerable. At 3 metres, the audio quality impairment caused by some of the selected WPT devices is still perceptible, but would not necessarily be considered annoying. Beyond 4 metres, the audio quality impairment is imperceptible for most of the WPT devices tested, with the exception of WPT5 which required a separation of 5.87 metres to be imperceptible.

[19] In the UK, it was assumed a minimum field strength of 66 dBμV/m for commercial radio services in the Medium Wave band: Coverage and planning policy for analogue radio broadcasting services, Ofcom, June 2018.

A9.3 COMPARISON OF PROTECTION RATIOS

Table 49: Comparison of protection ratios(All values in the Table are given in dB)

Device ID	1 m separation		2 m separation		3 m separation		4 m separation		5.9 m separation (see note 1)	
	Idle	Charge	Idle	Charge	Idle	Charge	Idle	Charge	Idle	Charge
WPT1	-10.6	-2.5	7.4	15.5	18	26.1	25.4	33.5	-	-
WPT2	13.7	6.8	31.7	24.8	42.3	35.4	49.7	42.8	-	-
WPT3	32.4	-3.9	50.4	14.1	61	24.7	68.4	32.1	-	-
WPT4a	16.6	-2	34.6	16	45.2	26.6	52.6	34	-	-
WPT4b	16.6	-3.1	34.6	14.9	45.2	25.5	52.6	32.9	-	-
WPT5	-13.2	-12.9	4.8	5.1	15.4	15.7	22.8	23.1	32.6	32.9
Note 1: The 5.9 m separation distance is equivalent to increasing the broadcasting signal level by 10 dB										

A9.3.1 Repeatability of Results

During testing it was found that care must be taken to get repeatable results:

- It was found out that the frequency of the WPT device can drift as the device charges;
- In some cases, the frequency appears to jump to a different channel without warning;
- The fundamental frequency (and hence the frequency of the harmonics) when idle and when charging is different (apart from one device tested);
- Small changes in alignment between the WPT device and the radio can change the results.

For these reasons there is a small level of uncertainty in the results, but the general conclusions still hold.

A9.4 TABULATED RESULTS OF HARMONIC EMISSION MEASUREMENTS

Table 50: WPT1-5 in idle mode

	WPT1		WPT2		WPT2 Vertical		WPT3		WPT4		WPT5	
Odd Harmonics	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m
1st	164.8	+28	174.8	+3	174.8	+32	139.9	+11	152.8	+3	126.9	+34
3rd	494.4	+5	524.4	-19	524.4	+10	419.7	-42	458.4	-21	380.7	+9
5th	824	-3	874	-28	874	+1	699.5	-46	764	-31	634.5	-1
7th	1153.6	-9	1223.6	-34	1223.6	-4	979.3	-48	1069.6	-38	888.3	-7
9th	1483.2	-13	1573.2	-38	1573.2	-8	1259.1	-48	1375.2	-34	1142.1	-12

Table 51: WPT1-5 in charging mode (device 4a in cup warming mode)

	WPT1		WPT2		WPT2 Vertical		WPT3		WPT4		WPT5	
Odd Harmonics	kHz	dBµA/m	kHz	dBµ A/m	kHz	dBµA/m	kHz	dBµA/ m	kHz	dBµA/ m	kHz	dBµA/m
1st	139.9	19	152.8	10	140.9	19	126.9	24	130.9	12.5	126.9	33
3rd	419.7	-3	458.4	-12	422.7	2	380.7	0	392.7	-4.3	380.7	8
5th	699.5	-12	764	-21	704.5	-10	634.5	-12	654.5	-11	634.5	-1
7th	979.3	-18	1069.6	-27	986.3	-20	888.3	-21	916.3	-16.5	888.3	-7
9th	1259.1	-22	1375.2	-31	1268.1	-23	1142.1	-30	1178.1	-21.5	1142.1	-12

Table 52: WPT6-10 in idle mode

	WPT6		WPT7		WPT8		WPT9		WPT10	
Odd Harmonics	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m
1st	174.8	15.1	176.8	36.7	146.9	9.8	140.9	33.9	146.9	35.8
3rd	524.4	-7.0	530.4	14.3	440.7	-14.1	422.7	9.3	440.7	12.1
5th	874.0	-16.1	884.0	5.2	734.5	-23.4	704.5	0.1	734.5	3.1
7th	1223.6	-22.2	1237.6	-0.8	1028.3	-29.4	986.3	-5.8	1028.3	-2.7
9th	1573.2	-26.8	1591.2	-5.2	1322.1	-34.0	1268.1	-10.4	1322.1	-7.0

Table 53: WPT6-10 in charging mode

	WPT6		WPT7		WPT8		WPT9		WPT10	
Odd Harmonics	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m
1st	118.9	29.4	156.8	22.6	148.9	18.0	146.9	22.8	130.9	14.6
3rd	356.7	8.0	470.4	0.0	446.7	-1.9	440.7	0.8	392.7	-7.4
5th	594.5	-0.3	784.0	-9.6	744.5	-10.8	734.5	-8.7	654.5	-17.1
7th	832.3	-6.7	1097.6	-18.2	1042.3	-16.5	1028.3	-15.3	916.3	-23.1
9th	1070.1	-11.6	1411.2	-23.3	1340.1	-20.9	1322.1	-20.8	1178.1	-28.5

Table 54: WPT11-14 in idle mode

	WPT11		WPT12		WPT13		WPT14	
Odd Harmonics	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m
1st	148.9	11.5	174.8	11.6	142.9	0.4	41.0	4.2
3rd	446.7	-12.0	524.4	-10.9	428.7	-24.6	123.0	-33.7
5th	744.5	-21.1	874.0	-20.0	714.5	-34.3	205.0	
7th	1042.3	-27.1	1223.6	-25.9	1000.3	-40.2	287.0	
9th	1340.1	-31.5	1573.2	-30.3	1286.1	-45.6	369.0	

Table 55: WPT11-14 in charging mode

	WPT11		WPT12		WPT13		WPT14	
Odd Harmonics	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m	kHz	dBµA/m
1st	148.9	20.7	148.3	16.4	146.9	8.5	43.0	4.7
3rd	446.7	-0.8	444.9	-3.1	440.7	-15.0	129.0	-30.2
5th	744.5	-9.8	741.5	-11.3	734.5	-24.6	215.0	-39.7
7th	1042.3	-16.2	1038.1	-16.3	1028.3	-25.4	301.0	
9th	1340.1	-21.2	1334.7	-19.8	1322.1	-27.5	387.0	

ANNEX 10: IMPACT STUDY OF NON-BEAM INDUCTIVE WPT APPLICATIONS IN 300–400 KHZ ON THE AERONAUTICAL RADIONAVIGATION SERVICE

A10.1 PARAMETERS FOR SIMULATION

This study looked at the proposed value of -15 dBµA/m as the maximum emissions for the WPT devices. Modelling was used for near field propagation. All WPT devices for the study were assumed to be using the same frequency (400 kHz), while in real life quite a spread of the actual charging frequencies depending on the actual implementation, charging status etc. can be observed.

