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SM Series: Spectrum management

Impact analyses of non-beam magnetic inductive and magnetic resonant wireless power transmission for mobile and portable devices on radiocommunication services

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R SM.2449-1

Impact analyses of non-beam magnetic inductive and magnetic resonant wireless power transmission for mobile and portable devices on radiocommunication services

(Question ITU-R 210-4/1)

(2019-2024)

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1 Introduction[1]

With the increased demand for wireless devices and global mobility, wireless power transmission (WPT) technologies for powering these devices has evolved and are now readily accessible worldwide for consumers. The WPT by magnetic inductance is a well-known technology, applied for a very long time in transformers where primary and secondary coils are inductively coupled, e.g. by the use of a shared magnetic permeable core. This technology is also known as Tightly Coupled WPT. The WPT by magnetic resonance is also known as Loosely Coupled WPT, which uses a coil and capacitor as a resonator, transmitting electric power through the electromagnetic resonance between transmitter coil and receiver coil. Compare with inductive WPT, resonant WPT uses resonant technologies, and have more spatial freedom than inductive technology.

There are generic studies in Report ITU-R SM.2303 that also apply to portable and mobile WPT chargers in particular in § 7.2 and Annex 3.

This Report intends to study the non-beam mobile and portable WPT devices employing magnetic inductive and resonant technologies, operating in the 100-148.5 kHz, 315-405 kHz, 1 700-1 800 kHz, 2 000-2 170 kHz, as well as 13 553-13 567 kHz frequency ranges to minimize their impacts to incumbent radiocommunication services. Non-beam WPT for mobile and portable devices such as electric vehicle charging and home appliances are outside the scope of this Report.

2 Applications for magnetic inductive and resonant mobile and portable device charging

Based on Report ITU-R SM.2303-1, inductive and resonant WPT technology is applied to mobile and portable devices such as smartphones, tablets and laptop computers. After this Report was published, inductive and resonant WPT technology have been utilized for wearable devices such as smart watches, smart/3D glasses and fitness tracking devices. Non-beam inductive WPT for mobile and portable devices are currently available and authorized in several countries operating in the 100-148.5 kHz, 315-405 kHz, 1 700-1 800 kHz and 13 553-13 567 kHz frequency ranges. Furthermore, usage of 2 000-2 170 kHz is also being planned to be used in future.

Non-beam inductive and resonant charging generally requires direct contact between the charging device and the power source. When direct contact is made and charging begins, the emission power is assumed to be below 30 watts. Once the contact is broken the device stops charging; however, the device may emit some energy for device detection purposes only. Section 4 of this Report outlines the operations and technical characteristics of non-beam induction and resonant WPT for mobile and portable devices in further detail.

3 International standards for non-beam inductive wireless power transmission application in the 100-148.5 kHz frequency range

The available international standards for non-beam inductive WPT for mobile and portable devices are contained in section 4 of Report ITU-R SM.2303-1.

WPT for mobile and portable devices may be considered industrial, scientific and medical (ISM) (see RR Nos. **1.15** and **15.13**), generally, if there is no data communication between the charger and charging device. However, many administrations within their national spectrum regulations authorize WPT for mobile and portable devices under rules associated with short range devices or as license-exempt applications as they are classified as intentional radiators.

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[1] Two of the scenarios in the studies in this Report make use of building entry loss. Information from the responsible group in ITU-R was received that this has limited applicability.

4 Technical and operational characteristics of non-beam inductive and resonant WPT for mobile and portable devices

4.1 Operational characteristics

Inductive non-beam WPT for mobile and portable devices used for charging mobile and portable devices are used primarily indoors, such as in offices spaces and homes.

Most charging activity only occurs when direct contact is made between the charging device and power source. This activity usually only occurs for short durations until the battery of the charging device is full. Once the battery is completely charged, or if direct contact is broken, emissions drop significantly.

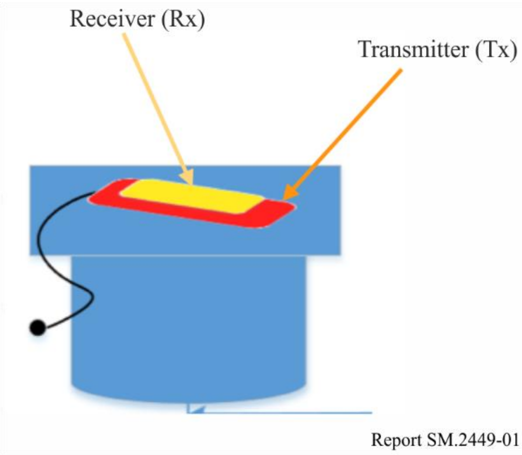
The applications included in this Report are available on the market and are certified under FCC license-exempt rules[2] as they are considered intentional radiators for the use and sale in the United States of America.

4.1.1 Charging scenarios

The testing was performed using both single-entry charging device (Fig. 1) and aggregate using five charging devices (Fig. 2).

FIGURE 1

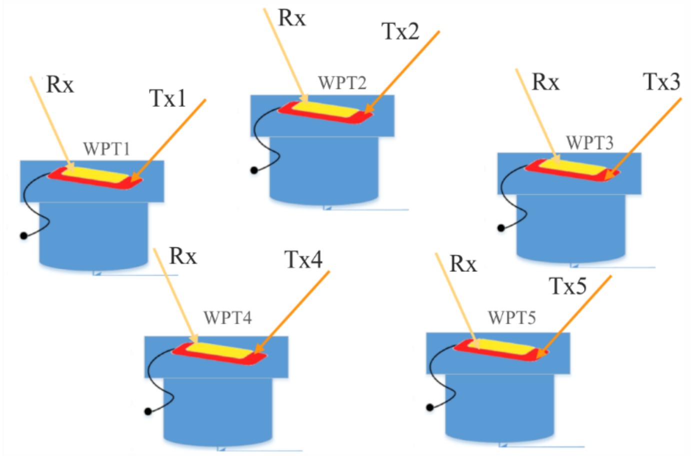
Depiction of single-entry deployment representative of a home environment



2 47 C.F.R. §§ 15 and 18 (2017).

FIGURE 2

Depiction of aggregate deployment representative of an office environment



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4.1.2 Technical characteristics

For technical characteristics of portable and mobile devices, see section 3.1 in Report ITU-R SM.2303.

The expected densities of WPT densities are given in Table 1, and are based on ETSI TR 103 493.

TABLE 1

Expected urban densities of WPT devices

Frequency range (kHz)	Urban density (/km^2)	Comments
100-148.5	5 000	Portable and mobile devices
315-405	1 500	Portable and mobile devices
1 600-1 800	500	Wearable devices
1 950-2 150	500	Wearable devices

ETSI TR 103 493 in § 7.1.2.2 covers mobile and portable devices. The expected density for generic mobile devices is given as 5 000 devices /km^2 and for wearables 500 devices/km^2. This was translated into Table 1 above on the assumption that 30% of the portable and mobile devices may also be able to use the higher frequency range which is expected to see lower numbers given its higher technical complexity. For wearable devices, the number given in ETSI TR 103 493 was used.

4.1.2.1 Portable and mobile WPT devices in 100-148.5 kHz

WPT chargers for portable and mobile devices in this band using the Qi specification are the basis for the studies in this Report.

4.1.2.2 Portable and mobile WPT devices >315 kHz

Table 2 shows the envisaged characteristics of WPT devices above 315 kHz used for the studies in this Report.

TABLE 2

Technical characteristics and use case for WPT devices > 315 kHz

Permitted frequency range of operation (kHz)	Wanted emissions limits at 10 m (dBµA/m)	Notes	Activity
315-405	–15	Communication FSK (up to ±20 kHz) Frequency shift during charging to manage power transfer (efficiency) and/or to compensate alignment: up to 15 kHz	1-2 hr/day
1 700-1 800	–15	Communication 1 kHz or FSK (up to ±20 kHz) Frequency shift during charging to manage power transfer (efficiency) and/or to compensate alignment: up to 15 kHz	1-2 hr/day
2 000-2 170	–15	Communication FSK (up to ±20 kHz) Frequency shift during charging to manage power transfer (efficiency) and/or to compensate alignment: up to 15 kHz	1-2 hr/day

Note: 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 in Monte Carlo studies. The range of the effect is limited to 15 dB for the purpose of studies. More information on the effect of mis-alignment can be found in Annex 1.4 of ECC Report 333.

4.1.2.3 Portable and mobile WPT devices in 13 553-13 567 kHz

With the significant increase of smart wearable devices, wireless charging demand for high frequency and low power products has been emerged in recent years. The 13.56 MHz frequency band is also understood to be a frequency band for portable and mobile wireless charging. Table 3 shows the detailed technical characteristics.

TABLE 3

Technical characteristics of WPT devices with 13.56 MHz

Operation frequency bands	Key parameters	Data	Emissions limits of magnetic field (10 m, quasi-peak detection)
13 553-13 567 kHz	Charging power	<1 W	<42 dBµA/m (measurement bandwidth: 9 kHz)
	Charging distance between receiving coil and transmitting coil	<1 cm	
	Working principle	Magnetic resonance technology	
	Use-cases	Smart glasses Styluses Smart fit	

5 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). 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 in *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.2093) 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 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 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, there are noise measurements that stated that some amateur service antennas may be located as close as 10 m from the outside wall of a building containing WPT [1].

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 Recommendation ITU-R P.372 should not be applied 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. The median value of noise inside is generally higher than outdoors but the variance is generally far greater [2]. 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 [2] indicated that the median noise levels in buildings are significantly higher than 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 and further work to revise ITU-R P.372 taking a more detailed account of indoor man-made noise is ongoing. However, 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 current 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 [1], [3] indicated that, for certain locations, the actual noise level is about 10 dB higher than what Recommendation ITU-R P.372 states. Furthermore, they explicitly took into account realistic distances between buildings where most noise sources would be located and the measurement point. Such a finding confirms earlier work carried out by Iwama [4].

6 Impact study of non-beam inductive WPT for mobile and portable devices on the broadcasting services for WPT devices operating in 100-148.5 kHz and 315-405 kHz

Interference to AM broadcasting may occur in very close scenarios such as indoor, and testing for AM broadcasting interference should be universal, not limited to situations where the interference has the smallest impact.

Figure 1 of Recommendation ITU-R BS.560 shows that the greatest relative protection ratio is approximately 16 dB, which corresponds to frequency offsets of around 1.6 kHz. When the frequency offset between harmonics and AM broadcasting signal is 1.6 kHz, the protection distance may increase.

If the fundamental frequency of non-beam WPT operating in 315-405 kHz can be chosen and fixed to be a multiple of 9 kHz or 10 kHz, and any harmonics will lie on the broadcast frequency raster, which could be one mitigation strategy.

6.1 AM Broadcasting Study 1 for WPT devices operating in 100-148.5 kHz

The broadcasting service operates in the following frequency ranges:

– Region 1: 148.5-283.5 kHz and 526.5-1 606.5 kHz[3]

– Region 2: 525-1 625 kHz (subject to RR No. **5.89**)[4]

– Region 3: 526.5-1 606.5 kHz[3].

The testing conducted used non-beam induction WPT for mobile and portable devices that operate in the 100-148.5 kHz frequency range. The testing was conducted using the 810 kHz channel, which is the 7^{th} harmonic of the WPT for mobile and portable devices. The 810 kHz channel is the closest channel that met the minimum signal strength requirements for AM broadcasting in the United States of America.

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3 The broadcasting service is subject to the Plan established by the Geneva 1975 regional agreement 148.5-283.5 kHz Region 1 526.5-1 606.5 kHz Region 1 & 3 (Geneva, 1975).

4 RR No. **5.89**: In Region 2, the use of the band 1 605-1 705 kHz by stations of the broadcasting service is subject to the Plan established by the Regional Administrative Radio Conference (Rio de Janeiro, 1988).

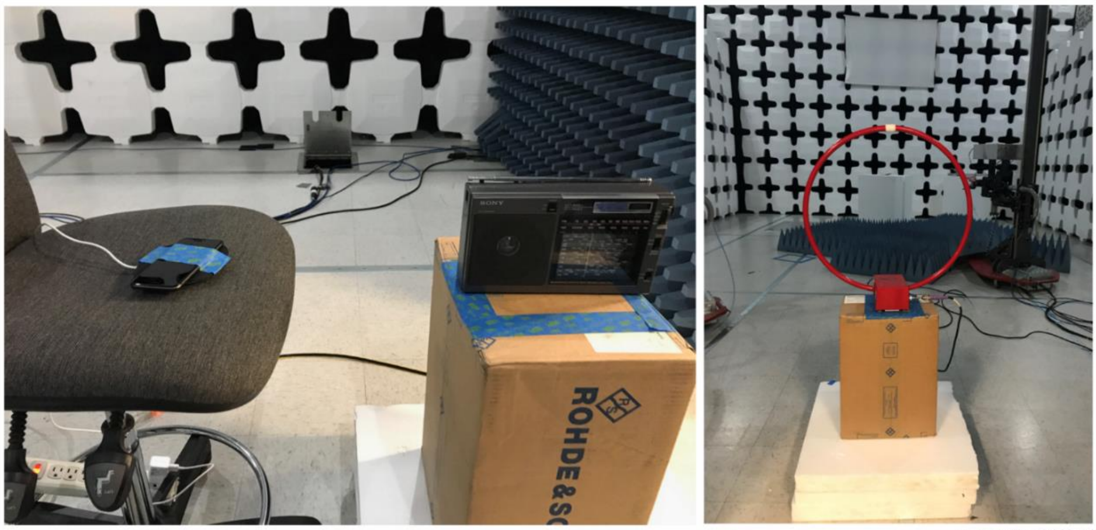
6.1.1 Test set-up

This study utilizes data collected through testing in a secured 3 m test chamber. Eight commercially available induction mobile device chargers were tested for interference into two commercially available AM radio receivers. The aggregate scenario used five of the eight mobile charging devices charging devices simultaneously.

The field strength was tested using a shielded loop antenna. Both the aggregate case and single device cases were measured against the two AM radios. The single-entry set-up is shown in Fig. 3.

FIGURE 3

Laboratory set-up for the single-entry case



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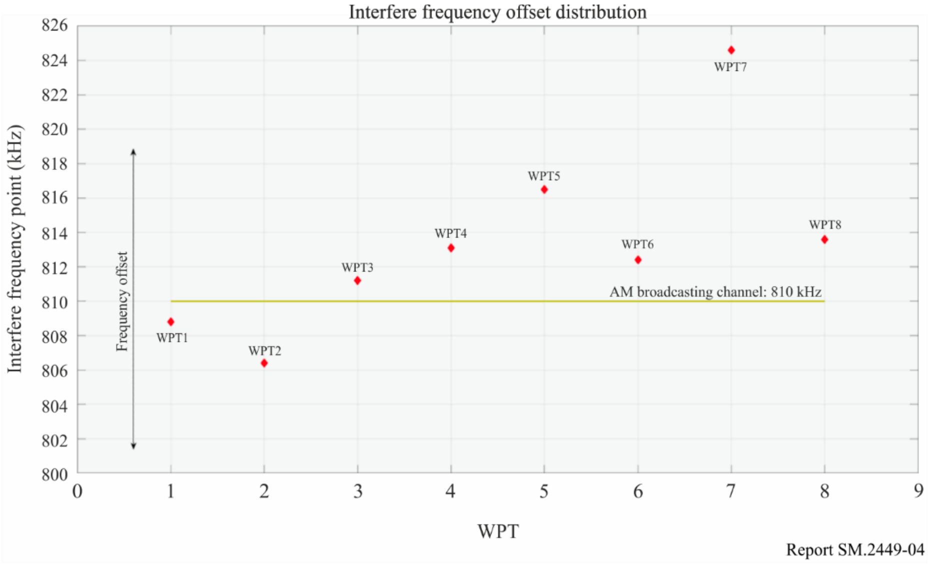
6.1.2 Subjective audible testing (single-entry and aggregate)

The section shows the data and results of the subjective audible testing. Figure 4 shows that all the 7^{th} harmonics of the wireless chargers inside frequency offset range −4 kHz ~ +14.6 kHz. For the aggregate scenario, the wireless chargers are placed approximately 0.6 m apart from each other surrounding the AM receiver.

FIGURE 4

7th harmonic frequency distribution from wireless chargers



The tested impact to both broadcasting receivers (AM1 and AM2) from each wireless charger is summarized in the following Figures and Tables. The Figures use three impact levels (see Table 4) to assess the level of audible noise each wireless charger caused to the AM receivers to plot the best and worst audible interference, level 1 being intolerable and level 3 being inaudible. The impact level decreases as the distances increases between the wireless charger and the AM receiver.

FIGURE 5

Receiver AM1 subjective audible test summary

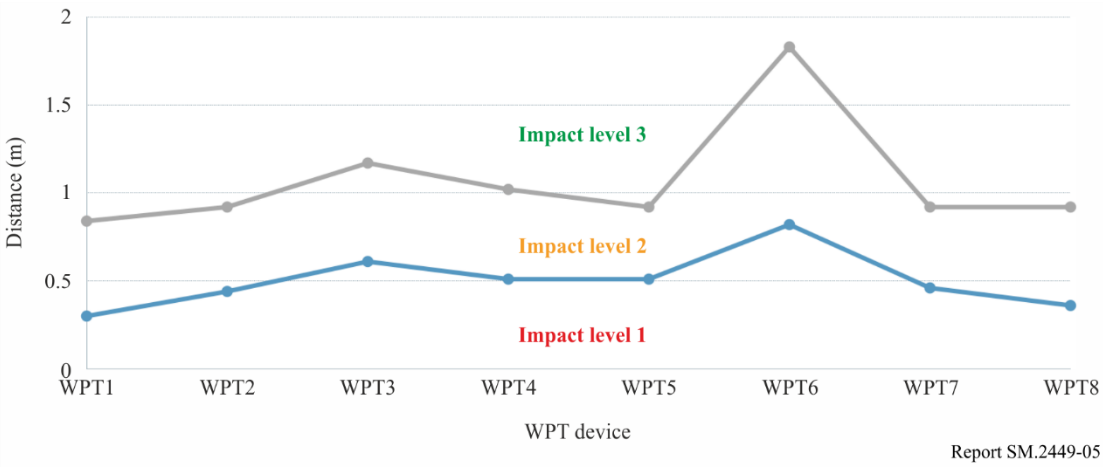


FIGURE 6

Receiver AM2 subjective audible test summary

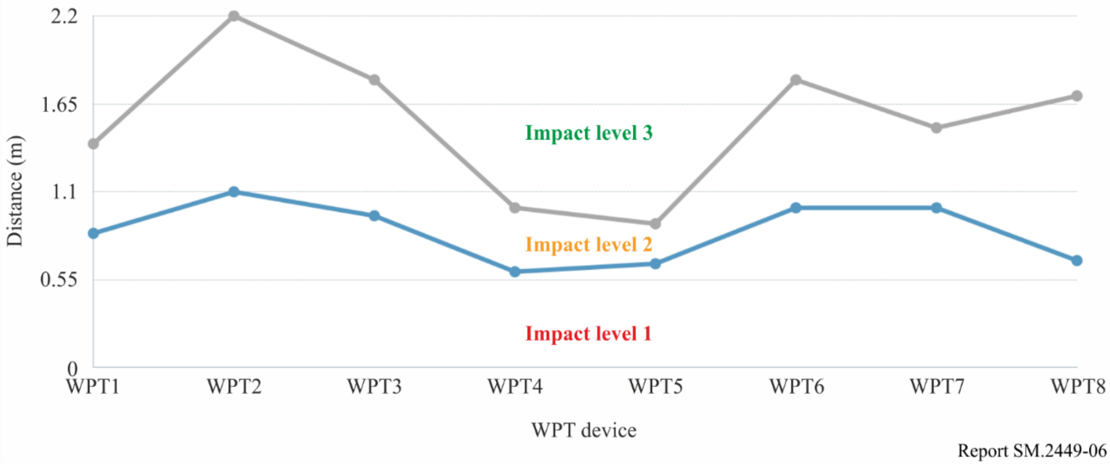


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TABLE 4

Description of impact levels

Impact level	Definition
1	Noise intolerable
2	Noise audible, but tolerated
3	Noise non-audible

Tables 5 and 6 summarize the data results for the single-entry case with AM receivers AM1 and AM2. The two far right columns show the distances that correspond to Figs 5 and 6 above. For AM1, if the wireless charger is placed at a distance greater than 1.83 m there is no audible interference. As for AM2, placing the wireless charger at a distance of greater than 1.8 m eliminates audible interference.

TABLE 5

Subjective audible testing AM1 receiver single-entry summary

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Wireless charger type	**7th harmonic field strength (dBμA/m) at 3 m**	**7th harmonic field strength (dBμA/m) at 10 m**	**AM radio signal strength (dBμA/m) (810 kHz channel) (wanted signal)**	**7th harmonic field strength (dBμA/m) at level 2/3 boundary Note 1**	**Wanted signal to interference ratio: C/I (dB) Note 2**	**Boundary between level 1 and level 2 (m)**	**Boundary between level 2 and level 3 (m)**
WPT1	−22.06	−53.36	2.85	11.1	−8.25	0.3	0.84
WPT2	−27.11	−58.41	2.85	3.7	−0.85	0.44	0.92
WPT3	−12.65	−43.95	2.85	11.9	−9.05	0.61	1.17
WPT4	−29.74	−61.04	2.85	1.6	1.25	0.51	1.02
WPT5	−16.02	−47.32	2.85	14.78	−11.93	0.51	0.92
WPT6	−28.8	−60.1	2.85	15.9	18.75	0.82	1.83
WPT7	−7.04	−38.34	2.85	3.7	−0.85	0.46	0.92
WPT8	−29.88	−61.18	2.85	3.7	−0.85	0.36	0.92

Notes to Table 5:

Note 1: This is a calculated emission level at the boundary point between level 2 and level 3 subjective degradation based on the near-field attenuation δ. The formula is δ = 60 log (d1/d2) where d1 is 3 m, d2 is the stated boundary point between levels 2 and 3 (column (h)) and δ is the adjustment factor in dB to compensate for the change in measurement distance. This adjustment factor is then added to the emission level in column (b).

Note 2: Where numbers are shown in bold the interfering signal is larger than the wanted broadcast signal.

TABLE 6

Subjective audible testing AM2 receiver single-entry summary

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Wireless charger type	**7th harmonic field strength (dBμA/m) at 3 m**	**7th harmonic field strength (dBμA/m) at 10 m**	**AM radio signal strength (dBμA/m) (810 kHz channel) (wanted signal)**	**7th harmonic field strength (dBμA/m) at level 2/3 boundary Note 1**	**Wanted signal to interference ratio: *C/I* (dB) Note 2**	**Boundary between level 1 and level 2 (m)**	**Boundary between level 2 and level 3 (m)**
WPT1	−22.06	−53.36	2.66	−2.2	4.86	0.84	1.4
WPT2	−27.11	−58.41	2.66	−19	21.66	1.1	2.2
WPT3	−12.65	−43.95	2.66	0.66	2	0.95	1.8
WPT4	−29.74	−61.04	2.66	−1.1	3.76	0.6	1
WPT5	−16.02	−47.32	2.66	15.35	−12.69	0.65	0.9
WPT6	−28.8	−60.1	2.66	−15.5	18.16	1	1.8
WPT7	−7.04	−38.34	2.66	11.0	−8.34	1	1.5
WPT8	−29.88	−61.18	2.66	15.1	−12.44	0.67	1.7

Note 1: This is a calculated emission level at the boundary point between level 2 and level 3 subjective degradation based on the near-field attenuation **δ**. The formula is δ = 60 log (d1/d2) where d1 is 3 m, d2 is the stated boundary point between levels 2 and 3 (column (h)) and δ is the adjustment factor in dB to compensate for the change in measurement distance. This adjustment factor is then added to the emission level in column (b).

Note 2: Where numbers are shown in bold the interfering signal is larger than the wanted broadcast signal.

Tables 7 and 8 show the results of the aggregate testing. The five wireless chargers used in this test were placed approximately 0.6 m from each other surrounding the AM receiver. Aggregate results for AM1 show that placing the five wireless chargers at a distance greater than 2.2 m prevents audible interference. For AM2, the five wireless chargers placed farther than 2.3 m will prevent audible interference to the receiver.

TABLE 7

Subjective audible testing AM1 receiver aggregate summary

(a)	(b)	(c)	(d)	(e)	(f)	(g)
Wireless charger type	**7th harmonic field strength (dBµA/m) at 3 m**	**7th harmonic field strength (dBµA/m) at 10 m**	**AM radio signal strength (dBµA/m) (810 kHz channel) (wanted signal)**	**7th harmonic field strength (dBµA/m) at level 2/3 boundary Note 1**	**Boundary between level 1 and level 2 (m)**	**Boundary between level 2 and level 3 (m)**
WPT1	−12.65	−43.95	2.66	−4.5	1.2	2.2
WPT2	−29.74	−61.04	2.66	−21.6		
WPT3	−28.8	−60.1	2.66	−20		
WPT4	−7.04	−38.34	2.66	+1.8		
WPT5	−29.88	−61.18	2.66	−21.9		

TABLE 8

Subjective audible testing AM2 receiver aggregate summary

(a)	(b)	(c)	(d)	(e)	(f)	(g)
Wireless charger type	**7th harmonic field strength (dBµA/m) at 3 m**	**7th harmonic field strength (dBµA/m) at 10 m**	**AM radio signal strength (dBµA/m) (810 kHz channel) (wanted signal)**	**7th harmonic field strength (dBµA/m) at level 2/3 boundary Note 1**	**Boundary between level 1 and level 2 (m)**	**Boundary between level 2 and level 3 (m)**
WPT1	−12.65	**−43.95**	2.66	−5.7	**1.1**	**2.3**
WPT2	−29.74	**−61.04**	2.66	−22.84		
WPT3	−28.8	**−60.1**	2.66	−21.9		
WPT4	−7.04	**−38.34**	2.66	−0.15		
WPT5	−29.88	**−61.18**	2.66	−23.0		

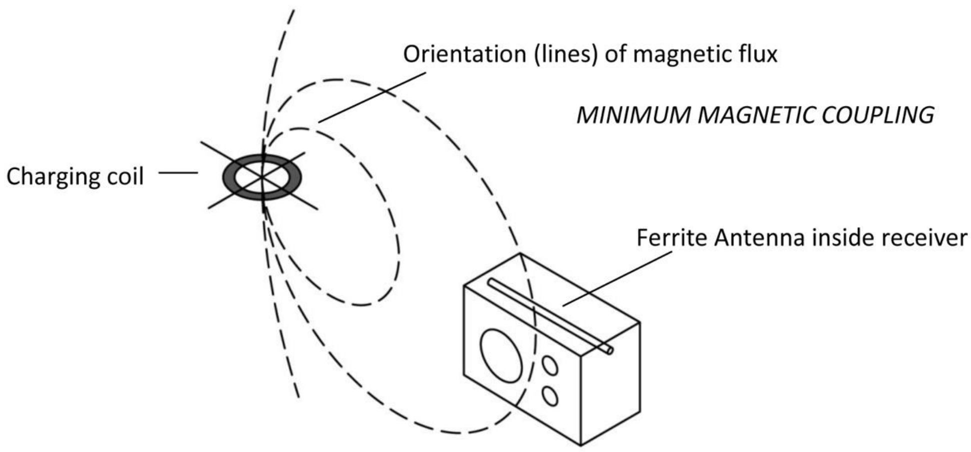
The observed boundary distances suggest that a mitigating factor was present since the measured Interfering signal, when recalculated at the point at which listening tests were done, exceeds the Wanted signal in some cases. The results of this study should be treated with caution. Further study is needed to explain the findings.

Potential explanation:

The results in Tables 7 and 8 suggest that the receiver is far less sensitive to incoming interference than might be expected. There are a number of reasons why this might be but principal among them is the degree of coupling between the incident filed and the receivers antenna.

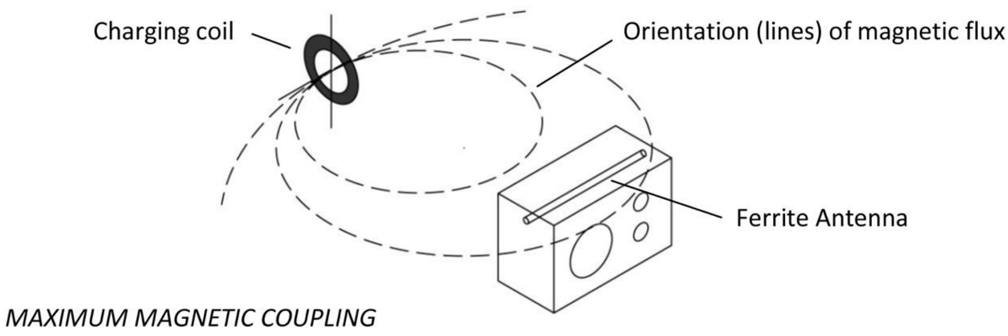
Nearly all portable radio receivers use magnetically sensitive ferrite rod antennas for LF and MF, AM broadcast reception. Such receivers will often also feature an electrically sensitive telescopic 'whip' antenna, but this will be for higher frequency HF and VHF (FM) reception. The ferrite antenna is usually mounted horizontally inside the receiver as shown in Fig. 1. As stated, ferrite antennas are sensitive to magnetic fields with maximum sensitivity occurring when the lines of magnetic flux are parallel to the axis of the ferrite rod. Ferrite antennas are directional because of their geometry with a sharp null in sensitivity when they are 'end on' to the direction of the incoming signal. It is common practice for listeners to orient receiver such that the direction of the incoming signal is at right angles to the axis of the ferrite rod to improve sensitivity and hence signal quality. Figure 7 shows a topology where the interference potential of a WPT charging coil is minimised. It can be seen that this is very similar to the topology depicted in Fig. 3. The charging coil is horizontal. The receiver is oriented such that the WPT charger is found in the direction of minimum sensitivity and the lines of magnetic flux are orthogonal to the ferrite antenna. In this configuration the effect of the interferer is considerably reduced.

FIGURE 7



By turning the receiver through 90 degrees horizontally, and the charging coil through 90 degrees vertically, as shown in Fig. 8, the magnetic coupling and hence the level of the interference will be considerably increased; in fact maximised. The orientation of the magnetic flux inside the receiver will be parallel with the axis of the ferrite antenna.

FIGURE 8



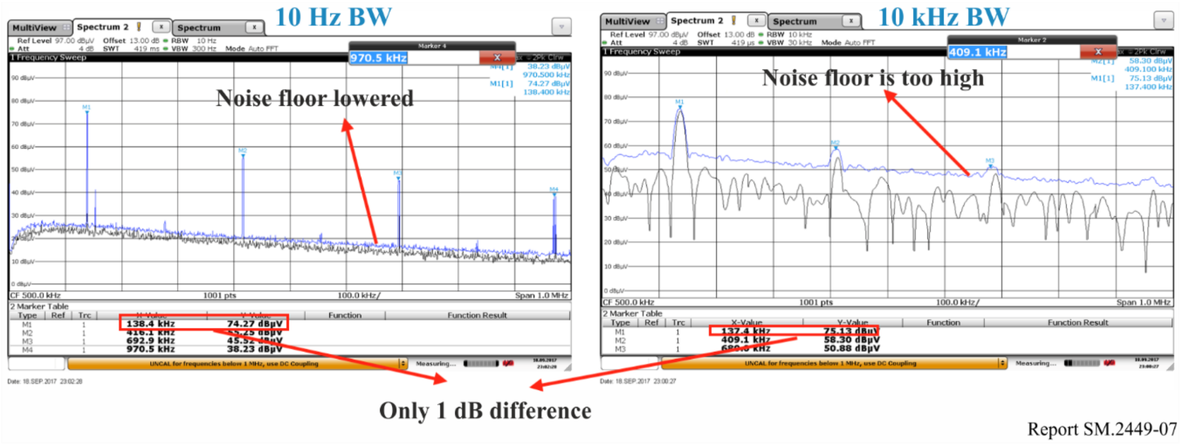
With the ability to move and rotate both the charging coil and the receiver in a three-dimensional space there is scope for the magnetic coupling between the coil and the receiver to be anything between the maximum and, potentially, none.

6.1.3 Open field strength quantification for WPT for mobile and portable devices and AM receivers

Figure 9 shows the bandwidth setting for the WPT harmonic measurements and the visual justification for using 10 Hz. As shown in the Figure, the difference between 10 Hz bandwidth and 10 kHz bandwidth is only 1 dB, but drastically reduces the noise floor. In addition, the use of 10 Hz is more in alignment with the characteristics of the WPT signal. The WPT signal is similar to a sine wave and therefore has little to do with bandwidth. The change to 10 Hz also enabled a better understanding of what was needed for the measurements.

FIGURE 9

Bandwidth justification



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The AM receiver signal bandwidth setting is shown in Fig. 10. Based on the 1 dB difference, 10 Hz was also used for the AM receivers.

FIGURE 10

AM receiver bandwidth setting

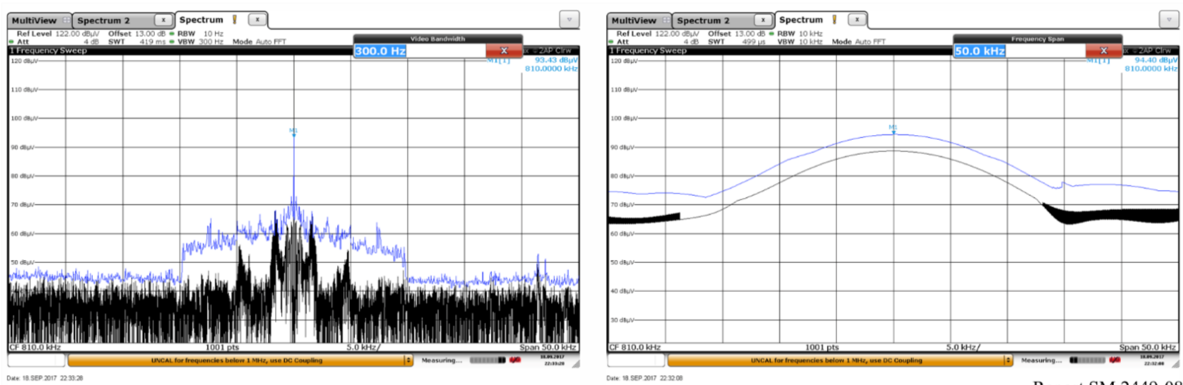

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FIGURE 11

7th harmonic field strength measurement at 3 m

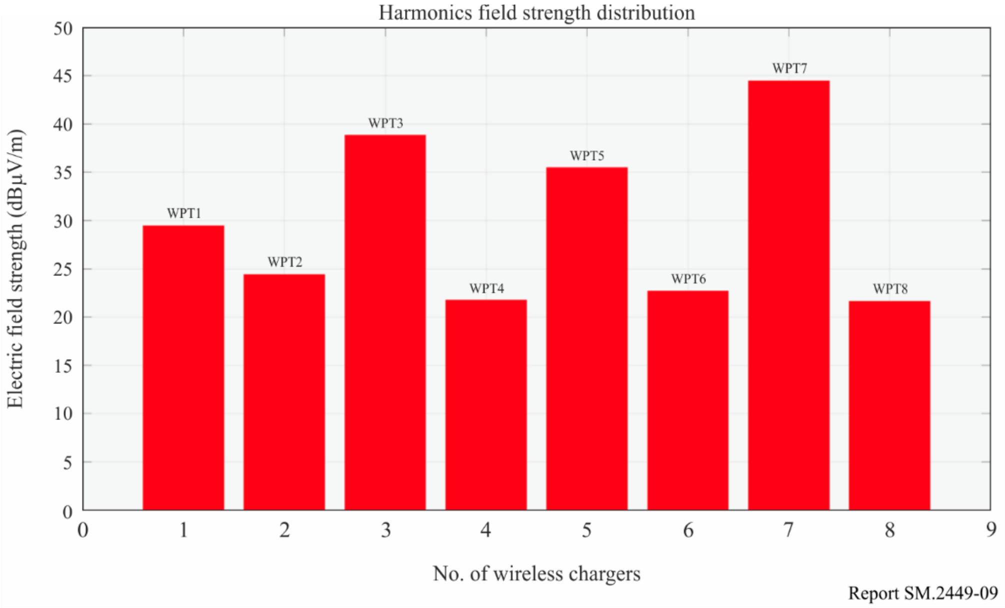

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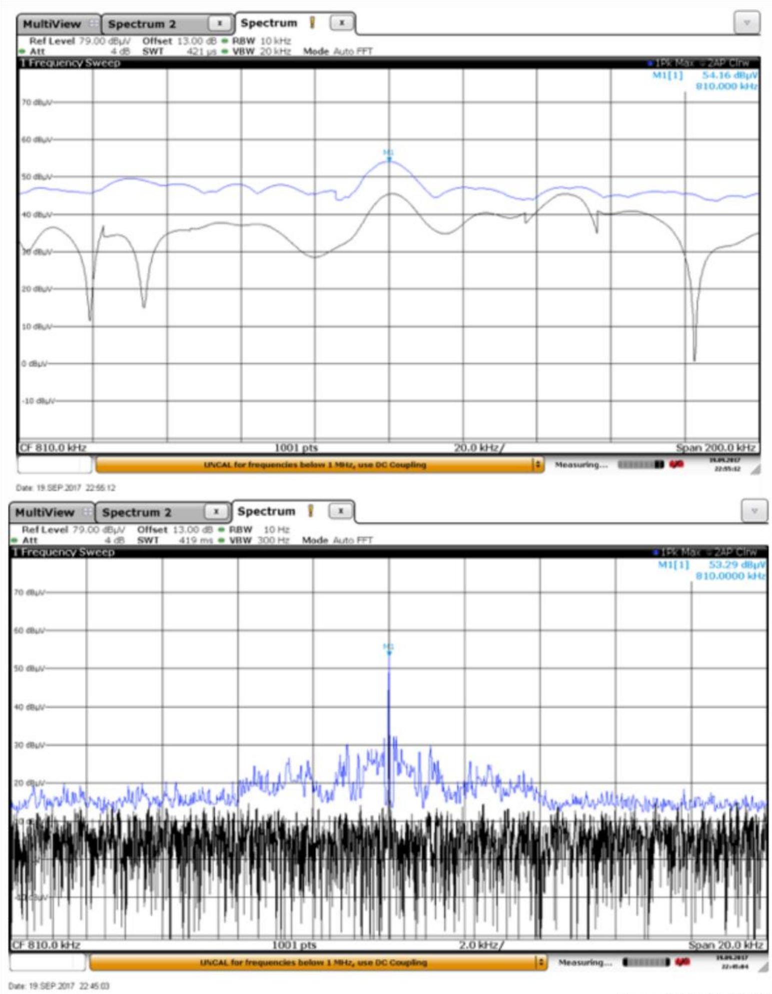
FIGURE 12

AM radio signal strength, 54.16 dBµV/m (0.5 mV/m = 54 dBµV/m)



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6.1.4 Summary of the test results

The laboratory testing results summarized in Table 9 show 2.3 m as the minimum separation distance required to prevent audible interference to AM broadcasting receivers of the 7th harmonic of the induction charging devices testing. Given that this is a mobile device typically used in offices and homes, this distance is achievable and therefore the impact to the broadcasting service is considered by the study as negligible.

TABLE 9

Experiment summary

AM radio receivers	**AM radio single strength(dBμV/m) (Target: 500 μV/m, 54 dBμV/m)**	**Single Impact at worst, 8 pcs wireless chargers separately tested**	**Aggregate Impact at worst, 5pcs WPT devices working simultaneously, 0.6 m interval to each other**
AM1	54.35	<0.82 m, Noise intolerable >1.83 m, Noise inaudible	<1.2 m, Noise intolerable >2.2 m, Noise inaudible
AM2	54.16	<1.1 m, Noise intolerable >2.2 m, Noise inaudible	<1.1 m, Noise intolerable >2.3 m, Noise inaudible

These results suggest that a mitigating factor was present since the measured Interfering signal, when recalculated at the point at which the listening tests were done, exceeds the wanted signal in some cases. The results of this study should be treated with caution. Further study is needed to explain the findings.

6.2 AM Broadcasting Study 2 for WPT devices operating in 100-148.5 kHz

6.2.1 General observations

A few predominantly subjective tests were carried out using a completely anonymous phone charger, a mobile phone simulator as a dummy load and a smartphone.

From the outset it was clear that repeatability was going to be a major issue. Also it was quite difficult to explain what was seen. What came out of the charger was critically dependent on the exact positioning of the load (or phone) on the charger, its exact location relative to the receiver and its orientation. Not only did the operating frequency change but also the nature of the interference as these parameters were changed. In general the ‘output’ appeared to be a pulsed and filtered, (seemingly) square wave at a frequency that varied even when the load was held firmly in one place relative to the charger. Even when there was no harmonic within the ‘channel’ to which the receiver was tuned[5] significant switching transients (at the repetition rate of the pulsing) could sometimes[6] be heard right across the MF band. As well as being somewhat dependent on the exact position of the charger relative to the receiver, the overall effect was markedly dependent on the (assumed) relative polarisation of the charger; the effect of the interference could be more or less eliminated by careful alignment. While the effects of location and polarisation were as might be expected, this was not always the case and in such instances was difficult to explain. The general variability and instability of the whole set up suggested that meaningful measurements might be difficult to make.

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[5] Very small changes in the position of the load relative to the charger could cause the harmonic to jump into an adjacent channel or even further.

[6] Again dependent on the position of the load and the orientation.

The performance of the charger when charging a phone was quite different from that with the dummy load. To what extent variations might be dependent on the state of charge of the phone's battery was not clear. The phone happened to be very nearly fully charged.

With no phone on the charger, effectively an 'off load' condition it would intermittently and fairly frequently emit a pulse of radiation – as sort of "are you there" request to any mobile phone that might be on or near the charger to initiate the charging sequence. Even with no phone being charged, these bursts were clearly audible on a nearby receiver.

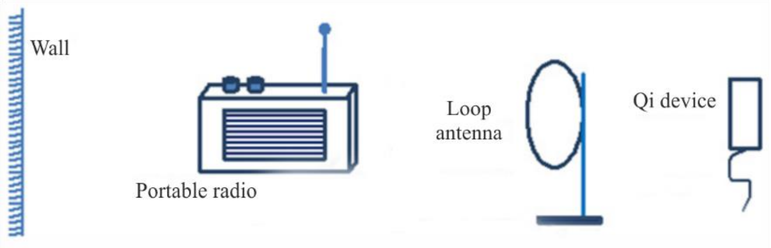
A subjective assessment suggested that with the coil load combination and an artificially generated[7], wanted incoming signal of +18.5 dBµA/m (equivalent to 70 dBµV/m – 10 dB above the minimum receiver sensitivity prescribed in Recommendation ITU-R BS.703) the effect of the interferer at 2 m separation could be made to be anything between more or less inaudible and extremely annoying by changing the orientation and/or precise position of the charger. This is markedly at variance with the results in Tables 5 and 6 of this Report, which suggest that for all the chargers tested the effect was inaudible when the separation had reached 2 m (sometimes much less than this) and the incoming (wanted) signal was 16 dB lower.

6.2.2 Test arrangements

The tests were performed in a screened room slightly less than 4 m in length. This imposed certain limitations on the tests that were possible; significantly that 2 m was the maximum possible separation between the receiver and the charger. The physical arrangement is shown in Figs 13 and 14.

FIGURE 13

Test set up (diagrammatic)



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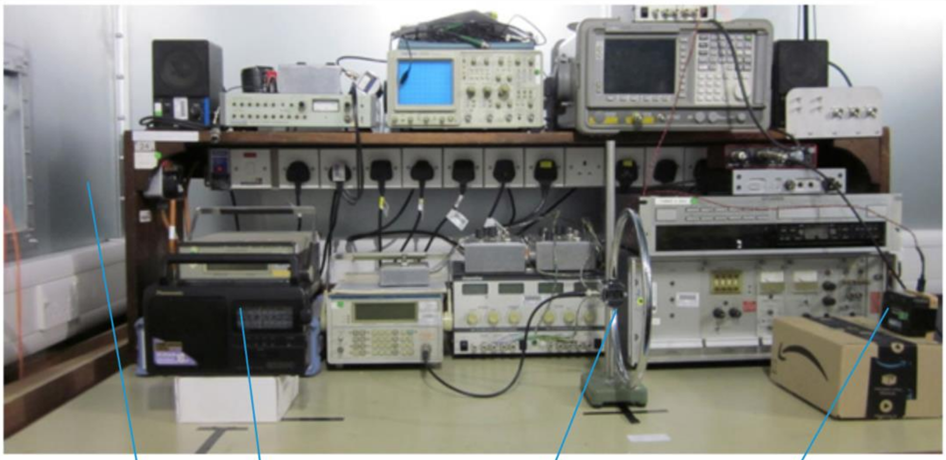
[7] The tests were carried out in a screened room.

FIGURE 14

Test set up (photographic)



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The ferrite antenna in the receiver and the charger were arranged to be on the perpendicular axis of the loop antenna. For the tests the receiver was 0.5 m from the wall, the loop antenna 1.0 m and the charger 1.2 m.

The loop antenna was used to generate a simulated broadcast signal. Simulating the broadcast signal in this way offered advantages over an off air signal.

The signal level at the receiver could be precisely controlled.

The frequency of operation could be precisely controlled; not only did this allow the receiver tuning frequency to be matched to the charger but also meant that different harmonics of the charger which would affect different carrier frequencies (different broadcast channels) could be investigated.

NOTE – The receiver could be / was 'tuned' to the charger and not the other way round.

The same audio samples (speech and music) could be used for all the tests thereby eliminating a potential source of uncertainty.

The ability to control the signal level at the receiver also meant that the effect of moving the charger closer to and further from the receiver could be simulated without actually moving it physically. As already explained, the dimensions of the screened room placed a severe limitation on the actual separation achievable. The effect of wall reflections was considered and taken into account where necessary (see § 6.2.6.1). Given the inverse cube law relationship between field strength and distance, an increase in the level of the wanted (broadcast) signal by 18 dB would have the effect of doubling the separation distance between the receiver and the charger. Clearly the receiver would be operating with a signal that was 18 dB stronger and so to retain the correct receiver signal to noise ratio an extra 18 dB of RF noise had to be injected into the receiver. This was easily achieved by adding noise to the wanted signal in the loop antenna[8]. In this way, the effective distance between the receiver and the charger could be set to any desired value[9] and the reduction in the effect of the interference with separation distance could be measured.

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[8] In practice, pseudo-random noise was generated and added to the audio signal in the PC.

[9] Up to the point where the RF front end in the receiver was overloaded by excessive signal strength.

The angle of the charger was adjusted to have the maximum (worst case) effect on the receiver and give the maximum coupling to the search coils. Minimum coupling of the charger into the receiver – with the interference virtually inaudible in many instances – occurred with the charger, load combination tilted to about 10° from horizontal with the load away from the receiver. The geometry of the situation would suggest that minimum coupling would occur with the charger coil horizontal because the interfering field would coincide with the minimum sensitivity of the ferrite antenna (be at right angles to the maximum sensitivity). In practice, the orientation for minimum sensitivity depended on the exact positioning of the load on the charger. Obviously, it also depended on the vertical and lateral offset of the charger from the axis of the ferrite antenna. Minimum sensitivity was sharp and pronounced while maximum sensitivity was less well defined. The 'cos θ' polar response of the charging coil would give rise to a sharp null at the minimum and a broader plateau at the maximum.

6.2.3 Receiver performance measurements

The 'characteristics of AM sound broadcasting reference receivers for planning purposes' are laid down in Recommendation ITU-R BS.703. The relevant parameters are:

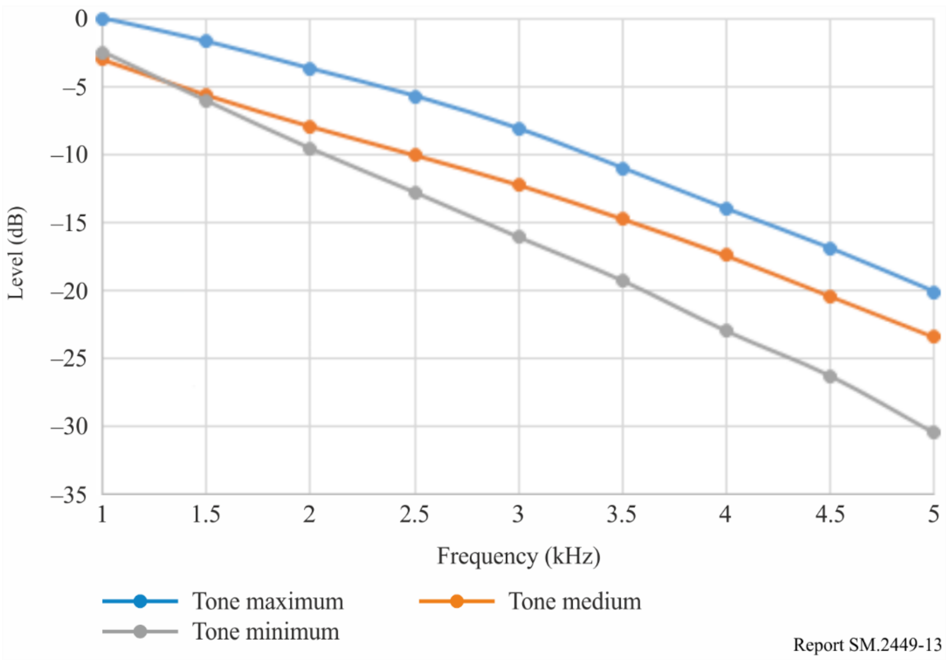
– Audio modulation (frequency) response −3 dB at 2 kHz; −24 dB at 5 kHz

– Audio *S*/*N* with 60 dB dBμV/m field strength 26 dB unweighted ref 30% modulation.

Two portable receivers, Receiver 1 and Receiver 2 were on hand, and were measured to determine how closely they conformed to the reference receiver. Receiver 1 was from the 1980s with push-button tuning and a wooden case. Receiver 2 was more modern; not expensive but with reasonable performance. The results are presented in Figs 15 and 16 – note the effect of the tone controls.