The parameters of the Aeronautical Radionavigation Service are described in section 4.5.

A10.2 SIMULATION SCENARIOS AND RESULTS

A10.2.1 Single-entry scenario

The single-entry scenarios place a single WPT device inside a building with the aircraft placed directly above the building outdoors (Figure 63).

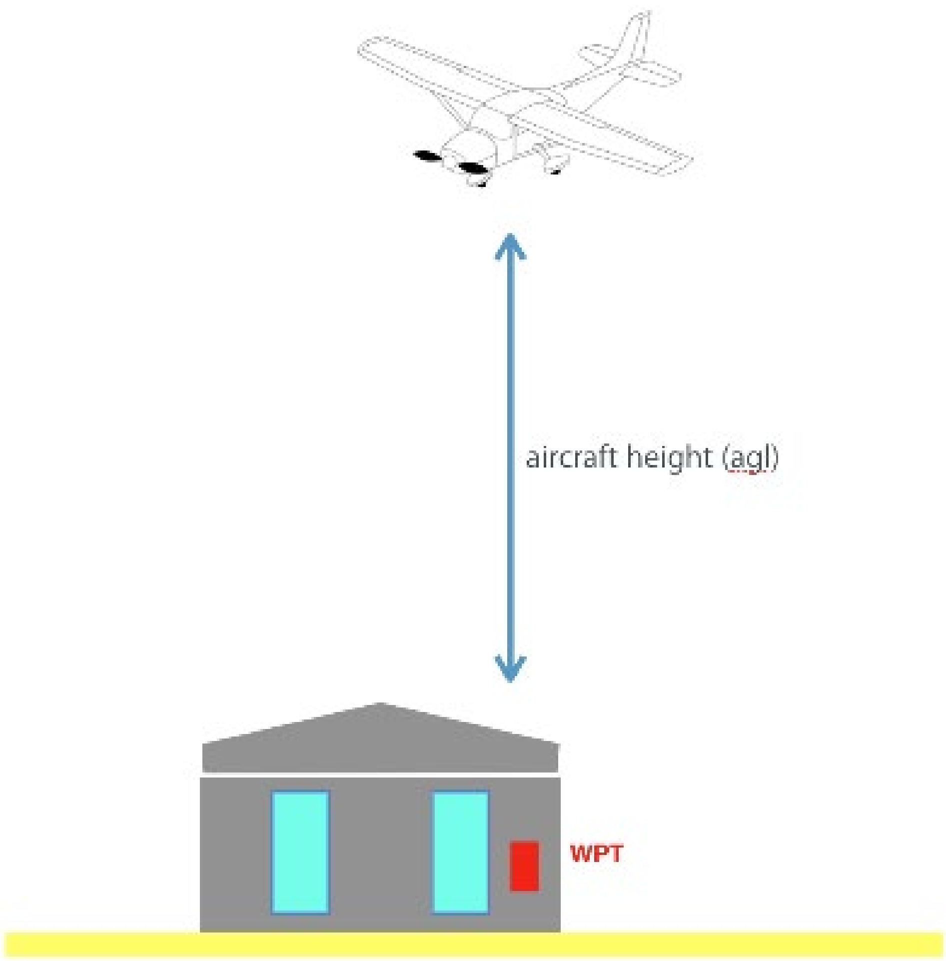


Figure 63: Single-entry scenario

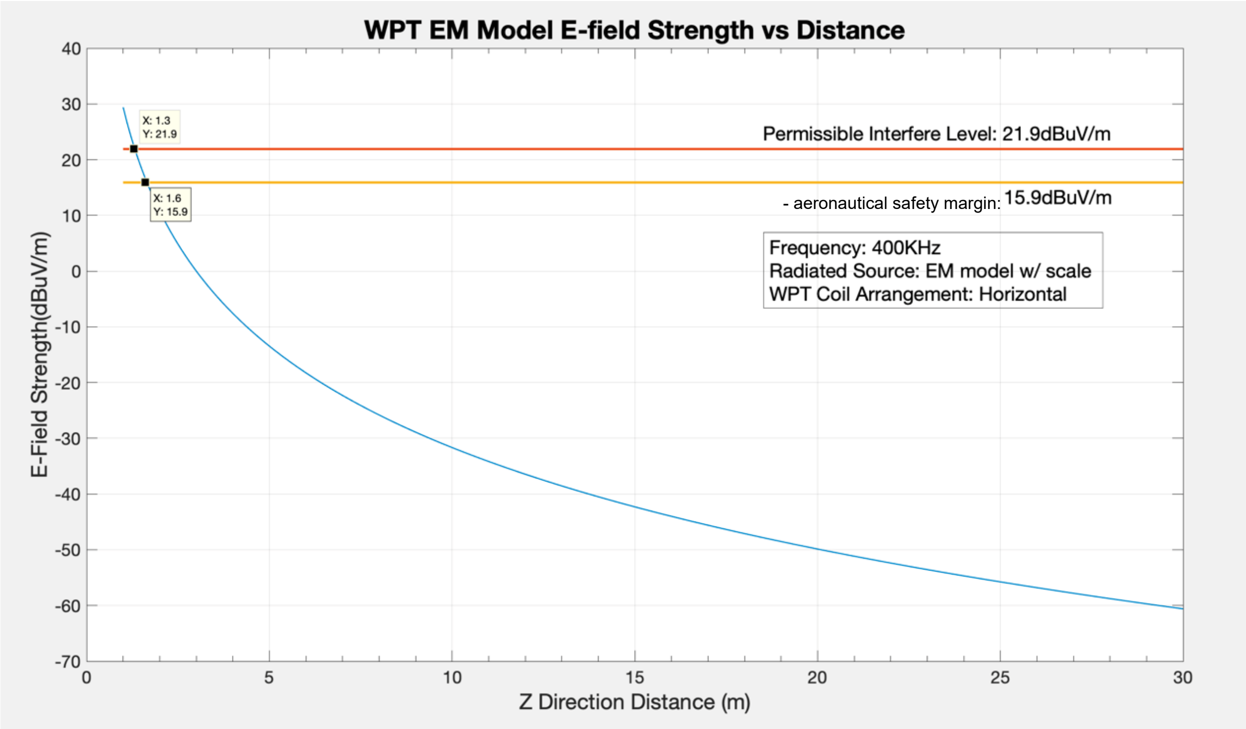


Figure 64: Single-entry E-field vs. height above ground level (m) for horizontal WPT coil

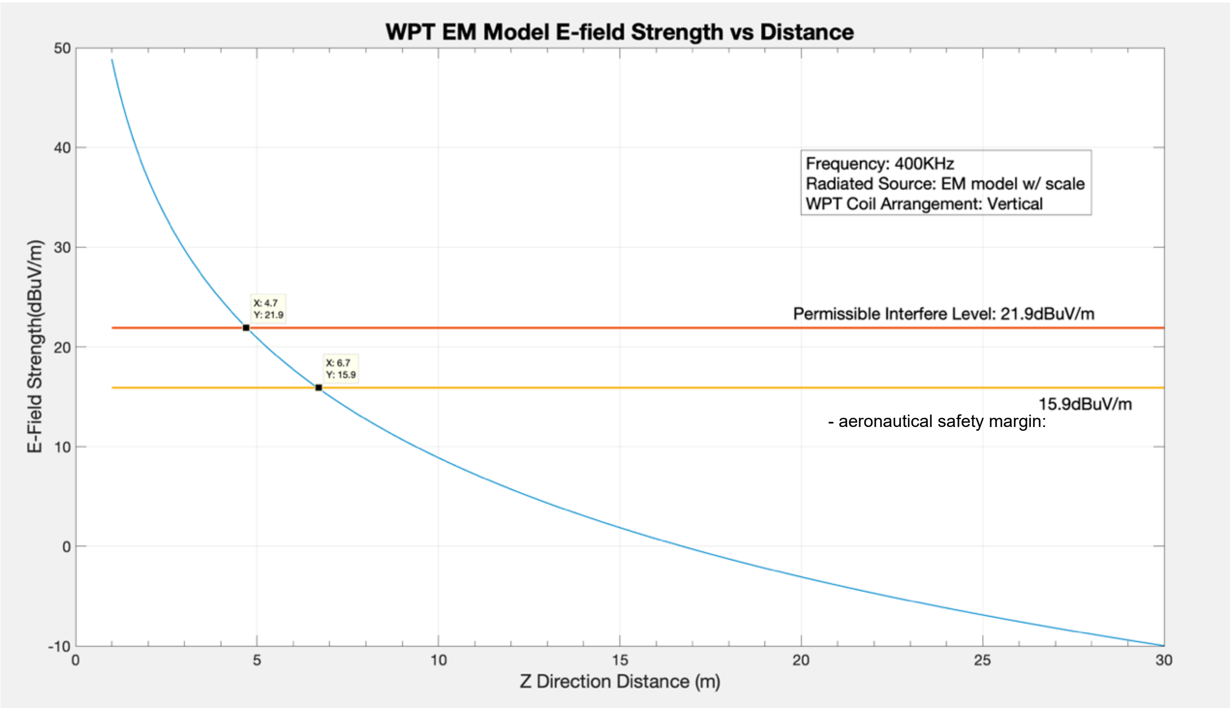


Figure 65: Single-entry E-field vs. height above ground level (m) for vertical WPT coil

Conclusions for single-entry scenario

The results for single-entry scenario show that the impact to the ADF receiver is below the threshold for a distance less than 5 m considering the worst case of a vertical WPT coil. Considering the aeronautical safety margin, the threshold is exceeded for distances less than 7 m. Building entry loss (roof/ceilings) were not included in the simulation but would further reduce the interference impact from WPT devices to ADF/NDB.

A10.2.2 Aggregate scenario

The aggregate scenario considers WPT devices separated by 10 m within a 500 m × 500 m square. This represents an array of 50 × 50 WPT devices. Different activity levels are simulated. Two aircraft altitudes were simulated at 100 m and 300 m. As a reference, the minimum safe altitudes in the UK are 500 feet (≈150 m) above open water or sparsely populated areas, and 1000 feet (≈300 m) above urban areas, respectively. The aircraft ADF receiver antenna is located over the centre of the square. The radiated fields are aggregated using vector aggregation. The spread of horizontal vs vertical alignment of the charging coil was 50/50. At each run the orientation of the coil was randomly assigned. No effects from buildings or other structures have been considered.

The density of WPT devices simulated is equivalent to 10000 devices/km^2.

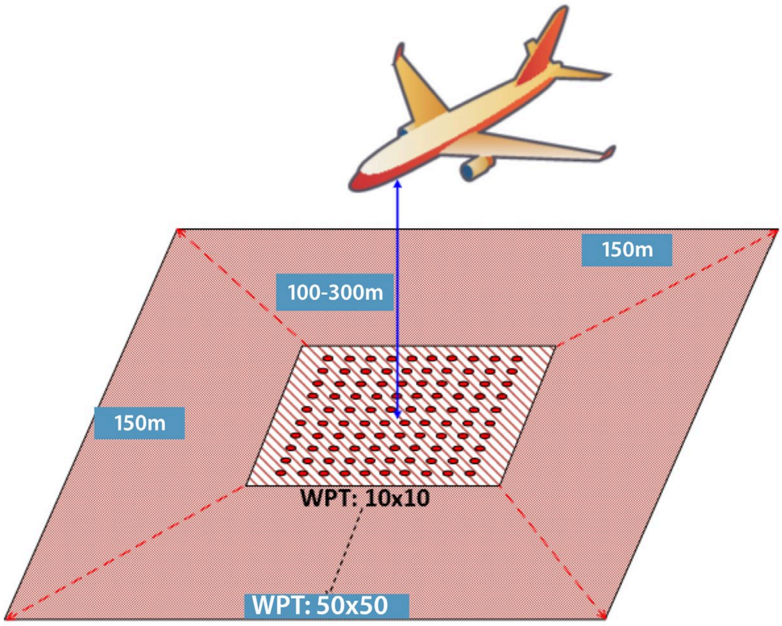


Figure 66: Depiction of aggregate scenario

Table 56 shows the results for an aircraft altitude of 100 m.