FIGURE 15

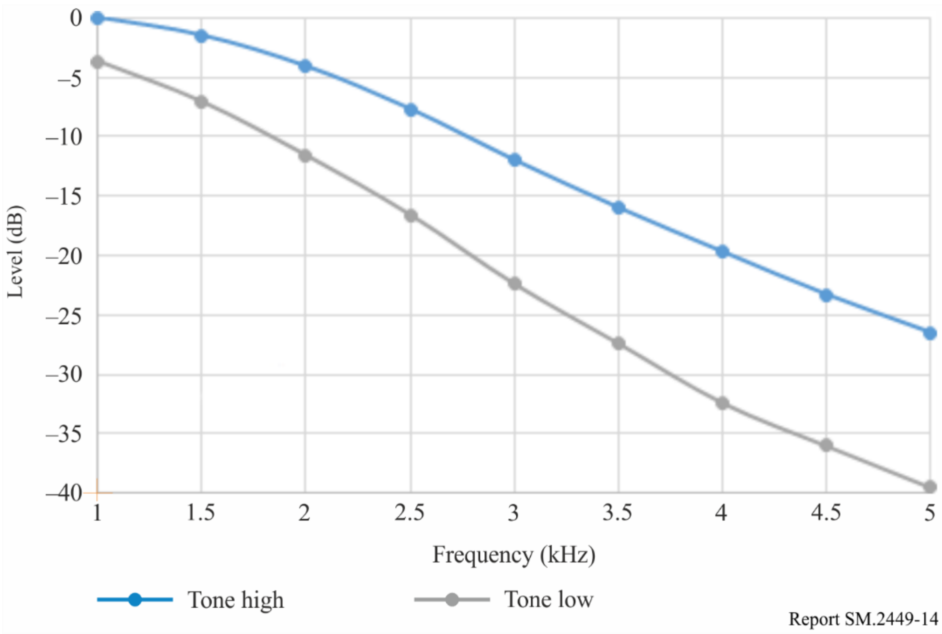
Modulation response of Receiver 1



The behaviour of the Receiver 1 tone control is rather strange; it seems to have more of an effect on the overall level than on the treble response, which is (presumably) largely determined by the IF filters. For the purpose of the interference tests, the control should be set to maximum, to keep the response about right at 2 kHz. The response at 5 kHz is less important, since the interferer would be deliberately placed at about 2 kHz offset from the wanted carrier to represent the worst case.

FIGURE 16

Modulation response of Receiver 2

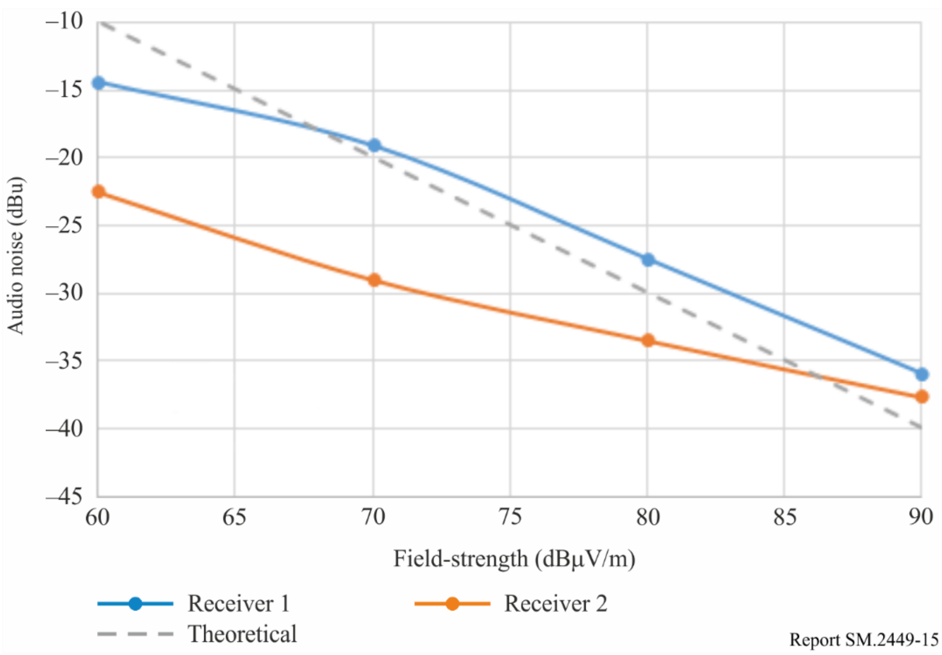


The action of the tone control (switch) is drastic indeed. It is clear that any testing should be carried out with the switch in the ‘High’ position – there is nothing intermediate between ‘High’ and ‘Low’ – where the modulation response is a good match to that of the Recommendation ITU-R BS.703 reference receiver.

Audio noise levels were measured as a function of field-strength and are plotted in Fig. 17.

FIGURE 17

Audio noise levels for both receivers



The noise levels are plotted relative to 30% AM modulation depth, as required by Recommendation ITU-R BS.703. (–30 dB ‘audio noise’ corresponds to 30 dB *S*/*N*). In theory, the *S*/*N* would be expected to increase dB-for-dB with the wanted signal, as per the dashed line. In practice, ‘backstop’ noise (in the later stages of the receiver) gives an upper limit, while at low signal levels the AGC runs out of range. At 60 dBμV/m signal strength, the Receiver 1 performance appears to be better than expected. However, this is misleading because the level of the wanted signal has decreased along with the noise.

Receiver 2 seems therefore to be the better receiver to use for tests as it more closely conforms to the Recommendation ITU-R BS.703 reference. It falls about 5 dB short on audio *S*/*N*, but that is not a significant problem because large distances are not practicable when assessing the effects of interference. Smaller separation distances and higher reference field-strengths were used as explained in § 6.2.6.1.

Note that the carrier frequency chosen for the tests was a ‘standard’ 999 kHz. If another frequency is used, the sensitivity of the receiver is likely to be different.

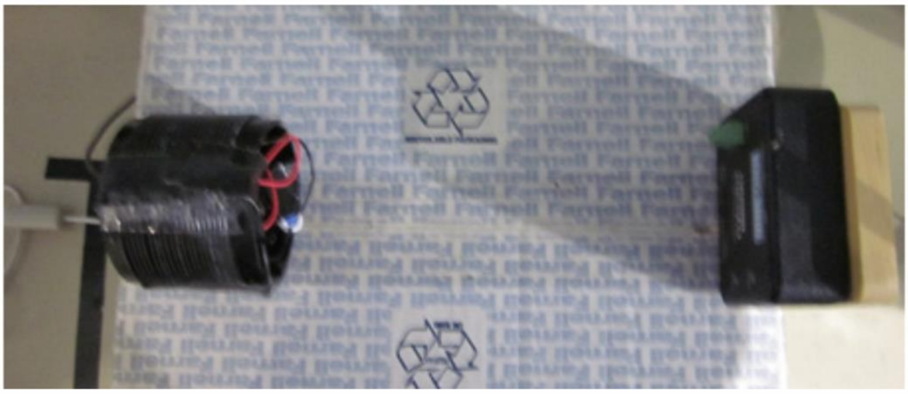
6.2.4 Emission levels from the charger

The emission levels from the charger were measured. The results are broadly in line with those given in Tables 5 to 8 of this Report.

A ‘home made’ detector was used. This comprised ten turns of wire wound on a short section of drainpipe; the coil diameter was 68 mm. The detector coil was followed by a (nominally) 30 dB low-noise amplifier.

FIGURE 18

Home-made detector (left) and Qi® charger (with load)



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At a distance of 1 m, the level measured on the spectrum analyser was –34 dBm. Since the gain of the preamplifier was 29 dB (measured), the output of the coil was –63 dBm. 0 dBm is equivalent to 224 mV, and so −63 dBm is equivalent to 0.159 mV.[10]

A magnetic field *H* passing through a coil of area *A* and number of turns *N* gives rise to an EMF *E* of $\mu_0 H A N \omega$, where μ_0 is the permeability of free space (defined as $4\pi \times 10^{-7}$) and ω is the angular frequency. Rearranging this gives:

$$H = E / \mu_0 A N \omega \quad (1)$$

[10] Strictly, dBm is the units of power in a constant-impedance system. In this instance the coil actually delivers a voltage into a high impedance.

Putting in figures: $H = 0.159 \times 10^{-3} / \{ (4\pi \times 10^{-7}) \times (\pi \times 0.034^2) \times 10 \times (2\pi \times 115 \times 10^3) \}$

Hence $H = 0.0048$ A/m, at a distance of 1 metre.

This is equivalent to 73.6 dBµA/m (or 125.1 dBµV/m for the equivalent electric field in free space). At 300 m, this would reduce by 60 log 300 dB, or 148.6 dB, to give −23.5 dBµV/m. Section 6.1 gives a figure of −15 dBµV/m. This is reasonable agreement given the various uncertainties.

6.2.5 Harmonic emission levels from the charger

The work described so far in Study 2 has involved only two devices. There may be differences between the models available on the market, and so a range of devices were assessed.

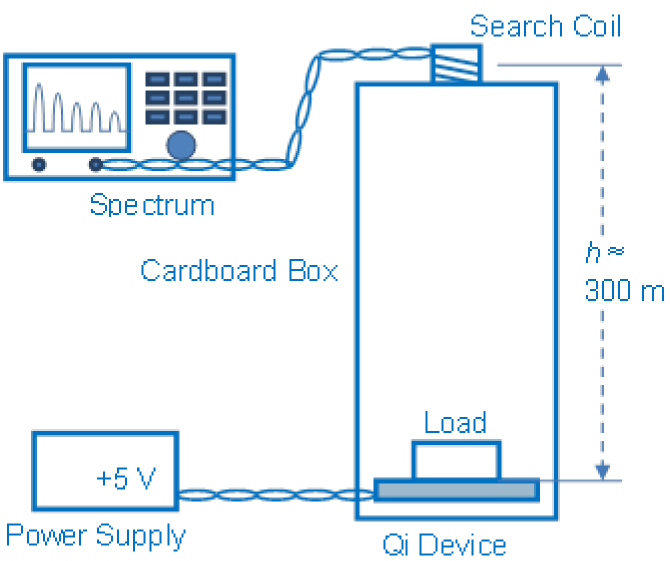
The test method was very simple. The Qi device in question was placed on the bench and supplied with +5 volts from a bench power supply. It was loaded by the Qi dummy load illustrated in Fig. 18 and set to draw 2 watts (its rated maximum). A three-turn search-coil was supported 300 mm directly above the Qi device, and the output connected to a spectrum analyser.

The spectrum analyser was set to scan from 0 to 2 MHz, and then the marker facility used to read off the levels of the first 13 harmonics – the odd harmonics only, since the even ones were normally of much lower level.

The Qi device was replaced with a pancake coil driven by a 1 MHz tone. The coil was similar to that used in Qi devices, and its magnetic field easily calculated. The output of the search coil was compared with the calculated level to ensure agreement between the measured and expected results.

FIGURE 19

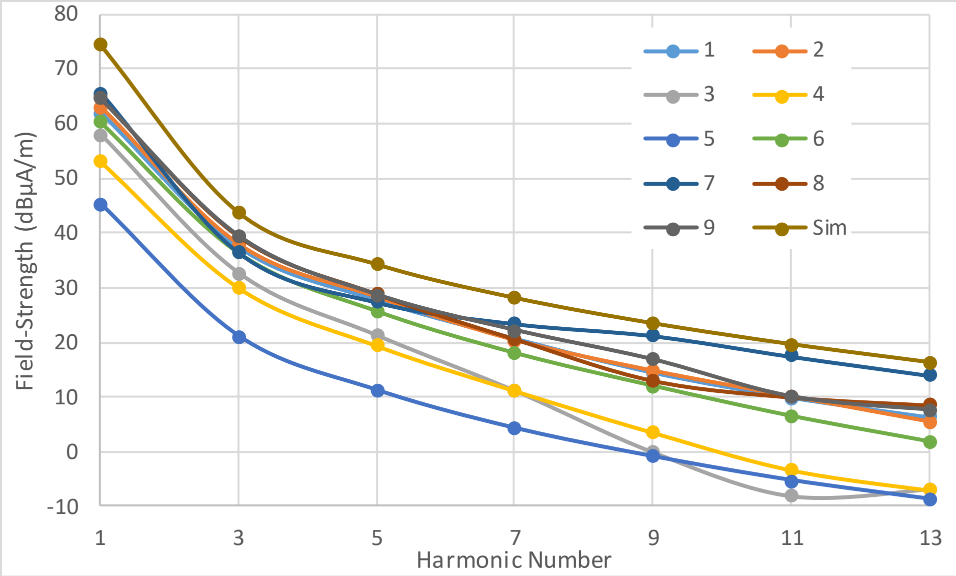
The Test Set-up



The results are plotted below. They have been normalised to a distance of 1 metre.

FIGURE 20

Harmonic levels of devices tested



In general, the level of harmonic *n* for each device obeys the expected (1/*n*) law. (The plots run parallel to the ideal 'Sim' figures.) This confirms that the tuned circuit is indeed driven by a square wave. As pointed out in Section 4, the 1/*n* relationship does not apply to the fundamental component, since the tuned circuit incorporating the coupling inductor is then close to resonance.

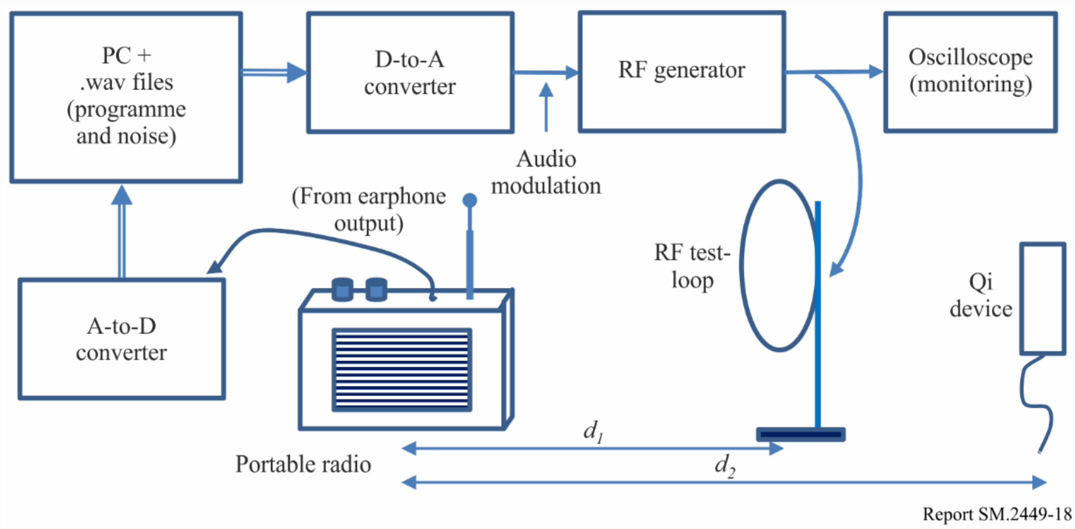
Since the simulation does not take into account any mitigating factors, such as possible magnetic screening, it is not surprising that the emissions from real devices are all somewhat lower. The performance of Device 5 is better than the simulation by about 25 dB.

6.2.6 Assessment of Interference levels

The effects of interference generated by the charger / load combination were measured both objectively and subjectively on the audio output of the receiver, using the set-up shown in Fig. 21.

FIGURE 21

Set-up for assessment of Qi® interference



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The sketch is mostly self-explanatory. The programme material is stored on the PC as .wav files, and is the same as used for the earlier WPT tests[11]. (It was provided by the BBC's Radio 5 studios, and compressed as it would be for transmission.) It is played out through a high-quality 'Benchmark' DAC, and used to modulate an RF generator. The RF generator then drives a test-loop antenna. By convention, the loop is placed 600 mm from the item under test (the radio), in which case the equivalent electric field in V/m is numerically equal to 1/10 of the generator source EMF in V.[12] Finally, the output of the radio, complete with interference, is converted into digital form and stored on the PC as .wav files.

In addition, pseudo-random noise was added to the programme material by the PC's *Audacity* program. This was helpful in allowing the audio S/N out of the receiver to be set to the reference value of 26 dB ref. 30% AM modulation depth, irrespective of the actual field-strength.[13] When carrying out subjective tests on interference, the masking effect of any background noise is obviously an important factor.

Finally, a sanity-check on the calibration of the system. The generator was set to –3 dBm, for a source EMF of 317 mV and a nominal field-strength of 31.7 mV/m (90 dBμV/m). The magnetic field-strength should then be 31.7 / 377 mA/m, or 38.5 dBμA/m. The 4-turn search-coil was again used to measure the actual field-strength and gave a reading of −92 dBm on the spectrum analyser.

Recalling equation (1) above:

$$H = E / \mu_0 \, A \, N \, \omega$$

Putting in figures $H = (5.63 \times 2 \times 10^{-6}) / \{ (4\pi \times 10^{-7}) \times (\pi \times 0.034^2) \times 4 \times (2\pi \times 999 \times 10^3)\}$

where 5.63×10^{-6} is −92 dBm in Volts and the highlighted 2 the termination

$$H = 9.818 \times 10^{-5} \text{ A/m, or } 39.8 \text{ dB}\mu\text{A/m}$$

Which is in reasonable agreement with the nominal field-strength.

6.2.6.1 Distance multiplication and the effect of the screened room

As mentioned earlier, increased levels of 'wanted' signal at the victim receiver could be useful for assessing the interference caused by a device at distances greater than available in the screened room. Supposing that the reference receiver is working at 60 dBμV/m, and that the interfering charger is 2 metres away. From the inverse-cube law, the interference would increase by 18 dB if the distance were halved to 1 metre. It follows that the effect on the output of the receiver would be exactly the same if the wanted signal were also to be increased by 18 dB. There are two provisos: first, any noise generated elsewhere within the system needs to be kept at the same level (−26 dBu, reference 30% AM); second, the automatic gain control within the receiver needs to hold the (wanted) output level sensibly constant.

Table 10 shows the signal generator levels appropriate for multiplication factors 1-4. It is assumed that a loop antenna is being used, and that the victim receiver is 600 mm from it.

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[11] For example as described in BBC White Paper WHP 322.

[12] There is no implication that the loop actually generates an electric field – indeed, the loop is screened to prevent it from doing so. The equivalent electric field is calculated using the standard far-field relationship E/H = 377 Ω.

[13] Assuming that the field-strength is sufficient for the reference audio *S*/*N* to be exceeded.

TABLE 10

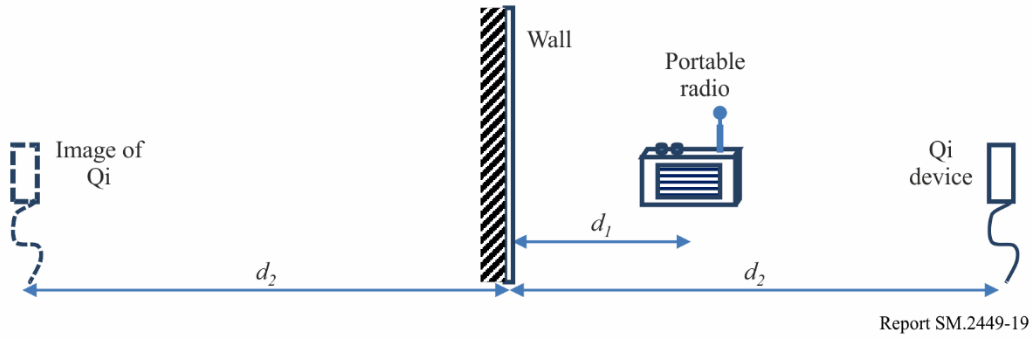
Generator levels for particular multiplication factors

Generator level (dBm)	–33	–15	–4.4	+3	A factor of 4 means that an interferer placed at 600 mm has the same effect as one at 2.4 m
Multiplication factor	1	2	3	4	

The practicable distances available in the screened room are more restricted than might be expected. This is because the room is made of metal, and the metal behaves as a near-perfect reflector. Despite being nearly 4 metres long, the interferer needs to be kept within about 1.2 metres of the receiver. The situation is as shown in Fig. 22.

FIGURE 22

The effect of a reflection



As measured at the radio, the normalised field-strengths for the Qi® device and its reflection are $1 / (d_2 – d_1)^3$ and $1 / (d_2 + d_1)^3$, respectively. To obtain the resultant field-strength, the reflected signal needs to be subtracted from the direct signal:[14]

Resultant field-strength $\quad 1 / (d_2 – d_1)^3 – 1 / (d_2 + d_1)^3$

Ratio of resultant to direct field-strengths $\quad \{ 1 / (d_2 – d_1)^3 – 1 / (d_2 + d_1)^3\} / 1 / (d_2 – d_1)^3$
$= 1 – \{(d_2 – d_1) / (d_2 + d_1) \}^3$

Putting in actual distances (d_1 = 0.5 m, and d_2 = 1.2 m) gives a ratio of 0.93 – an error of 0.6 dB. In this case, the effect is too small to be serious, and can be corrected by reducing d_2 slightly. However, the error increases rapidly as d_2 becomes greater.

6.2.6.2 Audio Samples

Some preliminary recordings were made, with 30 seconds of speech and 30 seconds of music being ‘transmitted’ to the portable radio. This was the same material as used previously, for earlier WPT tests, and was taken from the ‘Jerusalem’ clip provided by Radio 5. It had been processed for distribution to the Radio 5 MF transmitting stations.

The recordings made so far, with some comments, are as follows. In all cases, the 7th harmonic of the interferer was selected. The frequency was typically around 1 MHz, but did vary.

[14] Alternatively, it might be easier to think in terms of electric charges. The voltage needs to be zero at the wall (which is earthed). This can only be achieved if the real and imaginary charges are equal and opposite, and equidistant from the wall.

TABLE 11

The recordings

Identifier	Brief Description	Comments
as_clean	Speech, with no impairment apart from the system noise at –26 dBu	The background hiss is audible but not objectionable
bs_wp0_l2_2-4_onc	As above, plus on-channel interference from the unbranded charging pad	The interference at an effective 2.4 metres is very obtrusive
cs_wp0_l2_2-4_offc	As above, but with the interference off-channel	The interference probably would not normally be noticeable
ds_wp0_l2_2-4_idle	As above, but with the load removed from the charging pad	Again, the interference probably would not normally be noticeable
em_clean	Music, with no impairment apart from the system noise at –26 dBu	The background hiss is audible but not objectionable
fm_wp0_l2_2-4_onc	As above, plus on-channel interference from the unbranded charging pad	The interference at an effective 2.4 metres is very obtrusive
gm_wp0_l2_2-4_offc	As above, but with the interference off-channel	The interference probably would not normally be noticeable
hm_wp0_l2_2-4_idle	As above, but with the load removed from the charging pad	Again, the interference probably would not normally be noticeable
is_wp7_s7_2-4_onc	A smartphone generating on-channel interference on ‘speech’	Much the same results as for the unbranded charging pad
jm_wp7_s7_2-4_onc	As above, with ‘music’ programme	As above

It was difficult to obtain consistent results, as the interferer was liable to jump to a different channel without warning. Even whilst stable, it would switch between two fixed frequencies, only one of which the radio would be tuned to. The switching rate was about one per second, giving rise to an easily identified audible ‘signature’. The off-channel interference was normally almost inaudible, but that would depend on how off-channel it was.

The lack of subtlety of these effects means that the usual ITU 5-point impairment scale is hardly necessary: either the interference is overwhelming, or it is inaudible.

6.2.7 WPT charger in idle mode

The previous work has all assumed that the device is in active service. This might seem reasonable, but in practice the device may be left powered when not in use. Under those conditions, it emits a periodic signal, or ‘ping’. To find out, the previous tests were repeated, but this time without the dummy load. The only other difference was that the search coil was moved closer, to 175 mm, to increase the signal level presented to the spectrum analyser. The interference was also listened to on a portable radio.

When unloaded, all devices gave regular bursts with a fundamental frequency of 175 kHz. The repetition rate varied between 0.5 and 4 times per second. This signal appeared to only cause severe radio interference due to harmonics; the band was fairly ‘quiet’ in the spaces between the harmonics. A typical spectrum plot is shown overleaf in Fig. 23. It was made using the ‘peak hold’ facility on the spectrum analyser, so that the sideband content was allowed to build up over time – the harmonics looked ‘clean’ on a snapshot. The span is 0-2 MHz, and the vertical scale 10 dB/division. Note that the search coil has a proportional-to-frequency response.