Table 56: Aggregate WPT radiated E-field distribution (100 m aircraft height)

Activity Factor	Emax (dBµV/m)	Avg. (dBµV/m)	Std	Max. Permissible Interference (dBµV/m)	Margin/Gap (dB)	Permissible level including aeronautical safety margin (dBµV/m)	Margin/Gap (dB)
10%	−0.9	−4.5	1.14	21.9	22.8	15.9	16.8
30%	9.1	7.4	0.6	21.9	12.8	15.9	6.8
50%	15.6	14.4	0.4	21.9	6.3	15.9	0.3

Conclusions for aircraft altitude of 100 m

The simulation has shown that the maximum calculated field strength even at 50% activity factor is less than the maximum permissible interference by 6.3 dB. Considering the aeronautical safety margin the margin/gap reduces to 0.3 dB. Building entry loss (roof/ceilings) were not included in the simulation, but would further reduce the interference impact from WPT devices to ADF. It should be noted that 100 m height above ground in areas with such high population density are below the safe flight altitude.

Table 57 shows the results for an aircraft altitude of 300 m.

Table 57: Aggregate WPT radiated E-field distribution (300 m aircraft height)

Activity Factor	Emax (dBµV/m)	Avg. (dBµV/m)	Std	Max. Permissible Interference (dBµV/m)	Margin/Gap (dB)	Permissible level including aeronautical safety margin (dBµV/m)	Margin/Gap (dB)
10%	-5.5	-7.7	0.8	21.9	27.3	15.9	21.3
30%	3.2	1.8	0.5	21.9	18.7	15.9	12.7
50%	11.2	10.3	0.3	21.9	10.7	15.9	4.7

Conclusions for aircraft altitude of 300 m

The simulation has shown that the maximum calculated field strength even at 50% activity factor is less than the maximum permissible interference by 10.7 dB. Considering the aeronautical safety margin, the margin/gap reduces to 4.7 dB. Building entry loss (roof/ceilings) were not included in the simulation, but would further reduce the interference impact from WPT devices to ADF.

A10.2.3 Summary of the results

The simulations have shown that WPT chargers for mobile and portable devices do not interfere with the reception of ADF/NDB signals. Building entry loss (roof/ceilings) were not included in the calculation/simulation but would further reduce the interference from WPT devices to ADF.

ANNEX 11: CO-CHANNEL STUDY FOR THE AMATEUR RADIO SERVICE IN 136-138 KHZ

The parameters for the amateur service receivers came from Recommendation ITU-R M.1732 [8] and are shown in Table 58. This Recommendation does not contain interference protection criteria for amateur operations in this frequency range. A protection criterion of I/N=–6 dB is assumed for the purposes of this study.

Table 58: Parameters assumed for the Amateur service receiver

Parameters	Value
Centre frequency (kHz)	136.75
Bandwidth (kHz)	0.4
Antenna pattern	Omni-directional
Minimum noise level (dBµV/m)	31.6
Protection criteria (I/N) (dB)	−6
Permissible interference level (dBµV/m)	25.6

A11.1 PARAMETERS USED FOR SIMULATION

An actual Qi WPT charger was measured at a distance of 3 m to determine its emissions when charging a real phone as shown in Figure 67.

RADIATED EMISSIONS BELOW 30MHz (FRONT – WITH REAL PHONE)

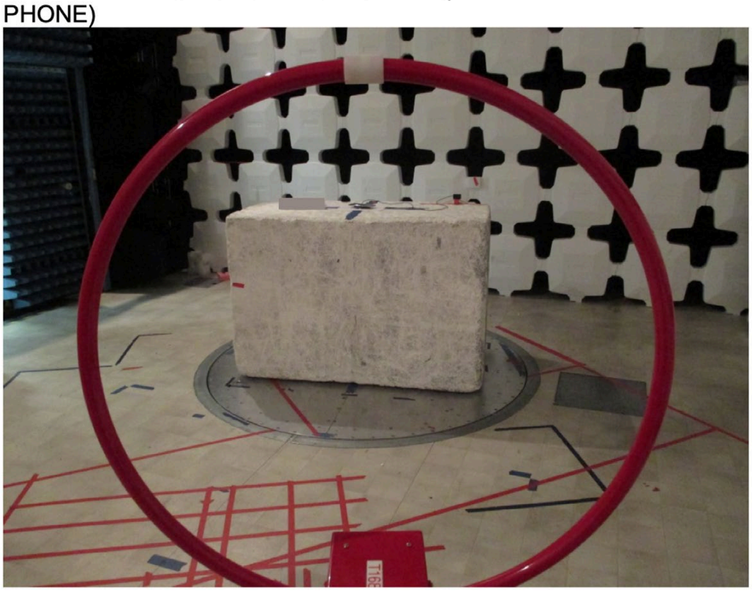


Figure 67: Measurement Setup

The level measured at 3 m distance was 13.3 dBµA/m. This level was then used to calibrate an EM Model implemented in MATLAB which was used to determine the near field propagation. The wireless charger model sized 120x80x5 (mm*mm*mm) with a 30 mm coil radius was simulated. A metal plate sized 120x80 (mm*mm) is placed under the coil as shown in Figure 68.