FIGURE 23

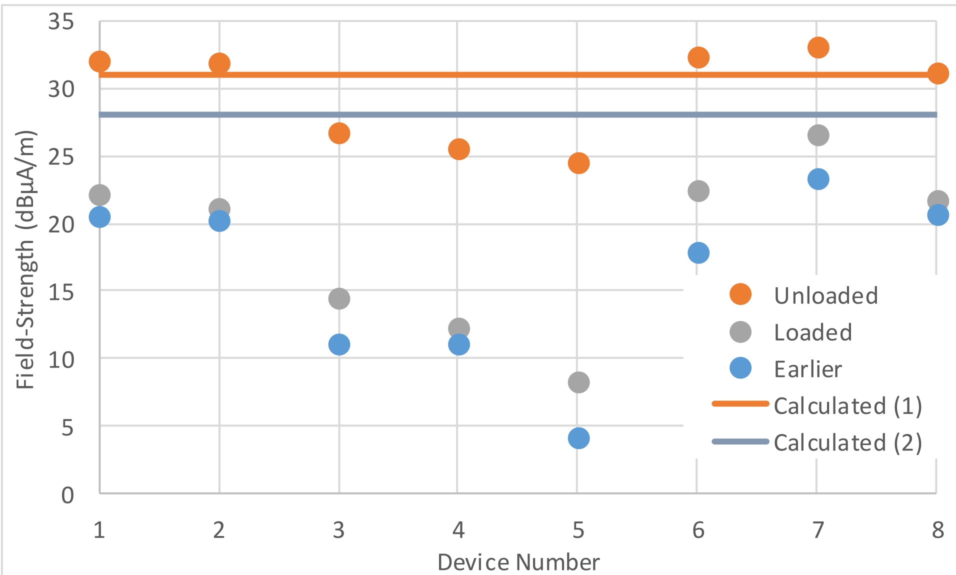
A typical spectrum (of device 2)

An interpretation of the spectrum is that the device spends most of its time at 175 kHz, but momentarily tries 100 kHz (its normal operating frequency). The audible effect on an AM receiver is a ‘double thump’ corresponding to the start and finish of the burst. This is as expected: the sudden changes in carrier level give rise to low-frequency transients.

The field-strengths of the 5th harmonic are plotted below, in orange, and contrasted with those of the 7th harmonic when the test load is in place (and set to 2 W). Note that the two sets of harmonics are conveniently at about the same frequency.

FIGURE 24

Harmonic levels of devices tested



Comments are as follows:

– The levels have been normalised to a distance of 1 metre.

– The ‘earlier’ (loaded) results are the seventh harmonic levels shown in Fig. 24.
– Device 9 has not been included, as it gave very erratic results.
– ‘Calculated 2’ is the harmonic level predicted by the simulation of § 4, whilst ‘Calculated 1’ is 2.9 dB greater, to allow for the 5th harmonic of the Fourier expansion being 7/5 times the level of the 7th harmonic.

Generally, there is good agreement between the calculated and actual harmonic levels for the ‘unloaded’ situation – the average of the actual values is only 1.2 dB different from the calculation. The story for the ‘loaded’ situation is less happy, where the measured results average 11 dB below the calculated value. There is reasonable agreement between the present and earlier ‘loaded’ results for the 7th harmonic, suggesting that this shortfall is real.

An attempt was made to find the reason for the shortfall. A ‘sanity check’ with the pancake coil was tried again, this time with the test load placed directly over the coil. With the test load in contact with the coil, the level fell by 13 dB. Raising the load by only 10 mm reduced the loss to about 4 dB. Some casual experimentation showed the loss to be very dependent on position, and to a lesser extent on frequency. Evidently, the ferrite screen and coil within the dummy load have a significant effect. Using a Qi charger as a screen in place of the test load gave some loss, but not as dramatic as before.

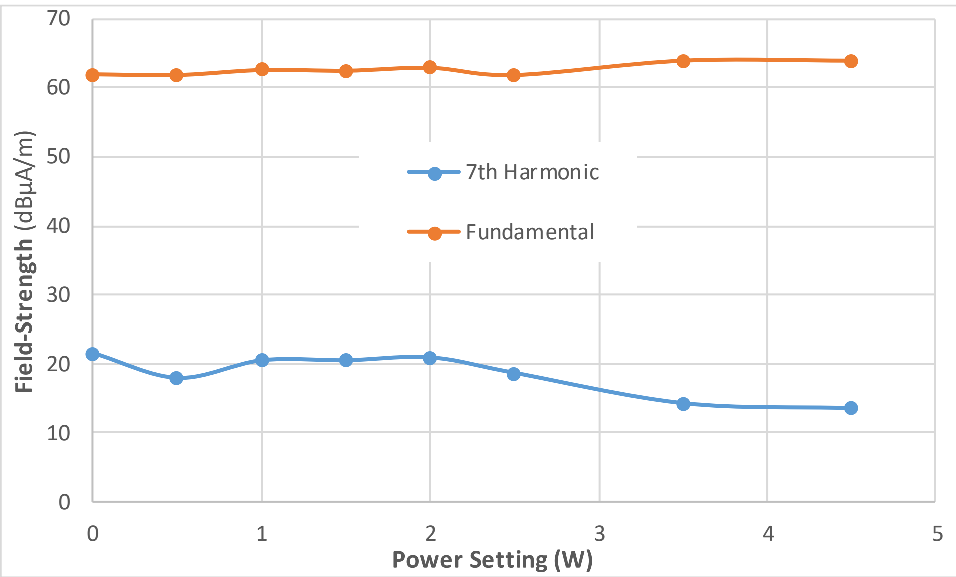
The above work suggests that the ‘idle mode’ emissions are a greater nuisance because there is nothing to screen them. As there is good agreement between calculation and practice, the conclusion reached in § 5 that the charger could cause interference to AM receivers at distances of up to 10 metres.

6.2.8 High power levels

So far, testing has been carried out at a power of 2 W the limit imposed by the internal resistors in the dummy load. However, the load allows the connection of external resistors, so raising the capability to 5 W. The Dummy load senses these resistors and configures the system accordingly. The fundamental and 7th harmonic levels of charger ‘2’ were measured beyond 2 W, with results as below.

FIGURE 25

Field-strengths at higher power levels



The power was limited to 4.5 W, as the system was showing signs of distress at the full 5 W.

Up to 2 W, at least, the harmonic level remains constant. Above that, the level falls somewhat, possibly because of a change of mode when external resistors are used. More surprising is that the level of fundamental also remains constant. This could partly be because the efficiency of the system improves with increasing power, resulting in less stray field.

6.3 AM broadcasting Study 3 for WPT devices operating in 315-405 kHz

6.3.1 Measurements comparing impact of different frequencies

This study has been carried out to explore whether the harmonics of a wireless charging device operating at the frequency range of 315-405 kHz will introduce harmful interference to AM broadcasting receivers operating at the frequency range of 526.5-1 700 kHz in practice.

6.3.2 AM broadcasting channel selection

This study is carried out on non-beam inductive WPT devices which operate around the frequency of 360 kHz. The chargers are either compliant with the Qi2 specification of the Wireless Power Consortium or very similar to the Qi2 specification and all are available off the shelf. The Qi2 specification defines WPT operations around 360 kHz with higher power and significantly higher efficiency than Qi1.

In theory, its 2nd , 3rd and 4th harmonics will fall into 526.5-1 700 kHz. However, the even harmonics are well suppressed through the charging circuit design.

Therefore, the study focuses on the 3rd harmonic from WPT devices. It was conducted respectively on AM broadcasting receivers for channels 1080 kHz and 1098 kHz in China. Channel 1080 overlaps with the 3rd harmonic while channel 1098 is the nearest adjacent channel found in real life during the study to 3rd harmonic of the WPT devices operating around 360 kHz.

The study collects data from a 3 m test chamber, office building and hotel in an urban area. Three different brands of wireless chargers from the open market were tested for interference into three commercial AM broadcasting receivers by different manufacturers.

6.3.3 Subjective audible testing

The subjective audible testing was conducted inside a building, where the signal strength of AM broadcasting is very close to the minimum signal level stated in Recommendation ITU-R BS.703. Then, an acceptable signal quality can be obtained by adjusting the placement and orientation of AM broadcasting receivers. The operator monitored the audible interference by gradually moving the wireless chargers towards the AM receivers. Considering the differences in hearing between different people, five people participated in the subjective test evaluation. The subjective audible testing is designed with the reference of ITU-R BS.1284-2, but to focus more on the experience of actual users.

The audible testing assessment can be defined by three levels[15]:

- Level 1 is intolerable,
- Level 2 is interference audible, but tolerable,
- Level 3 is interference non-audible.

[15] The levels from BS.1284 were simplified into: Level 1 = 1 (Very annoying) and 2 (annoying), Level 2 = 3 (slightly annoying) and 4 (perceptible, but not annoying), Level 3 = 5 (Imperceptible).

FIGURE 26

Subjective audible testing principle

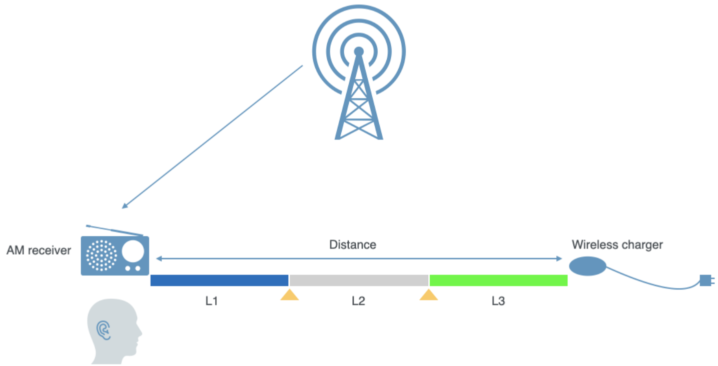


FIGURE 27

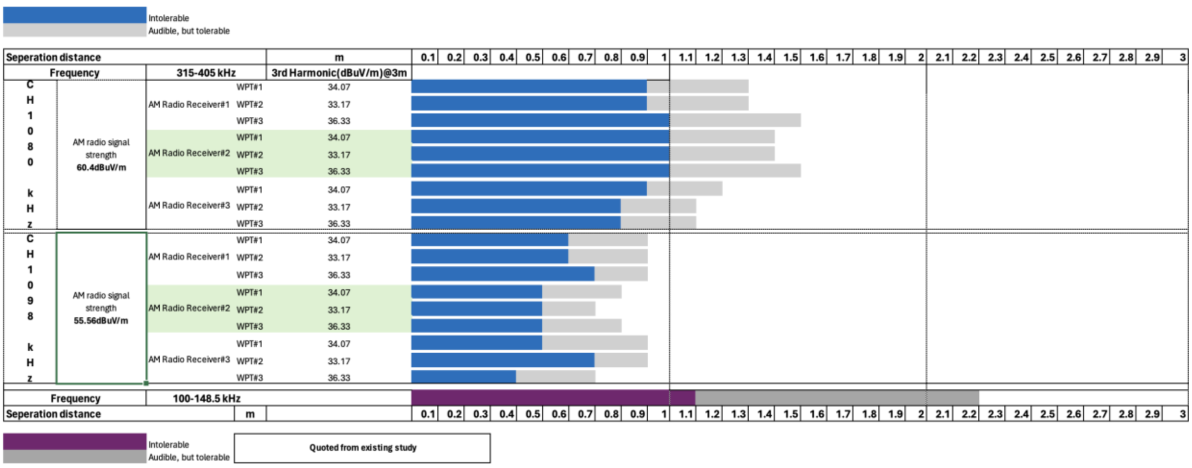
Subjective audible testing setup

6.3.4 Results summary

Figure 28 shows the results for AM receiver 1, AM receiver 2 and AM receiver 3 operating at Channel AM1080 kHz, which overlaps with the 3rd harmonic of all WPT chargers in the top part. In the lower part Channel AM1098 kHz is shown.

FIGURE 28

Subjective audible testing results



When the harmonic interference overlaps with the AM broadcasting channel, a separation distance of 1.5 m can effectively avoid the audible interference at the worst case.

However, when it is adjacent to the AM broadcasting channel, a separation distance of 0.9 m can prevent AM broadcasting receivers from audible interference at the worst case.

These distances are achievable and therefore the impact to the broadcasting service is considered by the study as avoidable.

When comparing the distances found with those in AM Broadcasting Study 1 (§ 6.1) with WPT operating in 100-148.5 kHz it can be seen that the distances for WPT operating in 315-405 kHz are much lower and the impact is much more limited.

6.3.5 Sensitivity analysis – Different orientation of charger coil and additional WPT devices

In addition to the usual usage scenarios where the charger coil is placed horizontally, the study also conducted research on some usage scenarios where the charger coil is placed vertically with the assistance of a pop-up stand or external stand. For this study two additional chargers that are only available as stand-up chargers were measured. The study estimates the impact in practice by adjusting the charger coil arrangement relative to AM radio receivers, such as back facing and parallel.

FIGURE 29

Orientation of charger coils vertically arranged

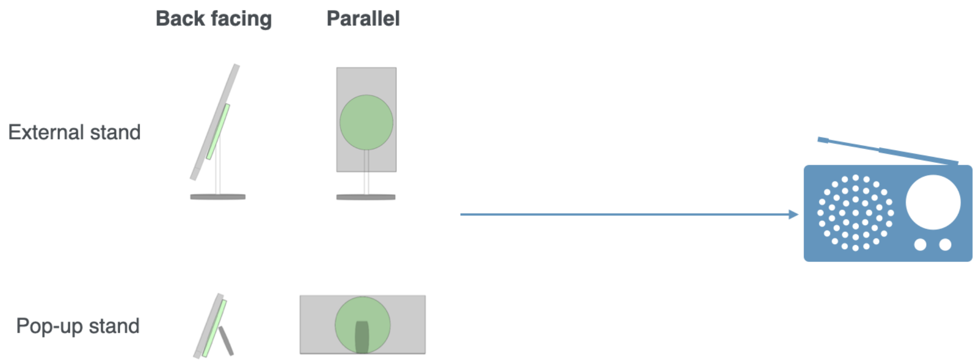
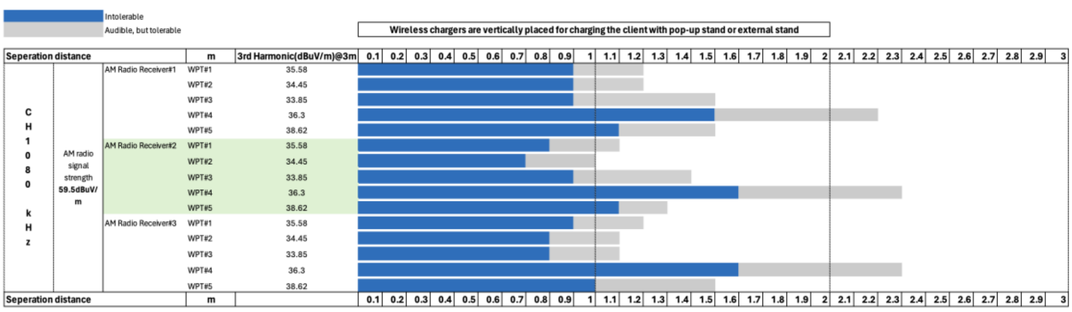


Figure 30 shows the results for AM receiver 1, AM receiver 2 and AM receiver 3 operating at Channel AM1080 kHz.

FIGURE 30

Results summary for WPT harmonics to channel AM1080 kHz (vertically arrangement)

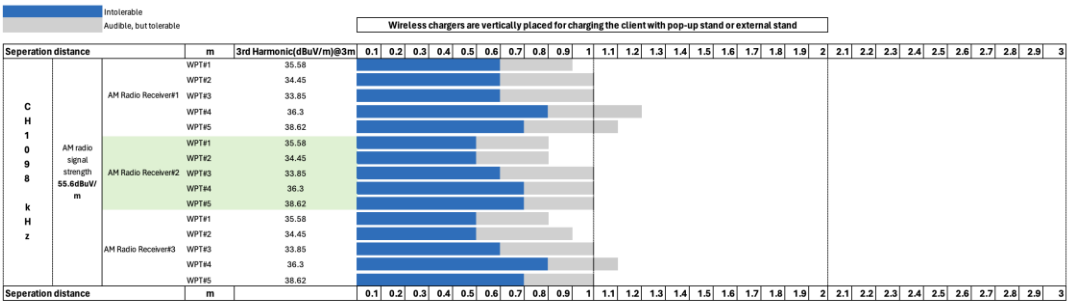


It is noted that a single WPT charger requires a larger protection distance than others. The 3rd harmonic of this wireless charger has around 500 Hz offset from the centre of the AM broadcasting channel. Figure 1 of Recommendation ITU-R BS.560 shows that the greatest protection ratio is approximately 16 dB, which corresponds to frequency offsets of around 1.6 kHz. When the frequency offset between harmonics and AM broadcasting signal is 1.6 kHz instead of 500 Hz, the protection distance increases by a factor of 1.17.

Figure 31 shows the results for AM receiver 1, AM receiver 2 and AM receiver 3 operating at Channel AM1098 kHz.

FIGURE 31

Results summary for WPT harmonics to channel AM1098 kHz (Vertically arrangement)



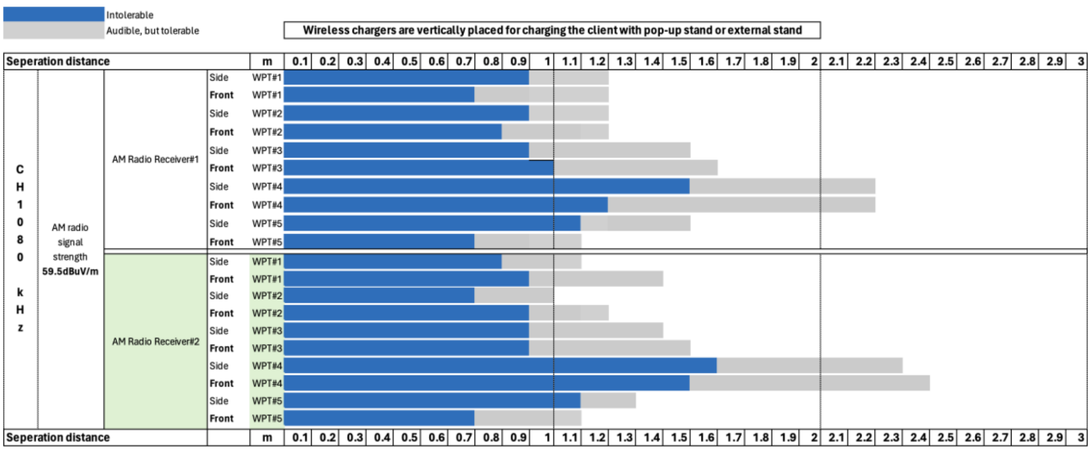
The study result shows that the impact is comparable with the horizontal arrangement of wireless charger coil.

6.3.6 Sensitivity analysis – Different orientation of the AM broadcasting receiver

Another sensitivity analysis was carried out to analyse the directivity of an AM broadcasting receiver.

FIGURE 32

Sensitivity analysis of different orientation of the AM broadcasting receivers



The study also clarified the sensitivity to couple the interference on different orientation of radio broadcasting receivers. The wireless chargers approach the radio broadcasting receivers from different directions, then quantify how separation distance is required for avoiding the interference. Overall, there is 10~40 cm difference on separation distance request at different directions as shown in Fig. 32, that could be caused by antenna coupling character in near field or testing uncertainty.

6.3.7 Objective harmonic level comparison

Comparing to the frequency band of 100-148.5 kHz, the existing regulation e.g. ETSI EN300 330 requires meeting −15 dBuA/m at 360 kHz, compared to 66 dBuA/m at 119 kHz, does have much stricter limit on the fundamental radiated emission at 315-405 kHz. This makes the harmonics caused by 315-405 kHz to be friendlier to AM broadcasting services than by 100-148.5 kHz.

An additional 5 WPT devices operating in 100-148.5 kHz were measured for the purpose of this comparison.

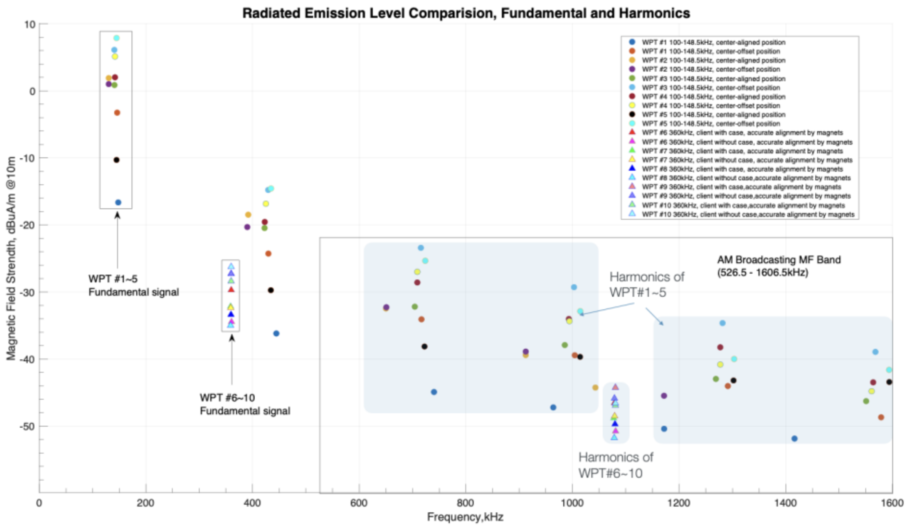
Their emission levels where then compared to the emission levels of the 5 WPT devices operating in 315-405 kHz used in this study.

Figure 33 shows the harmonic level comparison respectively from the different WPT frequency ranges. It clearly indicates that the harmonic level radiated from 315-405 kHz WPT devices is much lower than the ones radiated from 100-148.5 kHz WPT devices. Furthermore, as the charging frequency operating at 315-405 kHz is higher, fewer harmonics fall inside AM broadcasting MF band as well (2 versus 6 odd harmonics).

In summary, the impact of harmonics from the 315-405 kHz frequency band on intermediate frequency AM broadcasting is far less than that of 100-148.5 kHz.

FIGURE 33

Harmonic level comparison based on measurements



It should be noted that the interference risk from WPT devices for portable and mobile devices operating in 100-148.5 kHz seems to be very limited or non-existent. There are many millions of devices operating in this frequency range and no interference case has been recorded. Since WPT devices for portable and mobile devices operating in 315-405 kHz have a lower interference impact on broadcasting, it is even less likely that interference would be noticed by AM radio listeners.

7 Impact study of non-beam inductive WPT for mobile and portable devices to Amateur service

7.1 Parameters used for simulation

Within the United States § 47 CFR Part 15.31 (2) governs the measurement requirements for radio frequency devices operating in the near-field. After applying the FCC required extrapolation factor of 40 dB per decade to the −15 dBμV/m at 300 m, the limit on the non-beam WPT devices is 44.08 at 10 m. Modelling was used for near field propagation.

The parameters for the amateur service receivers came from Recommendation ITU-R M.1732 and are shown in Table 12. 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 12

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

7.2 Simulation analysis and results

7.2.1 Single-entry scenarios

The single-entry scenarios place a single WPT device inside a building with the amateur receiver located away from the building outdoors. The first simulation uses 10 dB building entry loss and the second uses 0 dB building entry loss to account for different building materials.