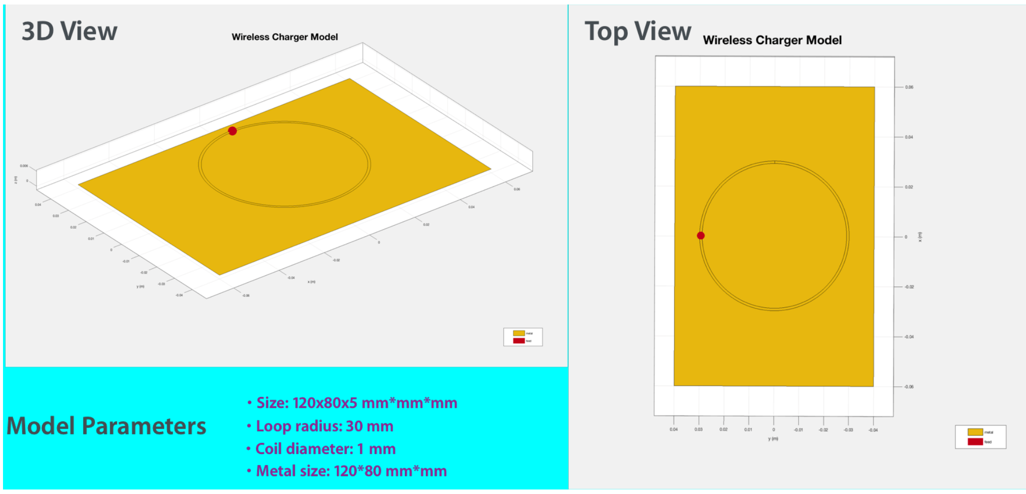


Figure 68: Wireless Charger Model

An example of simulated current distribution and electric and magnetic field distribution is shown in Figure 69.

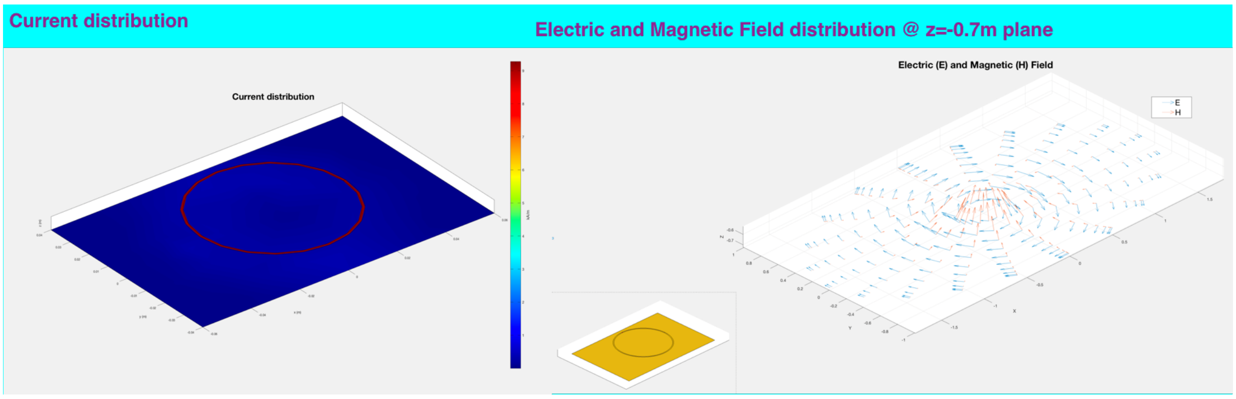


Figure 69: Example of Wireless Charger Current and Electric and Magnetic Field distribution

The emissions of the WPT device(s) in this study were then based on the EM model.

A11.2 SIMULATION ANALYSIS AND RESULTS

A11.2.1 Single-entry scenarios

The single-entry scenarios place a single WPT device inside a building with the amateur receive antenna located away from the building outdoors. The first simulation uses 0 dB building entry loss and the second uses 10 dB building entry loss to account for different building materials.