FIGURE 34

Single entry scenario

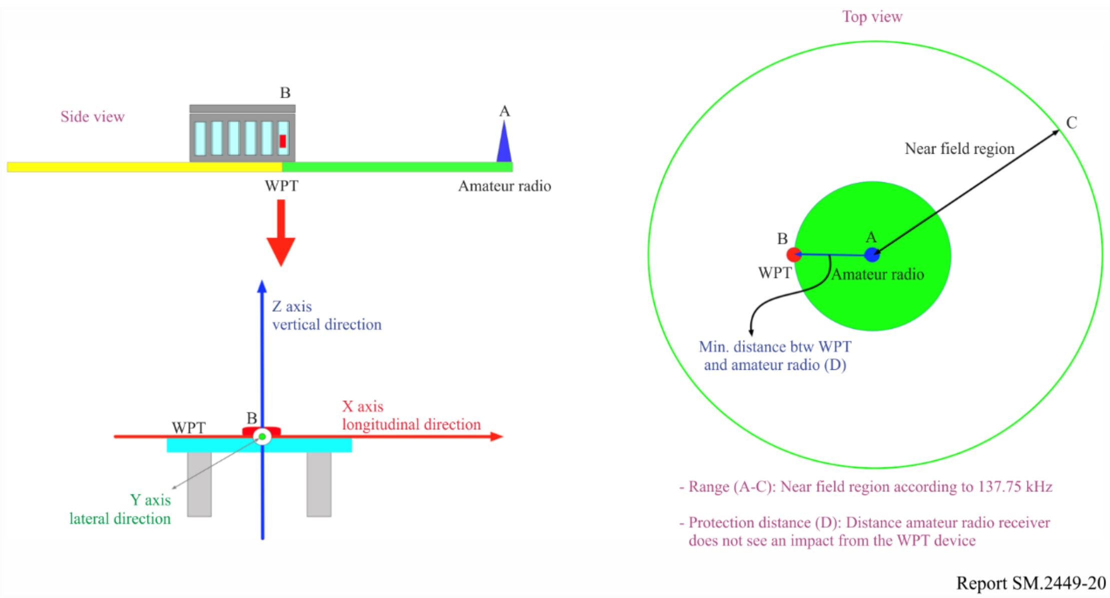
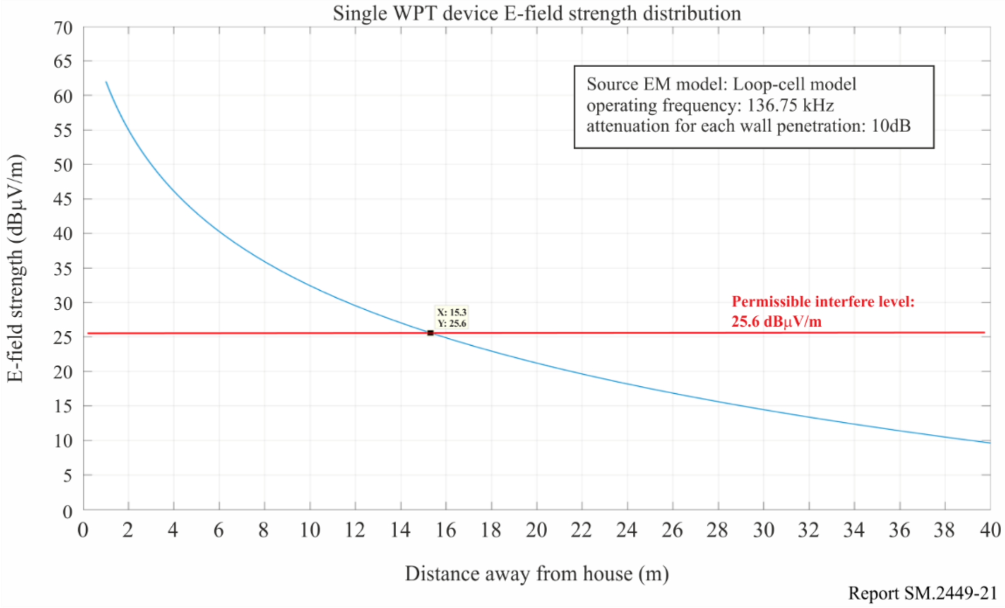


FIGURE 35

Single-entry distribution for scenario 1

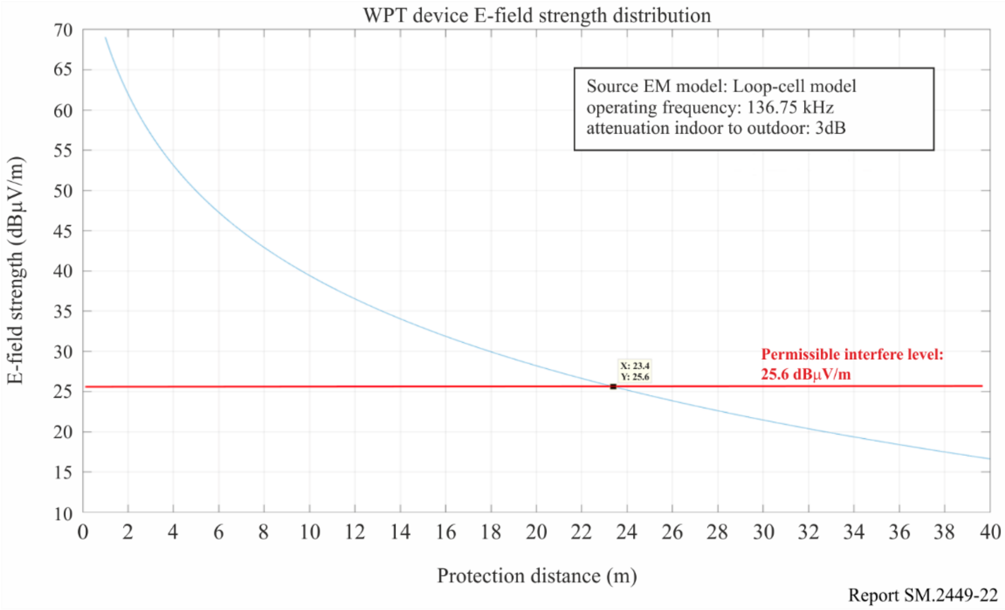


Conclusions for single-entry scenario 1

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 receiver.

FIGURE 36

Single-entry distribution for scenario 2



Conclusions for single-entry scenario 2

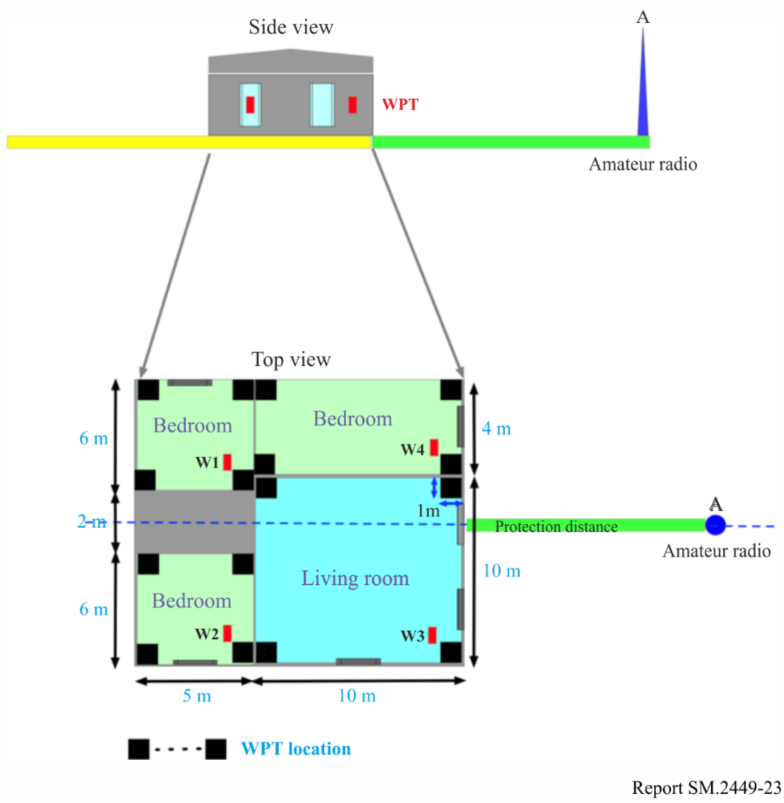
The results for single-entry scenario 2 using a 0 dB attenuation to simulate wooden building construction show the WPT device should be placed more than 28.1 m from the amateur radio receiver.

7.2.2 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 37

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 13.

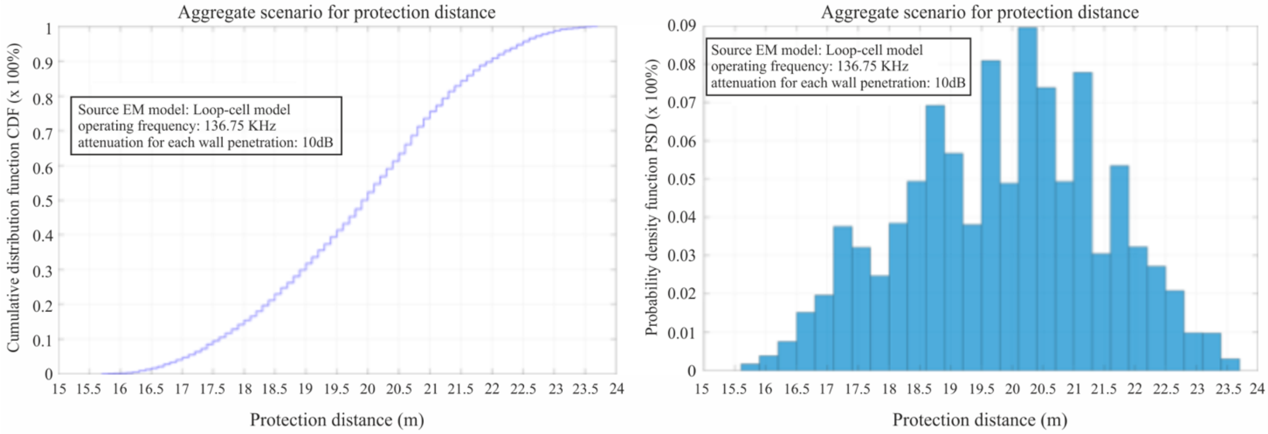
TABLE 13

Values used for building entry loss

Parameter	Number of walls	Wooden 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

FIGURE 38

Results of simulation with 10 dB building entry loss



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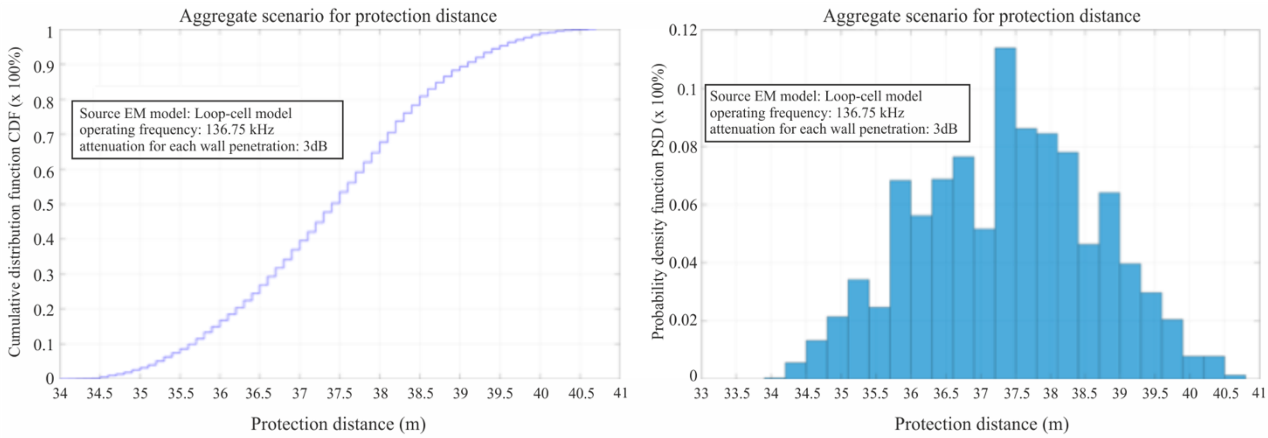
Conclusions for aggregate simulation 1

The median protection distance is 17.1 m, and the maximum protection distance is 23.2 m based on 10 dB building entry loss from concrete walls. The range of values is a result of WPT device placement near windows. 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 overlapping constructively and 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 39

Results of simulation with 0 dB building entry loss



Report SM.2449-26

Conclusions for aggregate scenario 2

The median protection distance is 42.0 m and the maximum protection distance is 51.3 m based on 0 dB building entry loss from wooden/brick walls. The range of values is a result of WPT device placement near windows. 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 overlapping 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.

7.3 Summary of results

Table 14 below summarizes the results of the simulations. Based on the simulation results, it can be concluded that non-beam WPT mobile charging devices impact amateur service receivers when the devices are less than 51.3 m away from the receiver.

TABLE 14

Summary of results

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	23.2
Aggregate scenario 2	25.6	51.3

The exact location (e.g. height difference) of the Amateur service receive antenna could mitigate the interference impact. Also, it is unlikely that all WPT chargers will operate on the same frequency which could further reduce the interference impact. Nevertheless, there could likely be multiple WPT devices within range of the single receiver since the protection distances are large for an urban area.

8 Impact study of non-beam inductive WPT for mobile and portable devices to radionavigation service in 90-110 kHz

Loran-C receiver is considered as an incumbent victim system, which is operating at 90-110 kHz, 20 kHz bandwidth. The characteristics of the Loran-C system are from Recommendation ITU-R M.583 as provided by WP 5B.

Generally, Loran-C system station is built in non-residential area. Figure 40 shows examples for reference. Loran-C receiver is on the ship.

FIGURE 40

Loran-C Stations in non-residential area

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8.1 Parameters for simulation

Tables 15 and 16 are parameters used during the simulation for interferer and victim respectively.

Within the United States § 47 CFR Part 15.31 (2) governs the measurement requirements for radio frequency devices operating in the near-field. After applying the FCC required extrapolation factor of 40 dB per decade to the −15 dBµV/m at 300 m, the limit on these devices is 44.08 dBµV/m at 10 m.

The propagation model used for near-field and far field is contained in Recommendation ITU-R SM.2028.

The interference scenarios simulated had the WPT device placed on a table inside a building 50 m from the shoreline in between the transmitter and the receiver located on-board a ship off-shore. The Loran-C transmitter is located 5 km inland from the shoreline.

TABLE 15

Assumption of parameters for WPT interferer impacting Loran-C receiver

Parameters	Details
Device type	WPT mobile device
Operating frequency (kHz)	100-148.5
Radiated E-field strength (dBµV/m at 10 m)	44.08
Antenna type	Omni-directional
Height (m)	0.7
Min Distance from shore (m)	50
Building entry loss (dB) [16]	10
Propagation model	Near field and free space propagation model

TABLE 16

Assumption of parameters for Victim – Loran-C receiver

Parameters	Details
Victim system	Loran-C receiver
Operating frequency (kHz)	100
Bandwidth (kHz)	20
Antenna pattern	Rod antenna
Loran-C station transmitter output power (kW)	40
Protected minimum Loran-C signal field strength (dBµV/m)	45
Protection criteria (I/S)	−20 dB

The protection criteria used is contained in Fig. 1 from Recommendation ITU-R M.589. According to this reference, the protection criteria from the in-band and out-of-band interference should follow the curve in Fig. 41. Worst curve (near-synch) is used to estimate interference risk.

The worst case is assumed to be −20 dB from near-synchronous at 100 kHz (0 kHz offset from 100 kHz); therefore, 25 dBµV/m is acceptable for noise at Loran-C receiver. Additionally, the worst

[16] Building entry loss in this case means building exit loss of the WPT signal. It is fully applicable here, since the attenuation effect of building material applies to the far field.

case is assumed to be −13 dB from near-synchronous at 110 kHz; therefore, 32 dBµV/m is an acceptable noise level at Loran-C receiver. Based on these assumptions, 25 dBµV/m at 100 kHz is used as the max acceptable noise level at Loran-C receiver in this assessment. Figure 41 below depicts the interference protection criteria from Recommendation ITU-R M.589 and Table 17 below summarizes the interference parameters used below.

FIGURE 41

Loran-C/CWI protection criteria

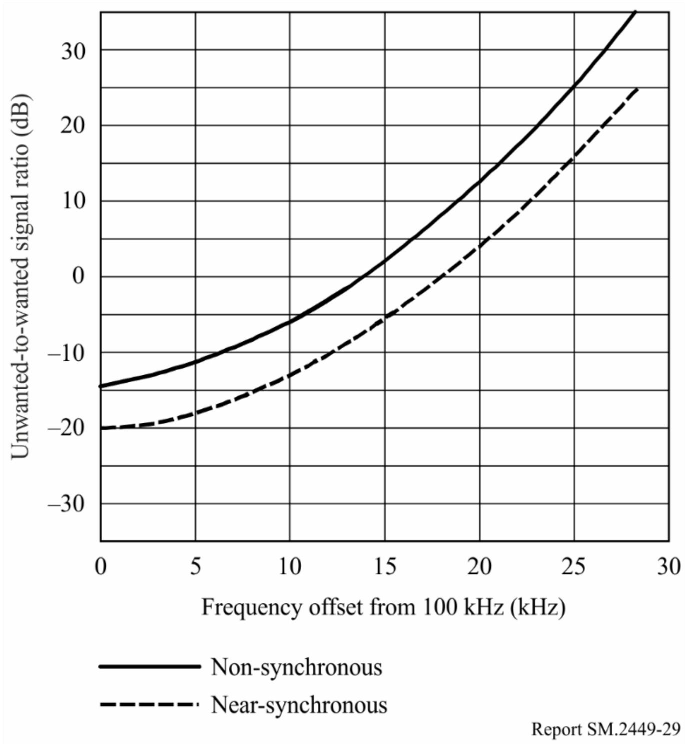


TABLE 17

Assumption of parameters for Victim – Loran-C

Interferer frequency	Min wanted signal field strength	Loran-C/CWI criteria (near-sync)	Acceptable noise at Loran-C receiver (dBµV/m)
100 kHz	45	−20	25
110 kHz	45	−13	32

TABLE 18

E/H ratio is used to calculate the near field E-Field strength from the WPT device

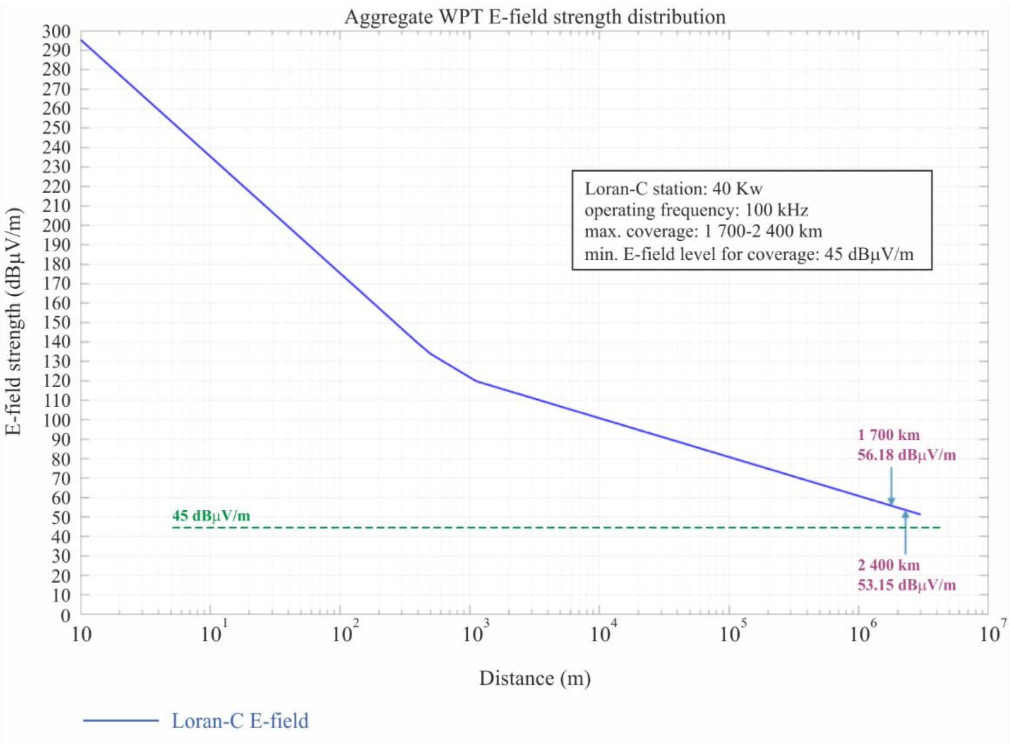
Distance (m)	E/H ratio (dB-ohms)
10	17.95
100	38.32
1 000	53.26
2 000	52.01
5 000	51.61
10 000	51.55

Loran-C signal strength distribution

Based on the 40 kW from Loran-C station, Fig. 42 depicts the Loran-C E-field distribution along the distance. Inside the 1 700-2 400 km targeted coverage, Loran-C signal strength is much stronger than the minimum required signal level.

FIGURE 42

Typical Loran-C E-field distribution



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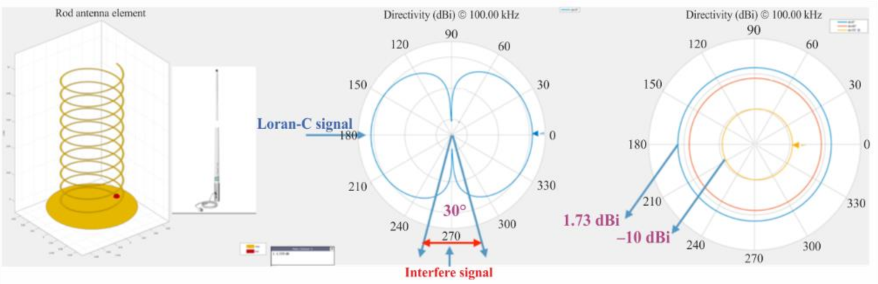
Antenna model for Loran-C receiver

In this assessment, a Rod antenna is considered as Loran-C receiver's antenna installed on top of the ship. According to the simulation result in Fig. 43, the delta gain between unwanted to wanted gain ratio is −11.73 dB.

FIGURE 43

Loran-C receiver antenna gain



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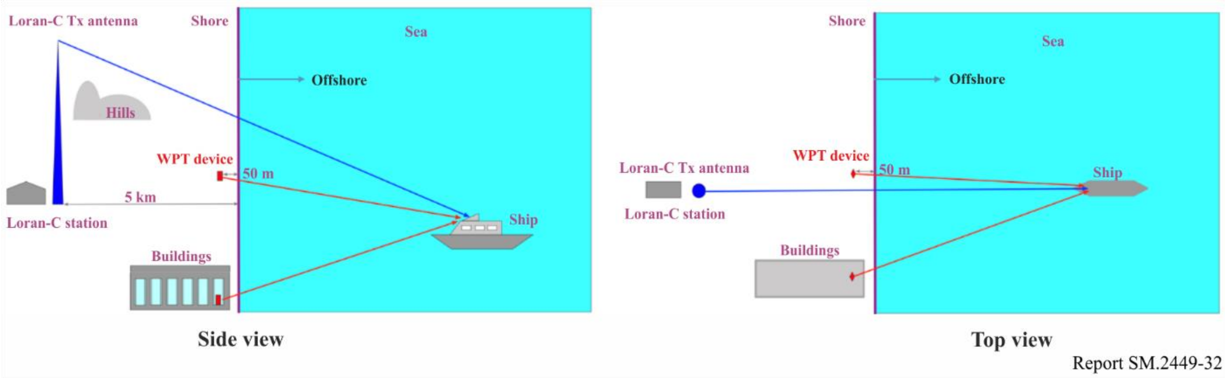
8.2 Simulation scenarios and results

8.2.1 Simulation Model #1

Model #1 considers the WPT device in a building or close to a building, which is 50 m onshore. Loran-C receiver is the victim, which is installed on the ship.

FIGURE 44

Model #1 for Loran-C receiver impact study



Report SM.2449-32

Figure 45 is the consolidated data results for the Model #1 – single entry scenario. When WPT device is working at 100 kHz, there is an 80 dB margin between the signal to be protected (26.21 dBμV/m) and the E-field strength of the Loran-C transmitter, which is greater than 110 dBμV/m at the shore.