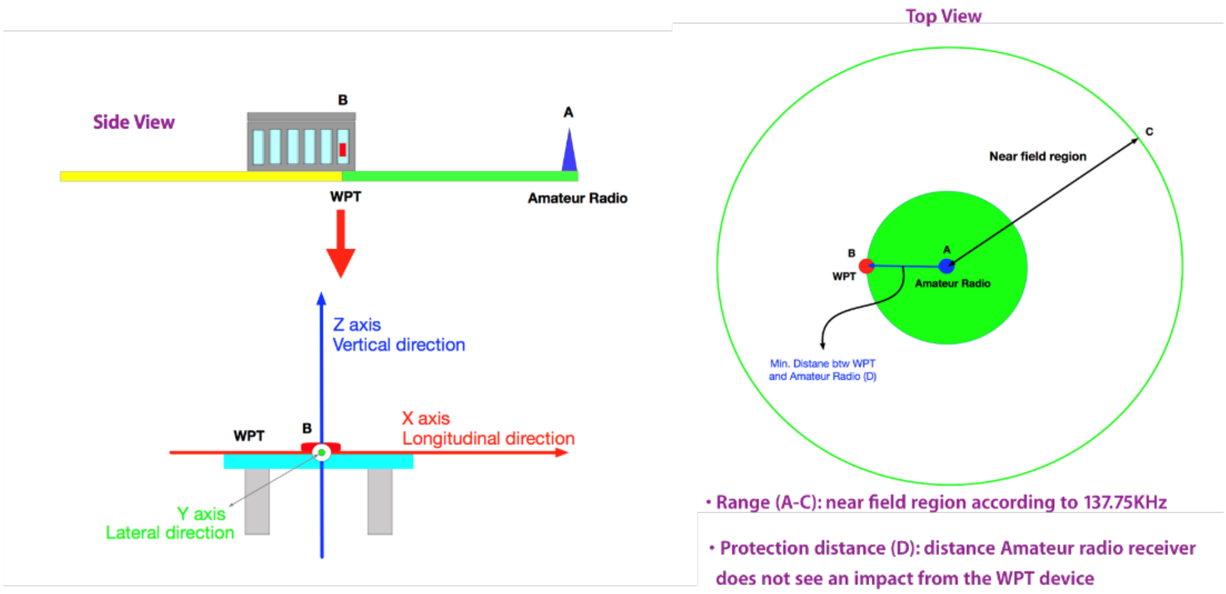


Figure 70: Single entry scenario

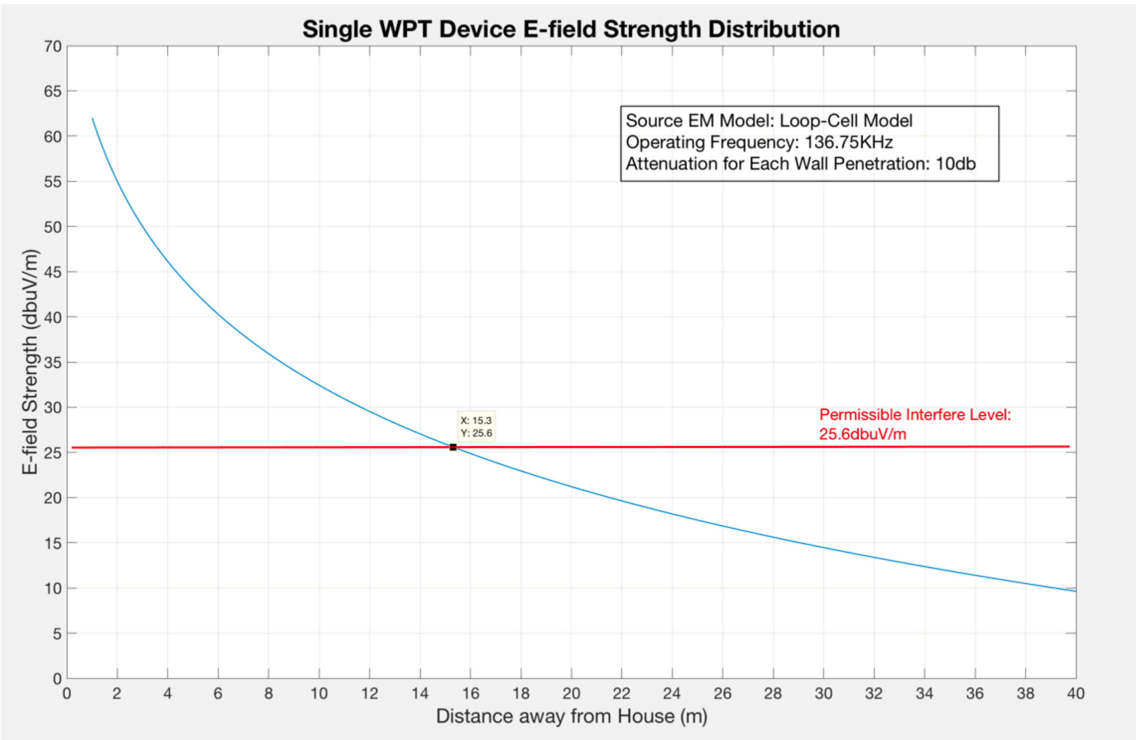


Figure 71: Single-entry distribution for scenario 1

Conclusions for single-entry scenario 1:

The results for single-entry scenario 1 using a 10 dB attenuation to simulate concrete building construction show the WPT device should be placed more than 15.3 m from the amateur radio receive antenna (see Figure 71).

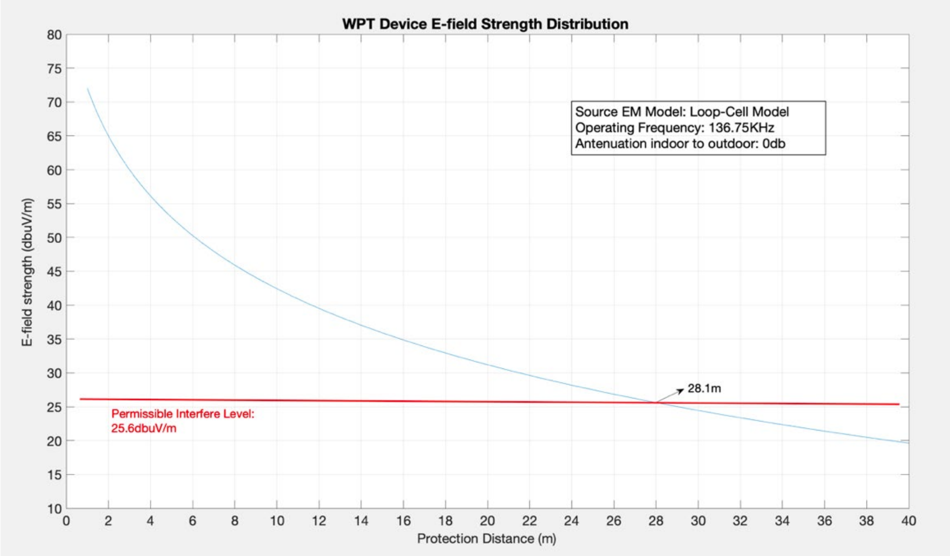


Figure 72: Single-entry distribution for scenario 2

Conclusions for single-entry scenario 2:

The results for single-entry scenario 2 using a 0 dB attenuation to simulate wooden building construction or brick walls show the WPT device should be placed more than 28.1 m from the amateur radio receive antenna (see Figure 72).

A11.2.2 Aggregate scenarios

The aggregate scenarios use four WPT devices located inside a house. Each of the WPT devices is positioned 1 m from the wall and then is randomly distributed in various corners of the rooms. The first scenario uses 10 dB building entry loss to simulate the effects of concrete walls (which is generally steel reinforced concrete) and the second scenario uses 0 dB for wooden construction or brick walls (perfect propagation conditions).

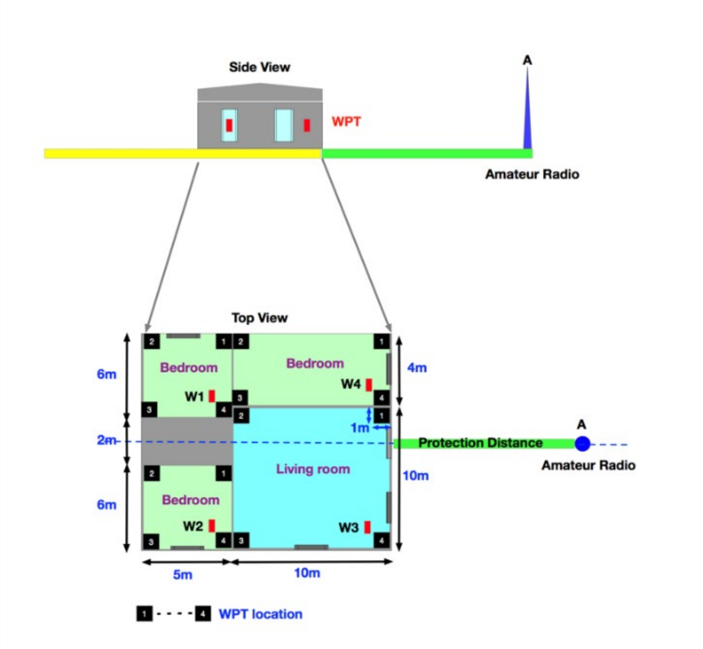


Figure 73: Depiction of Model #1 aggregate scenario

To simulate different building materials, the building entry loss for both wooden and concrete walls were assessed to determine the protection distance. The values are included in Table 59 below.