TABLE 19

Model #1 for Loran-C receiver – single entry

Parameters	Value
WPT E-Field strength at 300 m (dBμV/m)	−15
WPT E-Field strength at 10 m (dBμV/m)	44.08
WPT E-field strength at 50 m (dBμV/m) (away from shore)	16.12
Building entry loss (dB)	10
Protection ratio (dB)	20
Signal level to be protected (dBμV/m) 50 m protection distance base	26.12
Loran-C signal strength (dBμV/m) at Shore	>110
Margin (dB)	>80

FIGURE 45

Model #1 for Loran-C receiver – single entry scenario

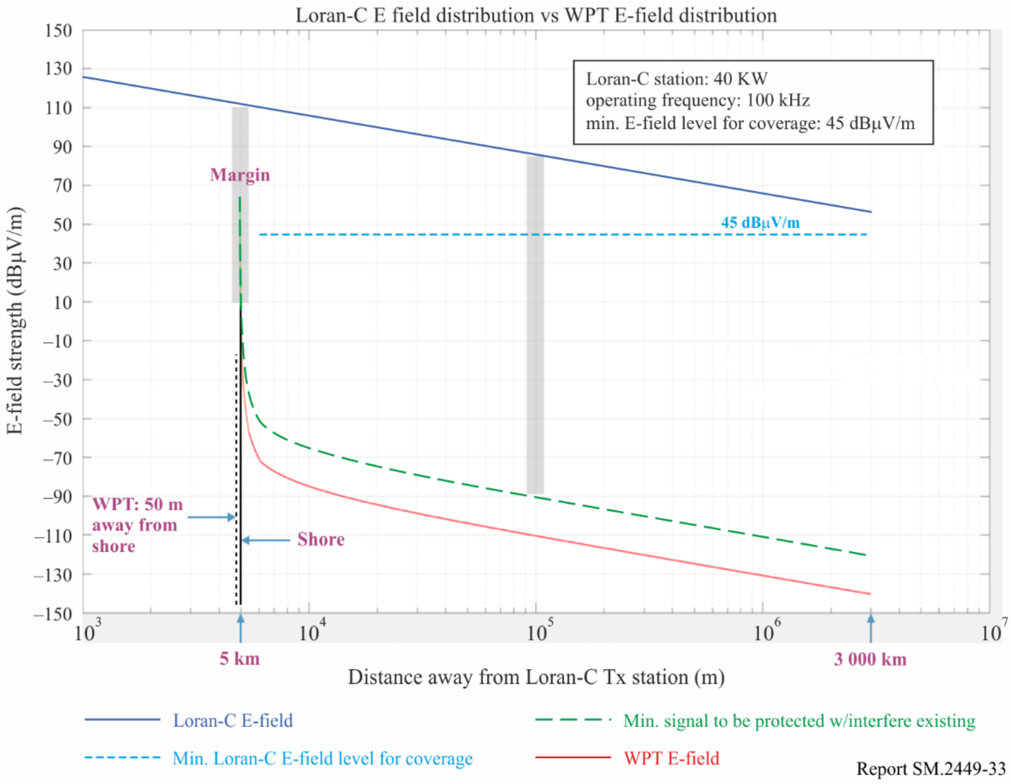


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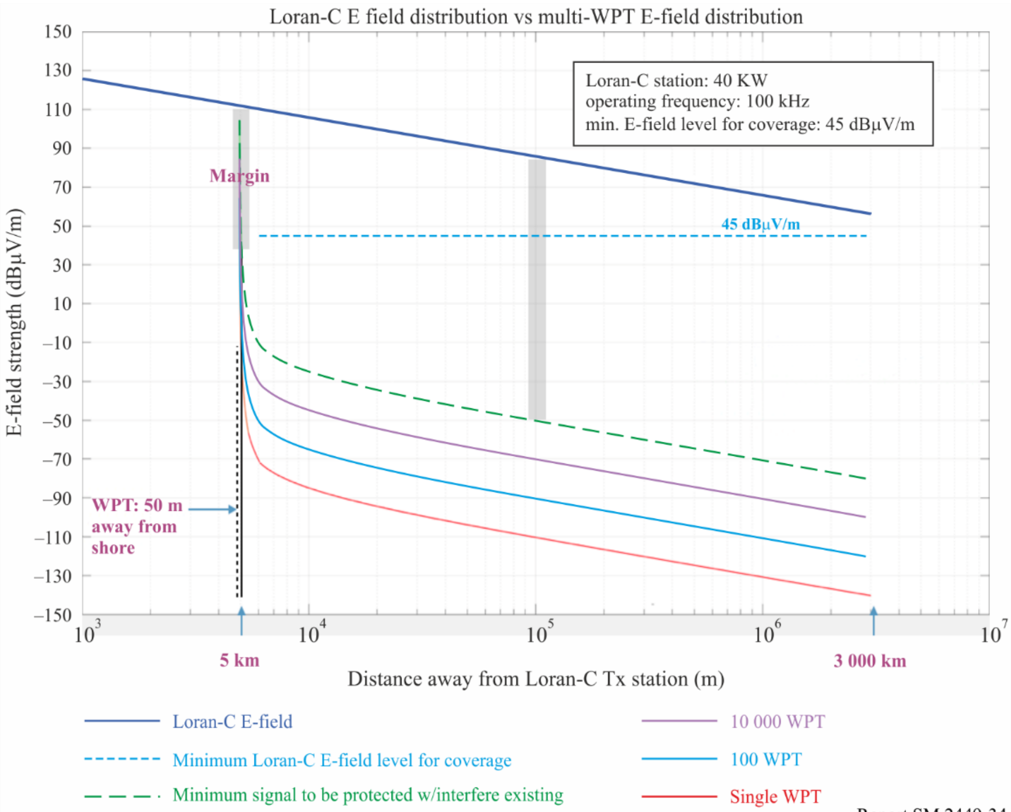
Figure 46 is the consolidated data for different aggregate cases. The Figure depicts the E-field signal levels of 100 and 10 000 active WPT devices operating simultaneously. When 10 000 active WPT devices are operating at 100 kHz simultaneously, there is a 3.88 dB margin between the signal to be protected (66 dBμV/m for 100 devices and 106.12 dBμV/m for 10 000 devices) and the E-field strength of the Loran-C transmitter, which is greater than 110 dBμV/m at the shore.

FIGURE 46

Model #1 for Loran-C receiver – aggregate scenario



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8.2.2 Simulation Model #2

The second Model #2 considers the Loran-C transmitter onshore located 5 km from the shoreline, with WPT mobile device is below the deck of the ship, and the Loran-C receiver antenna on the top of the ship. Considering 10 dB building entry loss and 17.95 dB E/H ratio from Table 18, the allowed interference E-Field at 10 m would be 34.08 dBμV/m. As listed in Table 16, −20 dB *I/S* ratio is required. The max acceptable interference signal level would be 42.35 dBμV/m according to the below equation, when a WPT mobile device is operating at 10 m away from Loran-C receiver antenna.

Maximum acceptable noise at Loran-C receiver equation:

Interfere level – delta gain + protection level = 34.08 – 11.73 +20= 42.35 dBμV/m

Model #2 – single entry scenario

Table 20 contains the input parameters and simulation results for the Model #2 single entry scenario. The simulation results show that a the WPT device with an E-field level of 34.08 dBμV/m should be placed at a distance greater than 5.37 m from the Loran-C receiver antenna in order to maintain the minimum signal level at the maximum 2 400 km coverage distance.

TABLE 20

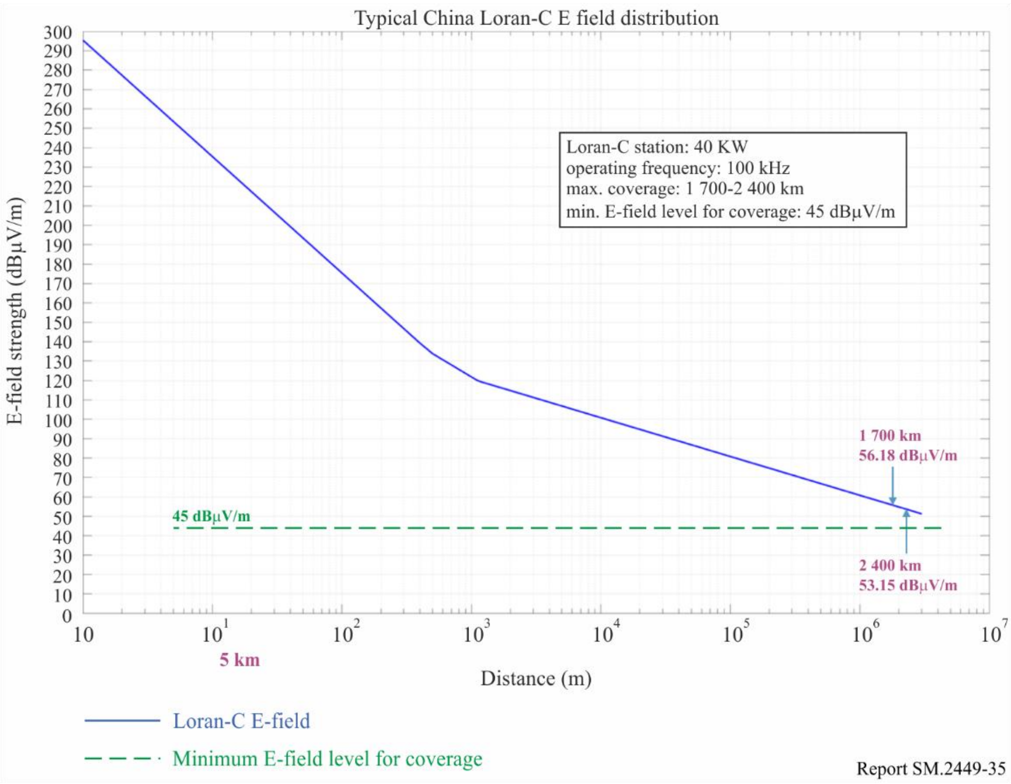
Model #2 for Loran-C receiver – single entry

Parameters	Value
WPT E-field strength at 300 m (dBµV/m)	−15
WPT E-Field Strength at 10 m (dBµV/m)	44.08
Building entry loss (dB)	10
WPT E-field strength at 10 m (dBµV/m) with building entry loss	34.08
Antenna gain delta for wanted signal and WPT interfere (dB)	−11.73
Protection ratio (dB)	20
Signal level to be protected (dBµV/m) – 10 m protection distance base	42.35
Coverage for signal level protected (km) – 10 m protection distance base	8355
Protection distance (m) – based on 1 700 km	4.51
Protection distance (m) – based on 2 400 km	5.37

Figure 47 is the consolidated data for the Model #2 single entry scenario. The Figure depicts the protection distance results contained in Table 20.

FIGURE 47

Model #2 for Loran-C receiver impact study – Single entry



Model #2 – aggregate scenario

In this scenario, five WPT mobile devices are assumed working at the same time below the deck of the ship with a separation of 3 m between each device, as shown in Fig. 48. The input parameters for the aggregate scenario are contained in Table 21.

FIGURE 48

Model #2 for Loran-C receiver – aggregate scenario

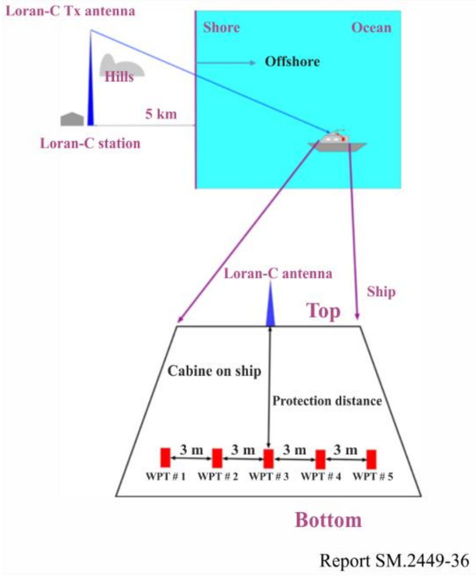


TABLE 21

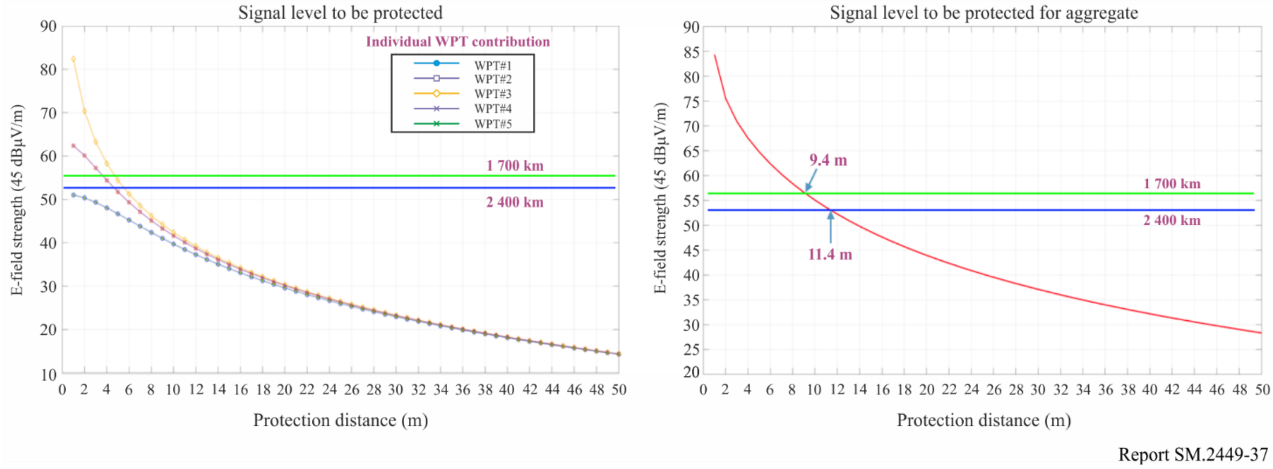
Model #2 for Loran-C receiver – aggregate scenario

Parameters	Value
Number of active WPT devices	5
WPT E-field strength at 300 m (dBµV/m)	−15
WPT E-field strength at 10 m (dBµV/m)	44.08
Building entry loss (dB)	10
WPT E-field strength at 10 m (dBµV/m) with building entry loss	34.08
Antenna Gain delta for wanted signal and WPT interfere (dB)	−11.73
Protection ratio (dB)	20
Coverage for signal level protected (km) – 10 m protection distance base	8355
Signal level to be protected at 1 700 km (dBµV/m)	56.18
Protection distance required for 1 700 km coverage (m)	9.4
Signal level to be protected at 2 400 km (dBµV/m)	53.13
Protection distance required for 2 400 km coverage (m)	11.4

Figure 49 is the consolidated data for Model #2 aggregate scenario. In order not to impact the Loran-C receiver at the max coverage 2 400 km, the closest WPT devices from the Loran-C receiver antenna should be kept 11.4 m away.

FIGURE 49

Model #2 for Loran-C receiver impact study – Aggregated signal level



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8.3 Summary of results

The Loran-C receiver is not impacted in Model #1 scenario when WPT mobile charging devices are onshore.

For the Model #2 single-entry scenario, the Loran-C receiver is not impacted by the on-board WPT mobile device charger when the device is located 4.51 m away from the Loran-C receiver antenna at its maximum coverage range of 1 700 km and 5.37 m away when the desired maximum coverage distance is 2 400 km.

In the Model #2 – aggregate scenario, the Loran-C receiver is not impacted by the on-board WPT mobile devices when the closest WPT device is 9.4 m away from the Loran-C receiver antenna at its maximum coverage range of 1 700 km and 11.4 m away when the desired maximum coverage distance is 2 400 km.

9 Impact study of non-beam inductive WPT for mobile and portable devices on aeronautical radionavigation service for WPT devices operating in 100-148.5 kHz and 315-405 kHz

9.1 Parameters for simulation

The simulation is carried out at two representative frequencies: 130 kHz relevant to WPT in 100-148.5 kHz and 400 kHz relevant to WPT in 315-405 kHz.

For 130 kHz, within the United States § 47 CFR Part 15.31 (2) governs the measurement requirements for radio frequency devices operating in the near-field. After applying the FCC required extrapolation factor of 40 dB per decade to the −15 dBμV/m at 300 m, the limit on the non-beam WPT devices is 44.08 at 10 m. Modelling was used for near field propagation.

For 400 kHz, the 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 responsible group within in ITU-R provided the basis to analyse the impact as provided in Table 22.

TABLE 22

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	130-535	2.7	21.9

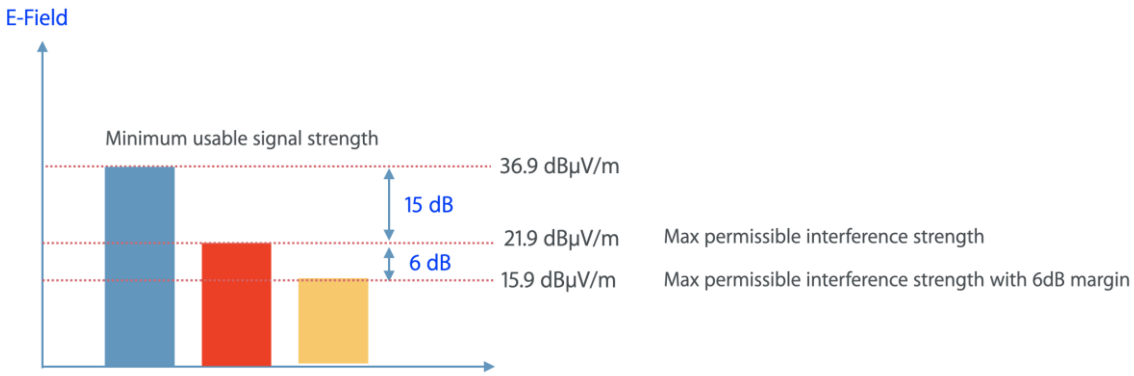
The aggregate effect is taken into account in the simulations through adding all the WPT emissions from each device.

As a sensitivity analysis, the results are also shown with an additional 6 dB margin.

The different levels are shown in Fig. 50.

FIGURE 50

Relevant field strength levels

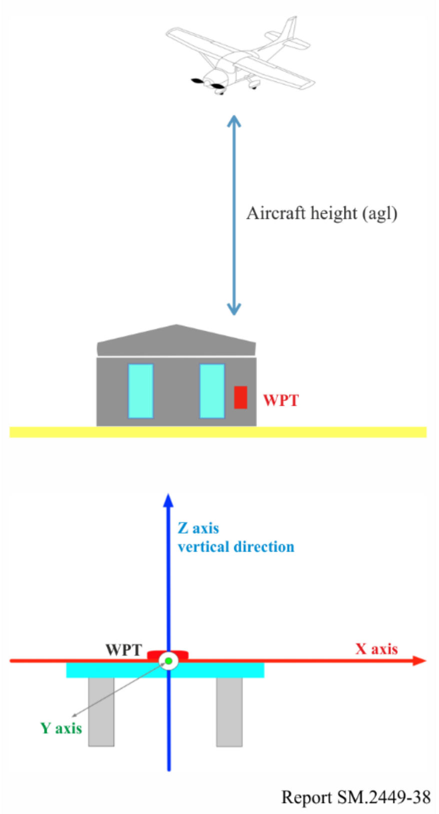


9.2 Single entry scenario

The single-entry scenarios place a single WPT device inside a building with the aircraft placed directly above the building outdoors.

FIGURE 51

Single-entry scenario



9.2.1 Single-entry results

FIGURE 52

WPT at 130 kHz: Single-entry E-field vs height agl (m)

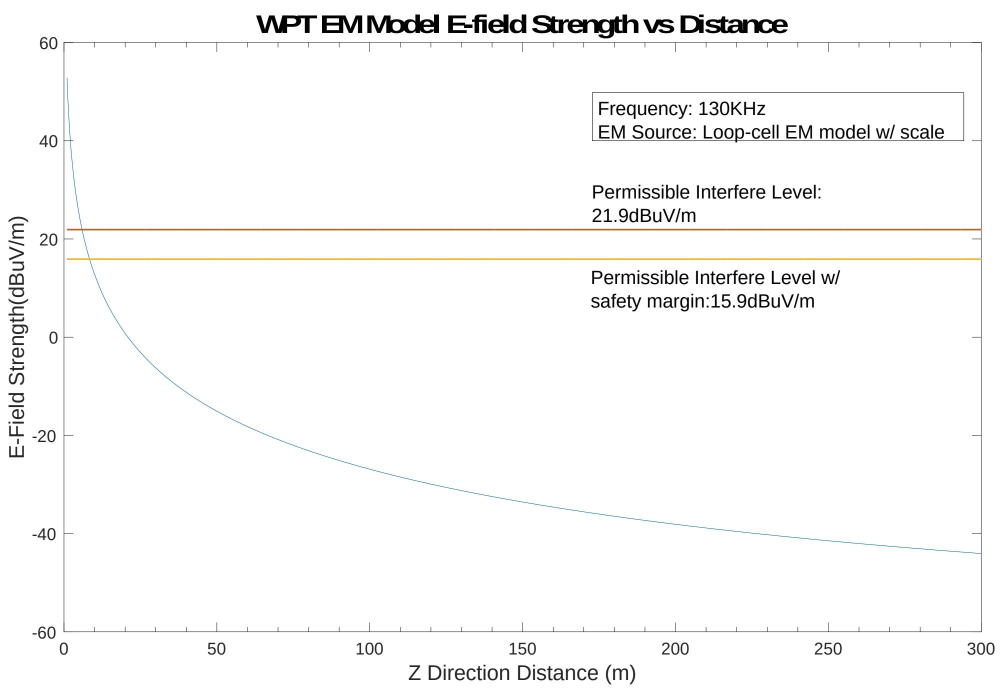


FIGURE 53

WPT at 130 kHz: Single-entry E-field vs height agl (m) (zoom in)

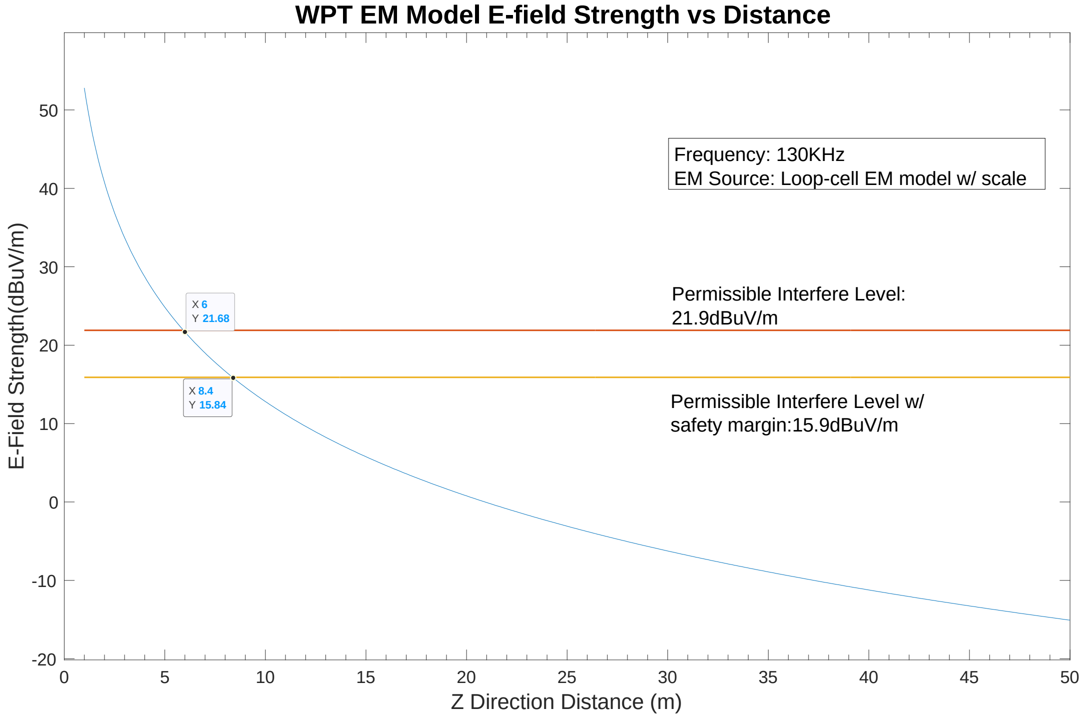


FIGURE 54

WPT at 400 kHz: Single-entry E-field vs height agl (m) for horizontal WPT coil

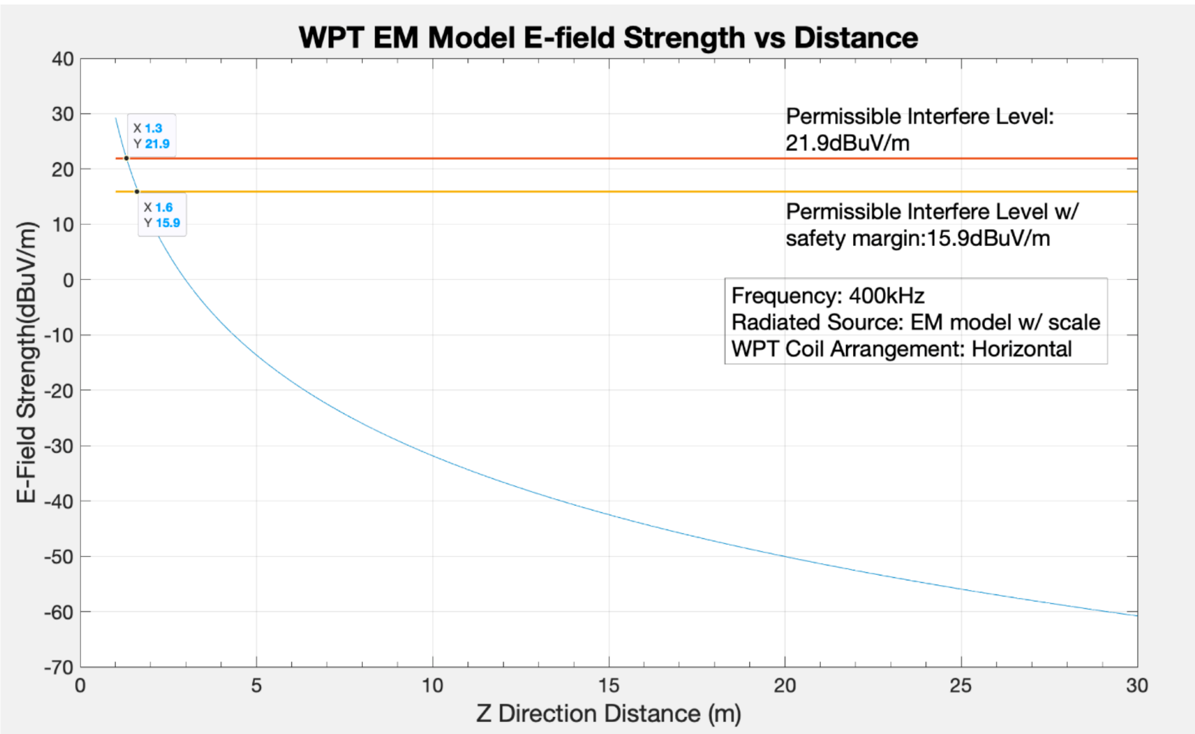
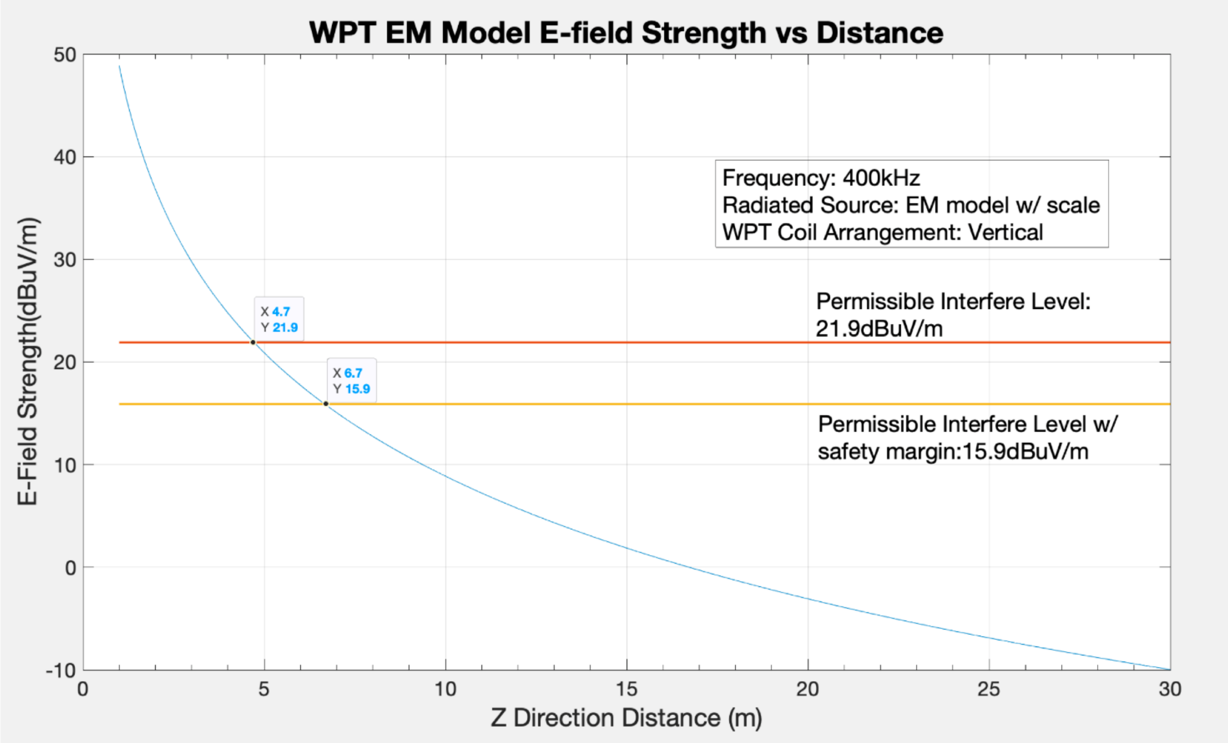


FIGURE 55

WPT at 400 kHz: Single-entry E-field vs height agl (m) for vertical WPT coil



9.2.2 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 greater than 6 m. Considering the safety margin, the distance is greater than 8.4 m Roof or floor penetration losses were not included in the calculation. The inclusion of these loses would further reduce the interference impact of WPT devices to the ADF receiver.

9.3 Aggregate scenario

The aggregate scenario is for 5 000 devices / km^2 for 130 kHz WPT and 1 500 devices / km^2 for 400 kHz based on Table 1.

This scenario makes worst case assumptions with all the devices transmitting at the same time and on the exact same frequency. In reality, the fundamental frequency of WPT devices varies.

9.3.1 WPT at 130 kHz

9.3.1.1 Scenario at 130 kHz

The aggregate scenario considers WPT devices evenly distributed within a square area. Different sizes of the area are used from 1 km × 1 km to 8 km × 8 km. Two aircraft altitudes were simulated at 100 m and 300 m. As a reference, the minimum safe altitudes in the US are 500 feet (≈150 m) above open water or sparsely populated areas, and 1 000 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.

FIGURE 56

Example depiction of aggregate scenario

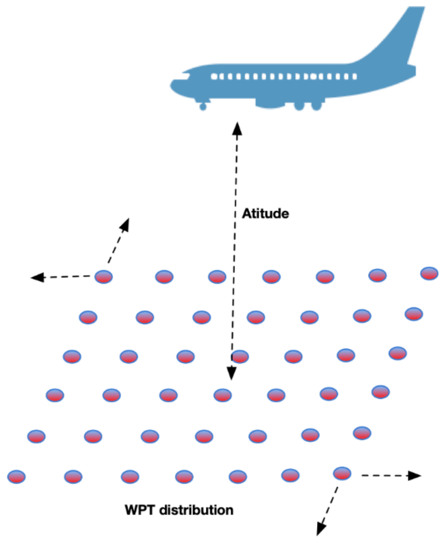


Table 23 shows the results for an aircraft altitude of 100 m.

TABLE 23

Aggregate WPT E-Field (100 m aircraft height)

Area (km × km)	Emax (dBμV/m)	Avg. (dBμV/m)	Max. permissible interfere (dBμV/m)	Margin/Gap (dB)	
				without safety margin	with safety margin
1 × 1	−6.3	16.7	21.9	28.2	22.2
2 × 2	−5.5	−15.9	21.9	27.4	21.4
4 × 4	−4.8	−15.3	21.9	26.7	20.7
8 × 8	−5	−14.6	21.9	26.9	20.9

9.3.1.2 Conclusions for aircraft altitude of 100 m

The simulation has shown that the maximum calculated field strength is less than the maximum permissible interference by more than 26 dB. Considering the safety margin, it is less than the maximum permissible interference by more than 20 dB. Roof or floor penetration loss were not included in the simulation but would further reduce the interference impact from WPT devices to ADF.

Table 24 shows the results for an aircraft altitude of 300 m.

TABLE 24

Aggregate WPT E-Field (300 m aircraft height)

Area (km × km)	Emax (dBμV/m)	Avg. (dBμV/m)	Max. permissible interfere (dBμV/m)	Margin/Gap (dB)	
				without safety margin	with safety margin
1 × 1	−16.5	−25.5	21.9	38.4	32.4
2 × 2	−13.4	−22.2	21.9	35.3	29.3
4 × 4	−11.0	−20.1	21.9	32.9	26.9
8 × 8	−10.4	−18.6	21.9	32.3	26.9

9.3.1.3 Conclusions for aircraft altitude of 300 m

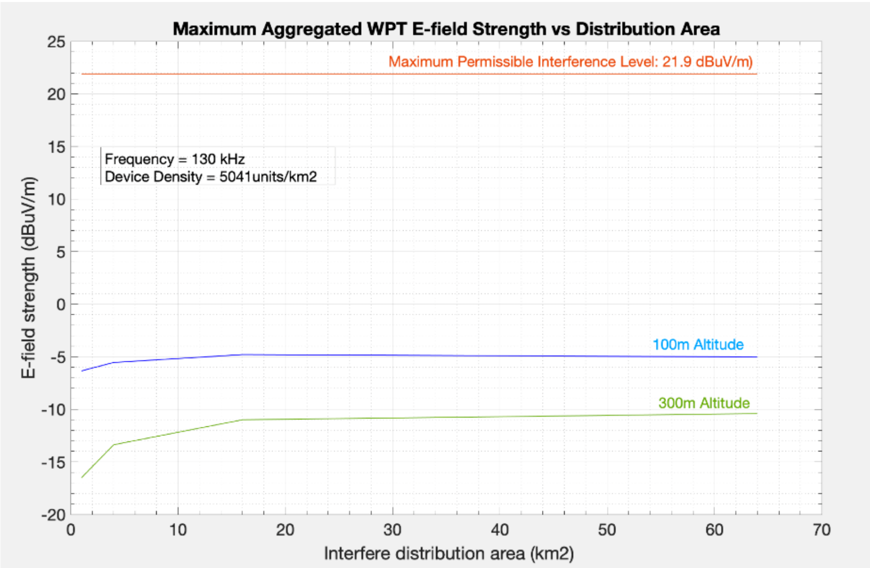
The simulation has shown that the maximum calculated field strength is less than the maximum permissible interference by more than 32 dB. Considering the safety margin, it is less than the maximum permissible interference by more than 26 dB. Roof or floor penetration losses were not included in the simulation but would further reduce the interference impact from WPT devices to ADF.

9.3.1.4 Impact of the size of the area on the received interference area

Increasing the calculation area shows that the interference level beyond 15 km^2 for 100 m altitude and 30 km^2 for 300 m altitude remain the same as shown in Fig. 57.

FIGURE 57

Field strength vs interfere distribution area



9.3.2 WPT at 400 kHz

9.3.2.1 Scenario at 400 kHz

The aggregate scenario considers WPT devices evenly distributed within a square area. Different sizes of the area are used from 1 km × 1 km to 16 km × 16 km. 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 1 000 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.

FIGURE 58

Example depiction of aggregate scenario

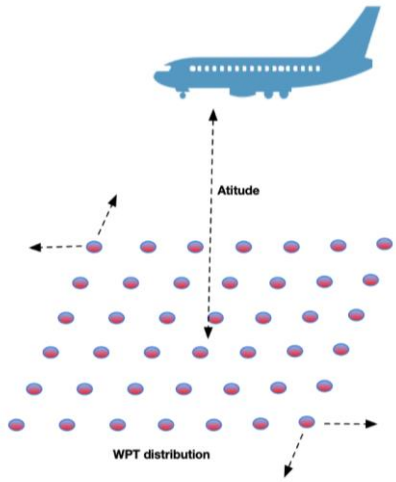


Table 25 shows the results for an aircraft altitude of 100 m.

TABLE 25

Aggregate WPT radiated E-field distribution (100 m aircraft height)

Area (km × km)	Emax (dBμV/m)	Avg. (dBμV/m)	Max. permissible interfere (dBμV/m)	Margin/Gap (dB)	
				without safety margin	with safety margin
1 × 1	−5.5	–14.4	21.9	27.4	21.4
2 × 2	−3.9	–12.7	21.9	25.8	19.8
4 × 4	−3.2	−11.7	21.9	25.1	19.1
8 × 8	−–3.5	−11.7	21.9	25.4	19.4

9.3.2.2 Conclusions for aircraft altitude of 100 m at 400 kHz

The aggregate simulation has shown that the maximum calculated field strength is less than the maximum permissible interference by more than 25 dB. Considering the safety margin, it is less than the maximum permissible interference by more than 19 dB. Building entry loss (roof/ceilings) were not included in the simulation but would further reduce the interference impact from WPT devices to ADF.

Table 26 shows the results for an aircraft altitude of 300 m.

TABLE 26

Aggregate WPT radiated E-field distribution (300 m aircraft height)

Area (km × km)	Emax (dBμV/m)	Avg. (dBμV/m)	Max. permissible interfere (dBμV/m)	Margin/Gap (dB)	
				without safety margin	with safety margin
1 × 1	−11.5	−20.3	21.9	33.4	27.4
2 × 2	−8.1	−16.6	21.9	30.0	24.0
4 × 4	−6.2	−14.2	21.9	28.1	22.1
8 × 8	−4.2	−12.6	21.9	26.1	20.1
16 × 16	−3.9	−11.5	21.9	25.8	19.8

9.3.2.3 Conclusions for aircraft altitude of 300 m at 400 kHz

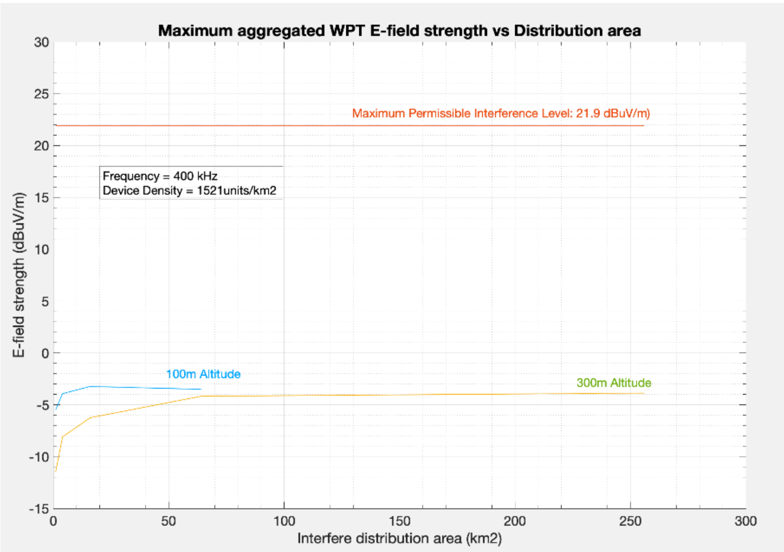
The aggregate simulation has shown that the maximum calculated field strength is less than the maximum permissible interference by 25 dB. Considering the safety margin, it is less than the maximum permissible interference by more than 19 dB. Building entry loss (roof/ceilings) were not included in the simulation but would further reduce the interference impact from WPT devices to ADF.

9.3.2.4 Impact of the size of the area on the received interference area at 400 kHz

Increasing the calculation area shows that the inference level beyond 20 km^2 for 100 m altitude and 60 km^2 for 300 m altitude remain the same as shown in Fig. 59.

FIGURE 59

Field strength vs interfere distribution area



9.4 Summary of the results

The simulations have shown that the E-field of WPT chargers for mobile and portable devices do not impact the reception of ADF/NDB signals. Roof or floor penetration loss were not included in the calculation/simulation but would further reduce the interference impact from WPT devices to ADF.

10 Generic impact analyses of WPT on radio communication services (e.g. fixed and mobile)

10.1 Single-entry co-channel Monte Carlo study on impact from WPT (315-405 kHz, 1 700-1 800 kHz and 2 000-2 170 kHz) on radio services

This study analyses the level of a single WPT device that is co-channel to the receiver of a radiocommunication service such as mobile or fixed service. It does not apply to receivers that are located inside buildings such as AM radio broadcasting where the interference impact would need to be compared to single carrier noise. Their level is higher than the white Gaussian noise used for comparison here, but it is unclear how much higher exactly.

10.1.1 Parameters

10.1.1.1 WPT devices

10.1.1.1.1 WPT emissions

The emissions of WPT used in this study are provided in Table 27.

TABLE 27

WPT emissions

Parameter	Value
WPT Max emissions, worst alignment (dBμA/m at 10 m)	−15
WPT Min emissions, best alignment (dBμA/m at 10 m)	−30
WPT operating frequency 1 (kHz)	400
WPT operating frequency 2 (kHz)	1 650
WPT operating frequency 3 (kHz)	2 000

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.

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

10.1.1.1.2 Radio service parameters

Table 28 provides the parameters for the radio services used in the analyses.

TABLE 28

Parameters of the radio services

Parameter	Value
Rx bandwidth (kHz)	2.7[(1)]
Rx frequency (kHz)	400, 1 650, 2 000
RX noise	Man-made noise (see § 10.1.2.3.3)
Antenna	Omni-directional
Height a.g.l. (m)	1.5

(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.

10.1.1.1.3 Propagation

10.1.1.1.3.1 Propagation model

See Annex 3.

10.1.1.1.3.2 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 which Recommendation ITU-R P.2109 describes as using metallised glass or foil-backed panels. The parameters used for the calculation are shown in Table 29.

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

TABLE 29

Additional propagation losses

Parameter	Applicable %	Value (dB)
Urban propagation loss	30%	10
Other environments	–	–

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

10.1.1.1.3.3 Noise environment

The frequency range under consideration is often dominated by man-made noise. The analysis uses Recommendation ITU-R P.372 as a baseline. In addition, man-made noise measurements carried out in the Netherlands (MN) are also used for analysis [1], [3]. These measurements were carried out at a distance of at least 10 m from the nearest building wall. In [3] it is clarified that the measurements aim at describing the man-made noise experience by radio service users, such as radio amateurs.

Tables 30 and 31 show the median noise levels from Recommendation 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 30

ITU-R P.372 noise levels

Parameter	Level (dBµA/m)	Std Dev (dB)
400 kHz		
City noise	–32.82	8.4
Residential noise	–37.12	5.8
1 650 kHz		
City noise	–37.56	8.4
Residential noise	–41.86	5.8
2 000 kHz		
City noise	–38.20	8.4
Residential noise	–42.50	5.8

TABLE 31

Noise levels from measurements in the Netherlands (MN)

Parameter	Level (dBµA/m)	Std Dev (dB)
400 kHz		
City noise	–18.47	5.6
Residential noise	–23.97	9.5
1 650 kHz		
City noise	–26.23	6.4
Residential noise	–32.34	5.5
2 000 kHz		
City noise	–27.28	6.4
Residential noise	–33.84	5.5

10.1.1.1.3.4 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:

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

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

10.1.2 Methodology

A single-entry Monte Carlo simulation is carried out in order to analyse the statistical impact of WPT charging at 400 kHz at 1 650 kHz as well as at 2 000 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 20 000 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;

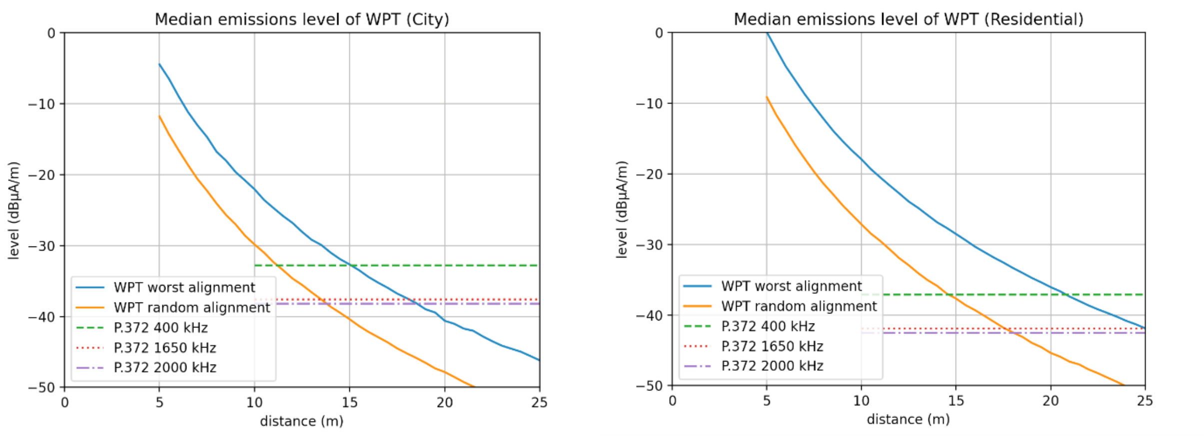
– Show how the median emission level from a WPT device change with distance from the radio service receiver.

10.1.3 Summary of results

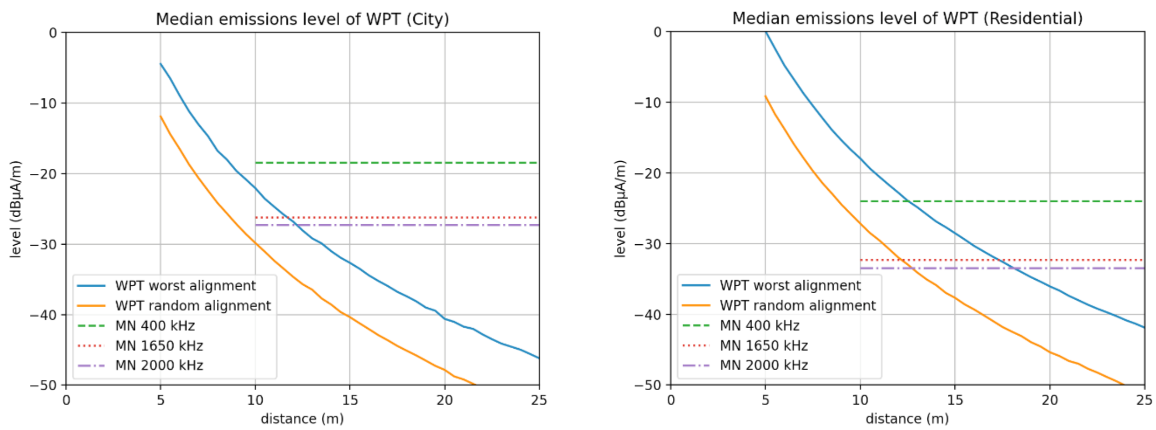
Figure 60 shows the detailed results. The blue curve is based on the WPT device always having the worst alignment between the WPT charger and receiver coils only (hence being the upper bound), while the orange curve is based on random alignment between the coils (i.e. varying from best to worst alignment hence emissions). The horizontal lines represent the median man-made noise levels at 400 kHz, 1 650 kHz and 2 000 kHz.

FIGURE 60

Detailed results



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



(b) for Measured Netherlands

Figure 61 shows the distance at which the median interference level from a WPT device drops below the median noise floor.

FIGURE 61

Detailed results

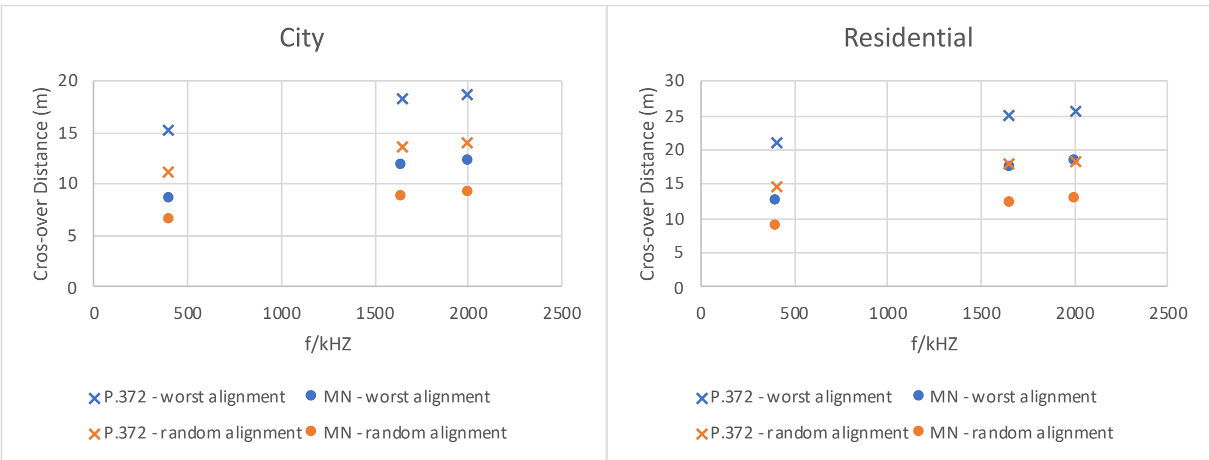


Table 32 shows a summary of the distance for which the emissions from the WPT charger drop below the median man-made noise level of a single-entry study.

TABLE 32

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	Distance worst alignment (m)	Distance random alignment (m)
Cities	ITU-R P.372	15 to 19	11 to 14
	Measured Netherlands	9 to 13	7 to 9
Residential areas	ITU-R P.372	21 to 26	15 to 18
	Measured Netherlands	13 to 18	9 to 13

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.

10.2 Aggregate Monte Carlo study on impact from WPT (315-405 kHz, 1 700-1 800 kHz and 2 000-2 170 kHz) on radio services

This study analyses the level of WPT devices to the receiver of a radiocommunication service such as mobile or fixed service. It does not apply to receivers that are located inside buildings such as AM radio broadcasting where the interference impact would need to be compared to single carrier noise. Their level is higher than the white Gaussian noise used for comparison here, but it is unclear how much higher exactly.

10.2.1 Parameters

10.2.1.1 WPT devices

10.2.1.1.1 WPT emissions

The emissions of WPT used in this study are provided in Table 33.

TABLE 33

WPT emissions

Parameter	Value
WPT Max emissions, worst alignment (dBμA/m at 10 m)	–15
WPT Min emissions, best alignment (dBμA/m at 10 m)	–30
WPT operating frequency 1 kHz	350 - 400
WPT operating frequency 2 kHz	1 750 - 1 800
WPT operating frequency 3 kHz	2 000 - 2 050
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.

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.

10.2.1.1.2 WPT height distribution

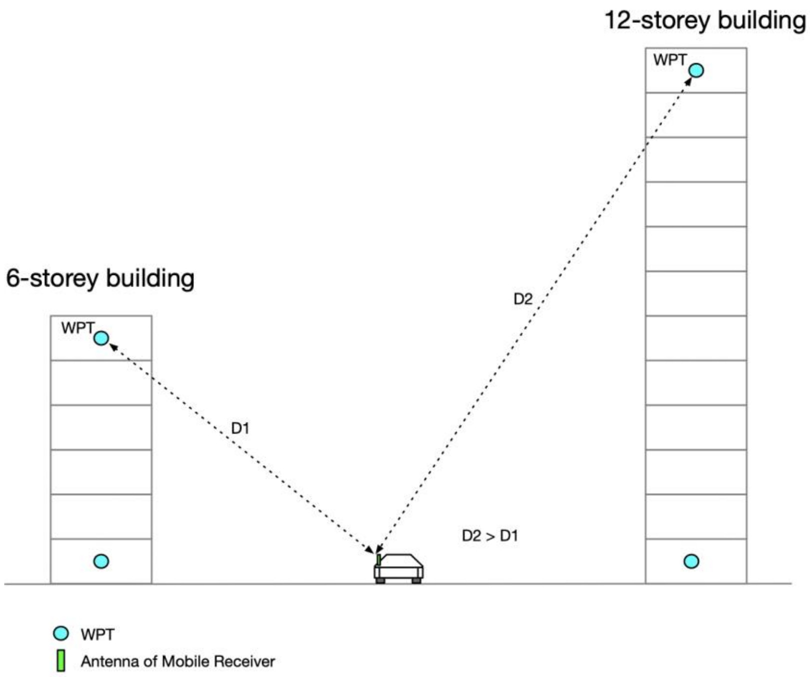
The WPT devices are evenly distributed over all floors of a building. The height of each floor is assumed to be 3 m. Devices on the lowest floor are assumed to be 1.5 m above ground. The height distribution is given in Table 34.