Table 59: Values used for building entry loss

Parameter	Number of walls	Wooden/Brick wall building entry loss (dB)	Concrete wall building entry loss (dB)
WPT1	2	0	20
WPT2	2	0	20
WPT3	1	0	10
WPT4	1	0	10

The WPT devices are assigned a random phase for each single calculation. All WPT devices operate exactly on the same frequency (worst case assumption).

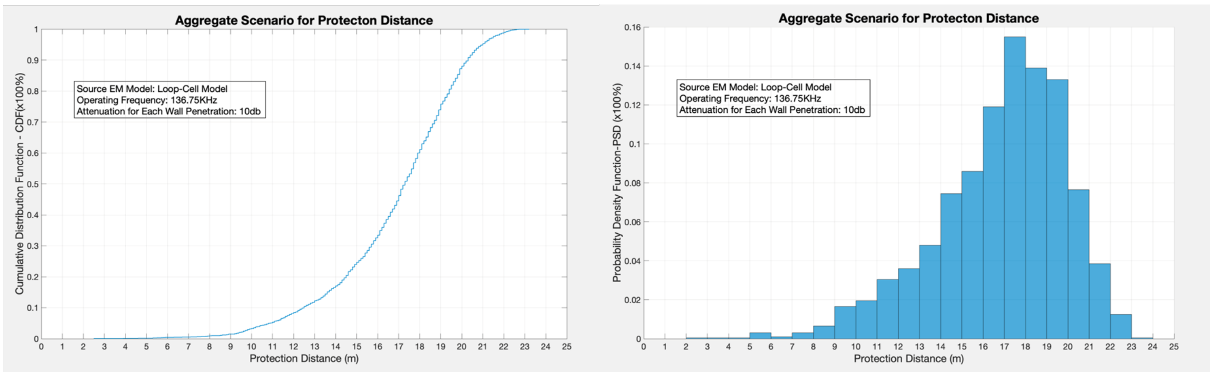


Figure 74: Results of simulation with 10 dB building entry loss

Conclusions for aggregate simulation 1

The median protection distance is 17.1 m and the maximum distance is 23.2 m based on 10 dB building entry loss from concrete walls (see Figure 74). The range of values is a result of the WPT device placement. The 23.2 m maximum distance is when the WPT device is placed within close proximity of the outdoor walls and phases of the signal overlap constructively. The minimum distance as low as 2.5 m is the case when the WPT device is placed near interior walls and/or phases of the signals overlap destructively.

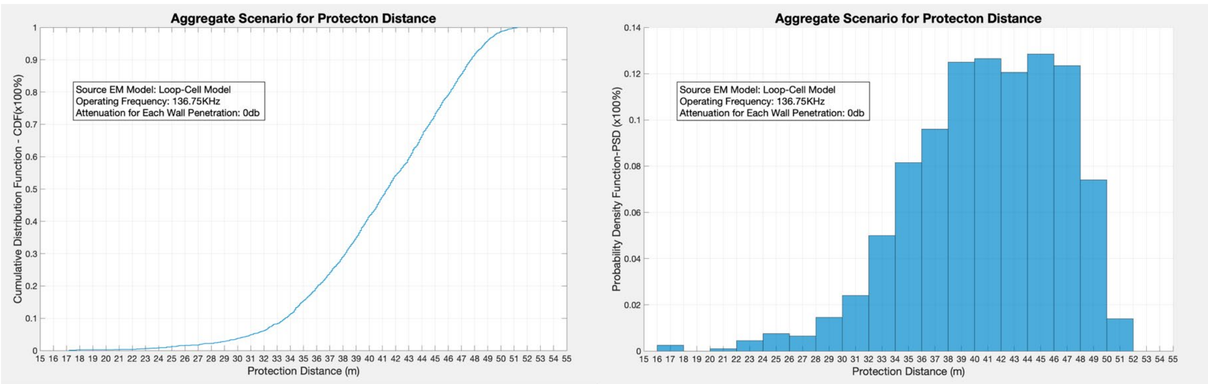


Figure 75: Results of simulation with 0 dB building entry loss

Conclusions for aggregate scenario 2

The median protection distance is 42.0 m and the maximum distance is 51.3 m based on 0 dB building entry loss from wooden/brick walls (see Figure 75). The range of values is a result of the WPT device placement. The 51.3 m maximum distance is when the WPT device is placed within close proximity of the outdoor walls and phases of the signal overlap constructively. The minimum distance as low as 17.2 m is the case when the WPT device is placed near interior walls and/or phases of the signals overlap destructively.

A11.3 SUMMARY OF RESULTS

Table 60 summarises the results of the simulations. Based on the simulation results, it can be concluded that non-beam WPT mobile charging devices do not impact amateur service receivers when the devices are placed more than 51.3 m from the receiver antenna as a worst case.

Table 60: Summary of results for a single WPT frequency

Scenario	Permissible interference level (dBµV/m)	Separation distance (m)
Single-entry scenario 1	25.6	15.3
Single-entry scenario 2	25.6	28.1
Aggregate scenario 1	25.6	23.8
Aggregate scenario 2	25.6	51.3

The exact location (e.g. height difference) and the actual radiation pattern of the Amateur service receiver antenna would mitigate the interference impact. Also, it is unlikely that all WPT chargers will operate on the same frequency which would further reduce the interference impact.

ANNEX 12: LIST OF REFERENCES

[1] ETSI TR 103 493: “System Reference document (SRdoc); Wireless Power Transmission (WPT) systems operating below 30 MHz”

[2] ISO 14708-3:2017: “Implants for surgery - Active implantable medical devices - Part 3: Implantable neurostimulators”

[3] EN/IEC 60601-1-2 - (4th Edition): “Medical electrical equipment - Part 1-2: General requirements for basic safety and essential performance - Collateral Standard: Electromagnetic disturbances”

[4] EC Directive 2014/53/EU on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment

[5] ETSI EN 303 417: “Wireless power transmission systems, using technologies other than radio frequency beam, in the 19 - 21 kHz, 59 - 61 kHz, 79 - 90 kHz, 100 - 300 kHz, 6 765 - 6 795 kHz ranges”

[6] ECC Report 289: “Wireless Power Transmission (WPT) systems for electrical vehicles (EV) operating within 79-90 kHz band”, approved January 2019

[7] Recommendation ITU-R P.372: “Radio noise”

[8] Recommendation ITU-R M.1732: “Characteristics of systems operating in the amateur and amateur-satellite services for use in sharing studies”

[9] Recommendation ITU-R M.1044: “Frequency sharing criteria in the amateur and amateur-satellite services”

[10] Recommendation ITU-R F.240: “Signal-to-interference protection ratios for various classes of emission in the fixed service below about 30 MHz”

[11] ERC Recommendation 74-01: "Unwanted emissions in the spurious domain", approved 1998, latest update October 2021

[12] ETSI EN 300 330: “Short Range Devices (SRD); Radio equipment in the frequency range 9 kHz to 25 MHz and inductive loop systems in the frequency range 9 kHz to 30 MHz; Harmonised Standard (draft) covering the essential requirements of article 3.2 of the Directive 2014/53/EU

[13] CISPR 11: “Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement. IEC 2015 amended to 2019”

[14] ETSI EN 50561-1:2013: “Power line communication apparatus used in low-voltage installations. Radio disturbance characteristics. Limits and methods of measurement. Apparatus for in-home use”

[15] ITU-T G.993.2 Amendment 2 (03/2016): “Very high speed digital subscriber line transceivers 2 (VDSL2)”, (Section 7.2.1.2 Egress Control); https://www.itu.int/rec/T-REC-G.993.2

[16] ITU-T G.9700 Amendment 2 (06/2017): “Fast access to subscriber terminals (G.fast) - Power spectral density specification (Section 6.5 Notching of specific frequency bands)”

[17] ITU Radio Regulations 15.12 § 8: Administrations shall take all practicable and necessary steps to ensure that the operation of electrical apparatus or installations of any kind, including power and telecommunication distribution networks, but excluding equipment used for industrial, scientific and medical applications, does not cause harmful interference to a radiocommunication service and, in particular, to a radionavigation or any other safety service operating in accordance with the provisions of these Regulations.

[18] ITU Radio Regulations 15.13 § 9: Administrations shall take all practicable and necessary steps to ensure that radiation from equipment used for industrial, scientific and medical applications is minimal and that, outside the bands designated for use by this equipment, radiation from such equipment is at a level that does not cause harmful interference to a radiocommunication service and, in particular, to a radionavigation or any other safety service operating in accordance with the provisions of these Regulations.

[19] ETSI EN 201 980: “Digital Radio Mondiale System Specification”

[20] Report ITU-R BS-2433 (2018): “Assessment of modulation depth for AM sound broadcasting transmissions”

[21] Recommendation ITU-R BS.703:“Characteristics of AM sound broadcasting reference receivers for planning purposes”

[22] Recommendation ITU-R BS.560: “Radio-frequency protection ratios in LF, MF and HF broadcasting”

[23] Final Acts of the Regional Administrative LF/MF Broadcasting Conference (Regions 1 and 3); Geneva 1975

[24] Final Acts of the Regional Administrative LF/MF Broadcasting Conference (Region 2); Rio de Janeiro 1981

[25] P. F. Panter: “Modulation, Noise and Spectral Analysis” McGraw Hill New York (1965)
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[30] ITU Radio Regulations, edition 2020

[31] ERC Recommendation 70-03: “Relating to the use of Short Range Devices (SRD)”, approved 1997, latest amended November 2021

[32] Recommendation ITU-R BS.1895: “Protection Criteria for Terrestrial Broadcasting Systems”

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[34] ITU-R WP1A Contribution 1A/449 “Reply liaison statement to Working Parties 1B, 5A and 6A - Building entry losses in the range 9 kHz to 10 MHz (far-field and near field)”

[35] Report ITU-R BS.2433 “Assessment of modulation depth for AM sound broadcasting transmissions”

[36] EC Decision (EU) 2017/1483; Amendment to Decision 2006/771/EC on harmonisation of the radio spectrum for use by short-range devices and repealing Decision 2006/804/EC (notified under document C(2017) 5464)

[37] Report ITU-R SM.2153-7 “Technical and operating parameters and spectrum use for short-range radiocommunication devices” (June 2019)

[38] EC Electromagnetic Compatibility (EMC) Directive 2014/30/EU

[39] BBC Research and Development White Paper WHP344 (2019) “Qi Charging Devices and AM Interference Levels”

[40] Recommendation ITU-R SM.329: “Unwanted emissions in the spurious domain”

[41] ECC Report 135: “Inductive limits in the frequency range 9 kHz to 148.5 kHz”, approved September 2009

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[43] ICAO "Handbook on Radio Frequency Spectrum Requirements for Civil Aviation": https://www.icao.int/safety/FSMP/Documents/Doc9718/Doc9718_Vol_I_2nd_ed_(2018)corr1.pdf

[44] ECC Report 67: “Compatibility study for generic limits, for the emission levels of inductive SRDs below 30 MHz”, approved October 2005

[45] ECC Report 7: “Compatibility between inductive LF RFID systems and radiocommunication systems in the frequency range 135 – 148.5 kHz”, approved April 2002

[46] ERC Report 44: “Sharing between inductive systems and radiocommunications systems in the band 9 – 135 kHz”, approved1997

[47] ERC Report 25: "The European Table of Frequency Allocations and Applications in the frequency range 8.3 kHz to 3000 GHz", approved 1994, latest amended October 2021

[48] Report ITU-R SM.2449: "Technical characteristics and impact analyses of non-beam inductive wireless power transmission for mobile and portable devices on radiocommunication services"

[49] ETSI EN 303 345: "Broadcast Sound Receivers"

[50] Recommendation ITU-R SM.1753: "Methods for measurements of radio noise"

[51] Recommendation ITU-R SM.2093: "Methods for measurements of indoor radio environment"

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