TABLE 34

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

FIGURE 62



The buildings in city areas may have more than six floors. For this study the device density over an area is assumed to be fixed. Using higher floors in the calculations would therefore lead to a lower impact. WPT devices on higher floors would contribute less impact as the distance from the victim is greater. The parameters used in this study may not apply to all environments.

10.2.1.1.3 Density/Deployment

Tables 35, 36 and 37 provide the density of WPT devices for the radio services used in the analyses based on Table 1.

TABLE 35

Density of WPT operating frequency 1 (400 kHz)

Parameter	Value
Device Density in City areas (Dense Urban: 20k pop/km^2)	1 500/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)	1/4

TABLE 36

Density of WPT operating frequency 2 (1 800 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

TABLE 37

Density of WPT operating frequency 3 (2 000 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 WPT devices are in operation during peak hours. That is not the case in reality. The level of impact is therefore likely to be overestimated.

There is correlation between man-made-noise levels and population density [3], therefore different WPT densities are considered linked to corresponding noise levels.

10.2.1.2 Radio service parameters

Table 38 provides the parameters for the radio services used in the analyses.

TABLE 38

Parameters of the radio services

Parameter	Value
Rx bandwidth (kHz)	2.7[(1)]
Rx frequency (kHz)	400, 1 800, 2 000
RX noise	Man-made noise in 2.7 kHz bandwidth (see § 10.2.1.3.3)
Antenna	Omni-directional
Height a.g.l. (m)	1.5

(1) The radio service receiver bandwidth used is 2.7 kHz. However, in order 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.

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. [3] 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.

10.2.1.3 Propagation

10.2.1.3.1 Propagation model

See Annex 3.

10.2.1.3.2 Additional propagation losses

In cities 30% of the paths are assumed to have a metal object between the interferer and the radio service receiver (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 which Recommendation ITU-R P.2109 describes as using metallised glass or foil-backed panels. The parameters used for the calculation are shown in Table 39.

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

TABLE 39

Additional propagation losses

Parameter	Applicable %	Value (dB)
Urban propagation loss	30%	10
Other environments	–	–

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

10.2.1.3.3 Noise environment

The frequency range under consideration is often dominated by man-mad noise. The analysis uses Recommendation ITU-R P.372 as a baseline. In addition, man-made noise measurements carried out in the Netherlands (MN) are also used for analysis [1], [3]. These measurements were carried out at a distance of at least 10 m from the nearest building wall. In [3] it is clarified that the measurements aim at describing the man-made noise experience by radio service users, such as radio amateurs.

Table 40 and Table 41 show the median noise levels from Recommendation 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 40

Recommendation ITU-R P.372 Noise levels

Parameter	Level (dBµA/m)	Std Dev (dB)
400 kHz		
City noise	–32.82	8.4
Residential noise	–37.12	5.8
1 650 kHz		
City noise	–37.85	8.4
Residential noise	–42.15	5.8
2 000 kHz		
City noise	–38.20	8.4
Residential noise	–42.50	5.8

TABLE 41

Noise levels from Measurements in the Netherlands (MN)

Parameter	Level (dBµA/m)	Std Dev (dB)
400 kHz		
City noise	–18.47	5.6
Residential noise	–23.97	9.5
1 650 kHz		
City noise	–26.7	6.4
Residential noise	–32.86	5.5
2 000 kHz		
City noise	–27.28	6.4
Residential noise	–33.84	5.5

Only the variation of noise over location (spatial distribution) is analysed. However, as Recommendation ITU-R P.372 clearly states noise also varies over time and such variations may be even larger, see Table 42.

TABLE 42

Values of decile deviations of man-made noise, from Recommendation ITU-R 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

10.2.1.3.4 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:

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

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

10.2.2 Methodology

A Monte Carlo simulation is carried out in order to analyse the statistical impact of WPT charging in 315-405 kHz, in 1 700-1 800 kHz as well as in 2 000-2 170 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 10 000 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) (Note 2);
  - Store noise + interference level;
– Create CDF of noise levels and noise + interference levels;

– Calculate increase of median noise levels.

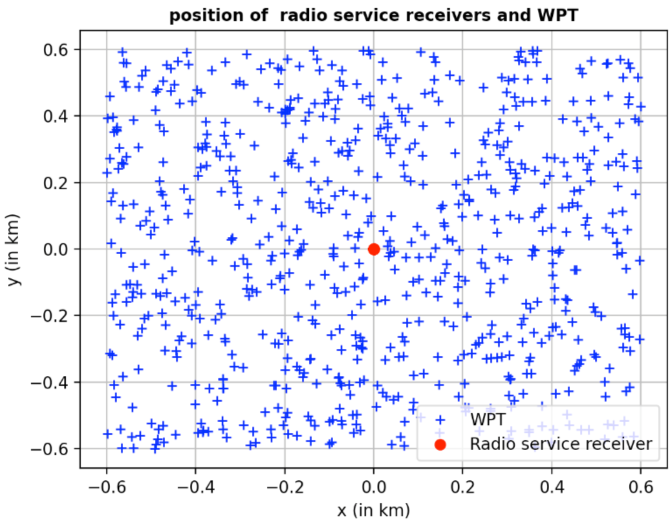
Note 1: The simulation area needs to be large enough so that sufficient statistical samples (power levels and spatial configurations) are reflected in the simulation.

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

Figure 63 shows the layout of a single simulation snapshot with a WPT density of 500 devices per km^2.

FIGURE 63

Example layout of the simulation



10.2.2.1 Results

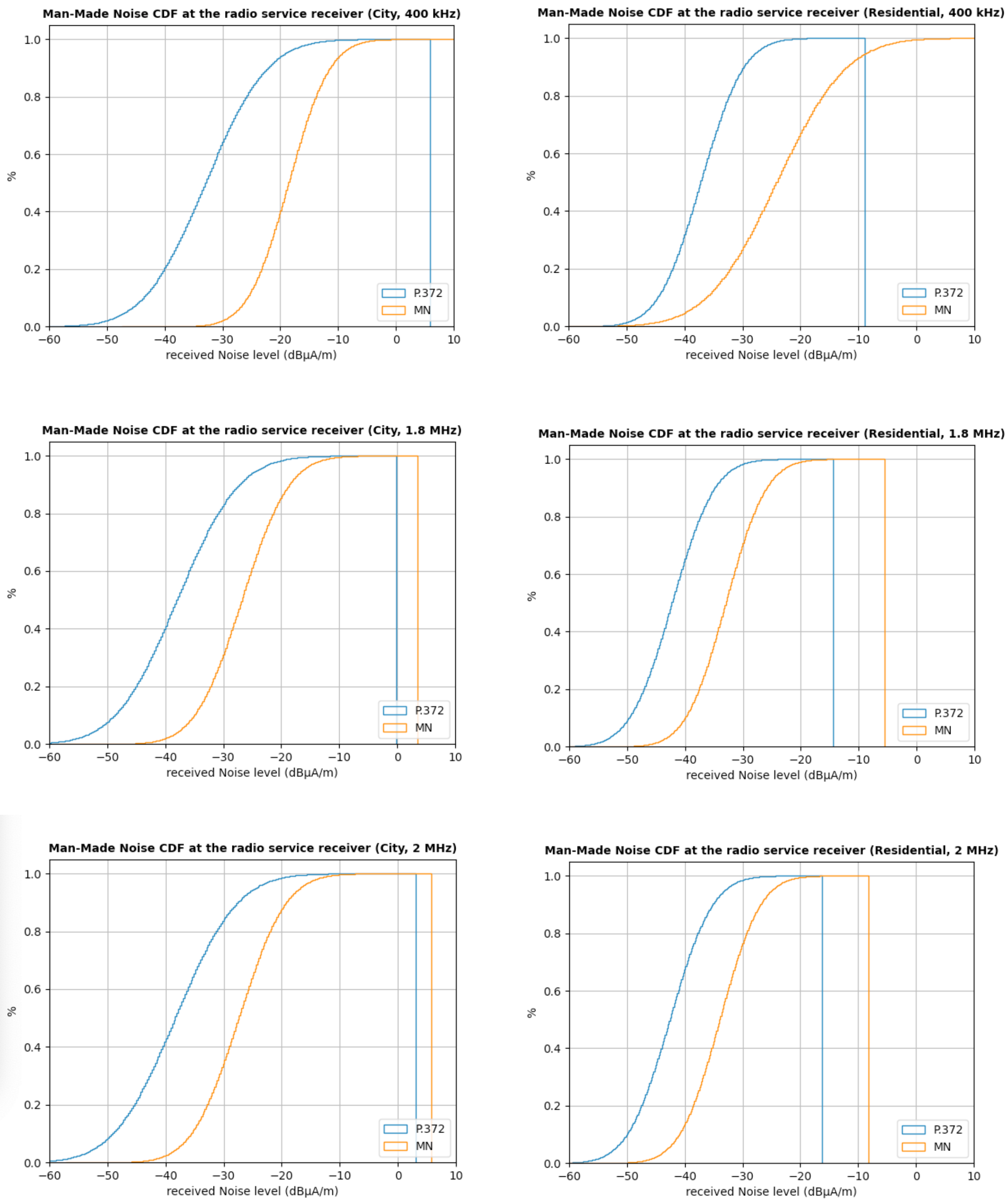
10.2.2.1.1 Interpretation of the results

Radio services operating in the frequency ranges 315-405 kHz, 1 606.5-1 800 kHz as well as 2 000-2 170 kHz face a noisy environment in some 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 64 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 64

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.

10.2.2.1.2 Results for 400 kHz

TABLE 43

Increase in noise level (WPT frequency at 400 kHz)

Environment	Day/Night	Density (/km^2)	Noise level	Increase of median noise (dB)
City (dense urban)	Night	1 500	P.372	1.2
			MN	0.3
	Day	375	P.372	0.3
			MN	0.1
City (urban)	Night	375	P.372	0.4
			MN	0.1
	Day	94	P.372	0.1
			MN	0
Residential	Night	150	P.372	0.2
			MN	0.1
	Day	38	P.372	0.1
			MN	0.0

10.2.2.1.3 Results for 1 800 kHz

TABLE 44

Increase in noise level (WPT frequency at 1 750-1 800 kHz)

Environment	Day/Night	Density (/km^2)	Noise level	Increase of median noise (dB)
City (dense urban)	Night	500	P.372	1.8
			MN	0.6
	Day	167	P.372	0.8
			MN	0.2
City (Urban)	Night	125	P.372	0.6
			MN	0.2
	Day	42	P.372	0.3
			MN	0.1
Residential	Night	50	P.372	0.4
			MN	0.2
	Day	17	P.372	0.2
			MN	0.1

10.2.2.1.4 Results for 2 000 kHz

TABLE 45

Increase in noise level (WPT frequency at 2 000 kHz)

Environment	Day/Night	Density (/km^2)	Noise level	Increase of median noise (dB)
City (dense urban)	Night	500	P.372	2.1
			MN	0.7
	Day	167	P.372	1
			MN	0.3
City (urban)	Night	125	P.372	0.8
			MN	0.2
	Day	42	P.372	0.3
			MN	0.1
Residential	Night	50	P.372	0.6
			MN	0.2
	Day	17	P.372	0.2
			MN	0.1

10.2.2.1.5 Summary of the results

The study shows that the envisaged deployment density of WPT devices in 315-405 kHz, leads, in very dense urban areas, to a 1.2 dB noise increase above the median level predicted in Recommendation ITU-R P.372. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.3 dB. For all other environments (urban and residential) an increase the median noise of 0.4 dB or less was found in 1 700-1 800 kHz, it leads to a 1.8 dB noise increase above the median level predicted in Recommendation ITU-R P.372. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.6 dB. For all other environments (urban and residential) an increase of the median noise of 0.6 dB or less was found.

In 2 000-2 170 kHz, it leads to a 2.1 dB noise increase above the median level predicted in Recommendation ITU-R P.372. When using actual measurements of radio noise in the Netherlands, the increase of the median noise is less than 0.7 dB. For all other environments (urban and residential) an increase of the median noise of 0.8 dB or less was found.

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 man-made noise levels that were used in this study. 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.

11 Impact study of non-beam WPT for mobile and portable devices on systems of maritime radionavigation service / Differential Global Navigation Satellite Systems (DGNSS) below 325 kHz

11.1 Introduction

The frequency band 315-325 kHz is allocated to the Maritime Radionavigation Service and used for differential transmissions for the global navigation satellite systems (DGNSS). Detailed parameters are provided in Recommendation ITU-R M.823-3. The 315-405 kHz band non-beam WPT for mobile and portable devices have the overlap with 315-325 kHz band DGNSS in Regions 2 and 3. As guided by WP 5B, the minimum wanted signal strength for DGNSS (at the edge of coverage) is from 40 to 100 µV/m and more details could be found in Table 45A. DGNSS is also used on inner waterways in some places (i.e. Europe and Canada) to provide accurate position information. In Region 1 its use is below 315 kHz.

The study therefore only analyses the effect of WPT above 315 kHz. This means that only the open sea scenario is considered.

All WPT devices for the study were assumed to be using the same frequency (315 kHz), while in real life quite a spread of the actual charging frequencies depending on the actual implementation, charging status etc. can be observed.

11.2 Parameters for simulation

The study looked at the proposed value of –15 dBµA/m as the maximum emissions for the WPT devices. All WPT devices for the study were assumed to be using the same frequency (315 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 DGNSS are given in Table 46.

TABLE 46

Differential Global Navigation Satellite Systems (DGNSS) parameters

Parameters	Value	Reference
Min. wanted signal strength at the edge (uV/m)	40/75/100 Between 40 and 100 µV/m	Region 3 countries selected IALA information, Table of DGNSS stations, Edition 1.8 2021
Protection ratio, C/I (dB)	15, co-channel	Rec. ITU-R M.823-3 Table 5
Max. permissible Interfere's signal strength at the edge (dBuV/m)	17.04 /22.5 /25	R3
Coverage	Between 50 and 500 km	IALA information, Table of DGNSS stations, Edition 1.8 2021
Max. permissible interfere's signal strength at the edge (dBuV/m)	18.89/11.02/17.04	R1/R2/R3
Signal availability (Navigation in ocean waters)	99.8 %	IMO Resolution A.1046 (27) Appendix 2.5

11.3 Scenarios and results

Considering the use scenarios of non-beam inductive WPT for mobile and portable devices, three scenarios are designated for this simulation study. One is single-entry in general, one is WPT device on the shore, and one is WPT device on the vessel.

11.3.1 Single Entry Study 1: impact study of non-beam WPT for mobile and portable devices on Differential Global Navigation Satellite Systems (DGNSS)

An impact study was carried out by using the parameters listed in Table 46 and the propagation model of Recommendation ITU-R SM.2028 was applied.

TABLE 47

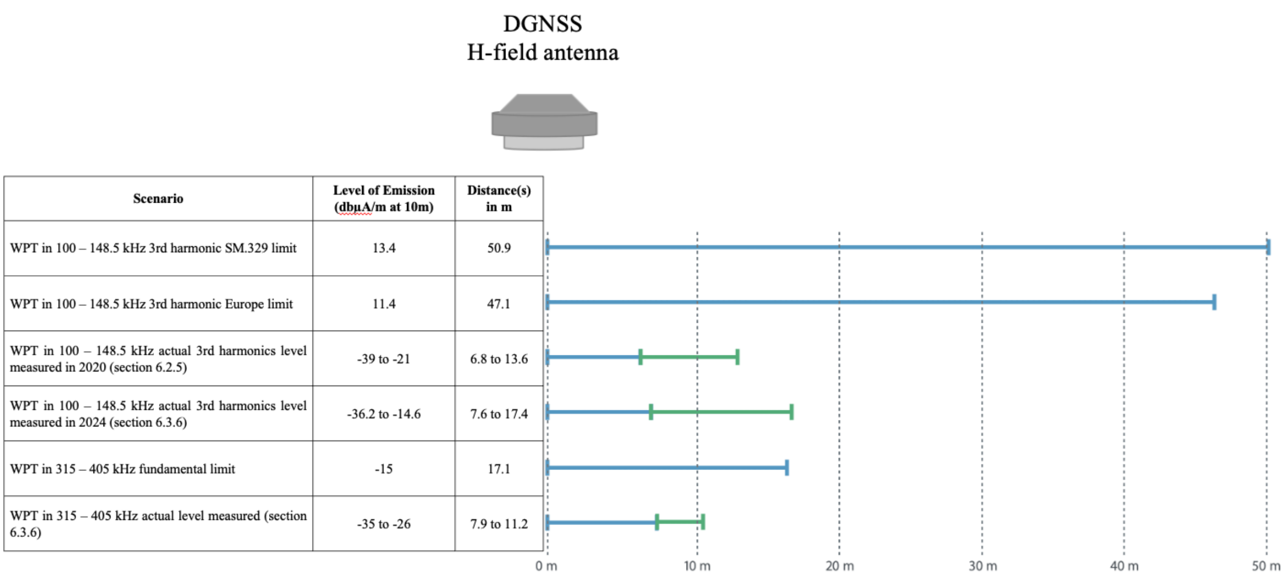
Differential Global Navigation Satellite Systems (DGNSS) parameters

Parameter	Value
Minimum wanted signal strength for DGNSS (µV/m)	75 (typical value)
Minimum wanted signal strength for DGNSS (dBµV/m)	37.5
Protection ratio(dB) co-channel	15
Interference field strength threshold (dBµV/m)	22.5
Propagation model	Rec. ITU-R SM.2028
DGNSS wanted frequency	315 kHz

Figure 65 shows the required separation From DGNSS H-field antenna for WPT devices with different levels of emission and frequencies.

FIGURE 65

Separation distances for various WPT emission levels (H-field)

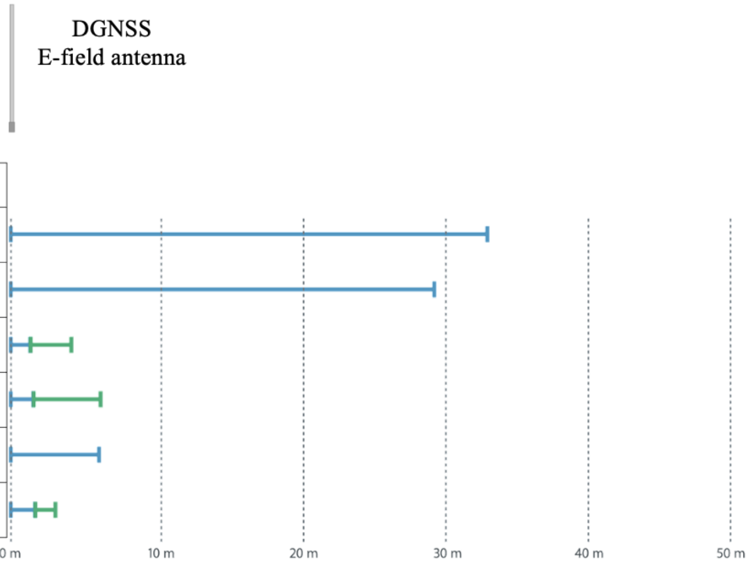


Scenario	Level of Emission (dbµA/m at 10m)	Distance(s) in m
WPT in 100 – 148.5 kHz 3rd harmonic SM.329 limit	13.4	50.9
WPT in 100 – 148.5 kHz 3rd harmonic Europe limit	11.4	47.1
WPT in 100 – 148.5 kHz actual 3rd harmonics level measured in 2020 (section 6.2.5)	-39 to -21	6.8 to 13.6
WPT in 100 – 148.5 kHz actual 3rd harmonics level measured in 2024 (section 6.3.6)	-36.2 to -14.6	7.6 to 17.4
WPT in 315 – 405 kHz fundamental limit	-15	17.1
WPT in 315 – 405 kHz actual level measured (section 6.3.6)	-35 to -26	7.9 to 11.2

Figure 66 shows the required separation From DGNSS E-field antenna for WPT devices with different levels of emission and frequencies.

FIGURE 66

Separation distances for various WPT emission levels (E-field)



Scenario	Level of Emission (dbµA/m at 10m)	Distance(s) in m
WPT in 100 – 148.5 kHz 3rd harmonic SM.329 limit	13.4	30.6
WPT in 100 – 148.5 kHz 3rd harmonic Europe limit	11.4	27.2
WPT in 100 – 148.5 kHz actual 3rd harmonics level measured in 2020 (section 6.2.5)	-39 to -21	1.5 to 4.1
WPT in 100 – 148.5 kHz actual 3rd harmonics level measured in 2024 (section 6.3.6)	-36.2 to -14.6	1.7 to 6
WPT in 315 – 405 kHz fundamental limit	-15	5.9
WPT in 315 – 405 kHz actual level measured (section 6.3.6)	-35 to -26	1.8 to 3.1

The comparison of these different emission levels in Figs 65 and 66 shows that the separation distances found for WPT devices operating in 315-405 kHz were less than those of the 3rd harmonics of WPT devices operating in 100-148.5 kHz. There are many million devices operating in the lower frequency range and no interference case has been recorded. Since WPT devices for portable and mobile devices operating in 315-405 kHz have a lower interference impact on DGNSS, it is even less likely that interference would occur.

Furthermore, in the case of an E-field antenna the interference is significantly reduced.

This study assumed perfect coupling between antennas which would require perfect alignment between the WPT device and the DGNSS antenna.

11.3.2 Impact study 2 of non-beam WPT for mobile and portable devices in 315-405 kHz on Differential Global Navigation Satellite Systems (DGNSS)

An impact study was carried out by using the parameters listed in Table 47 and the propagation model of Recommendation ITU-R SM.2028 was applied.

When a WPT device is near to the receiver of DGNSS, the protection distance r might be within the near field, then it can be calculated by the following equation as (13) in Annex 1 of Recommendation ITU-R SM.2028:

$$r = \sqrt[3]{\frac{m}{2\pi H_{limit}}}$$

m is described in equations (1) and (2) in Annex1 of Recommendation ITU-R SM.2028, and magnetic field strength limit H_{limit} (A/m) can be obtained from equation (8). m was chosen to be the maximum of m1 and m2. Here is supposed that the antenna used for DGNSS is the magnetic sensitive loop model antenna, and E field to H field conversion E/H = 51.5 dB without considering the other conversion factors because of the long distance between DGNSS transmitter and receiver. WPT is usually operated in very narrow bandwidth, which is smaller than the bandwidth for DGNSS, so the bandwidth ratio is 0. In the calculation, mitigating factors are not considered which would reduce the impact to receiver.

Result in Table 48 shows that, for a single entry of non-beam WPT for mobile and portable devices, protection distance for DGNSS is 21 m, i.e. the WPT devices should be 21 m away from the DGNSS receiver.

Different propagation models may produce different results, the actual interference distance may be reduced because of other factors. Field tests might provide further information for this interference scenario.

TABLE 48

Differential Global Navigation Satellite Systems (DGNSS) parameters

Parameter	Value
Minimum wanted signal strength for DGNSS (μV/m)	75 (typical value)
Minimum wanted signal strength for DGNSS (dBμV/m)	37.5
Protection ratio(dB) co-channel	15
Interference field strength threshold (dBμV/m)	22.5
WPT max emissions (dBμA/m at 10 m)	–15
Propagation model	Rec. ITU-R SM.2028
Protection distance from a single WPT(m)	21

11.3.3 Aggregate Study 1: Scenario of WPT device on the shore

The signal strength transmitted by radio beacon stations gradually decays with the distance away from the shore. The signal strength levels regarding to the coverage are stated in IALA information[8] about DGNSS stations by the countries. The victim receiver is equipped on the vessel. The vessel which is located at the edge of the coverage is considered as the worst case in this study. The scenario is depicted in Fig. 67.

FIGURE 67

Scenario of WPT devices on the shore

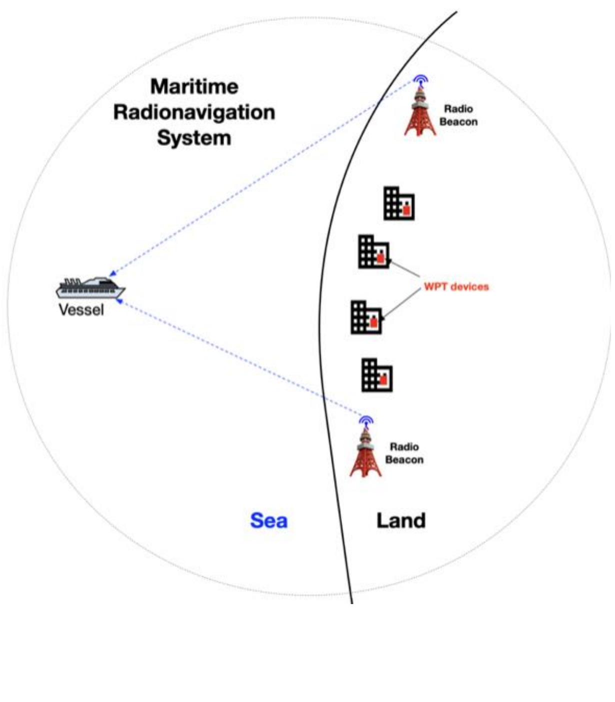
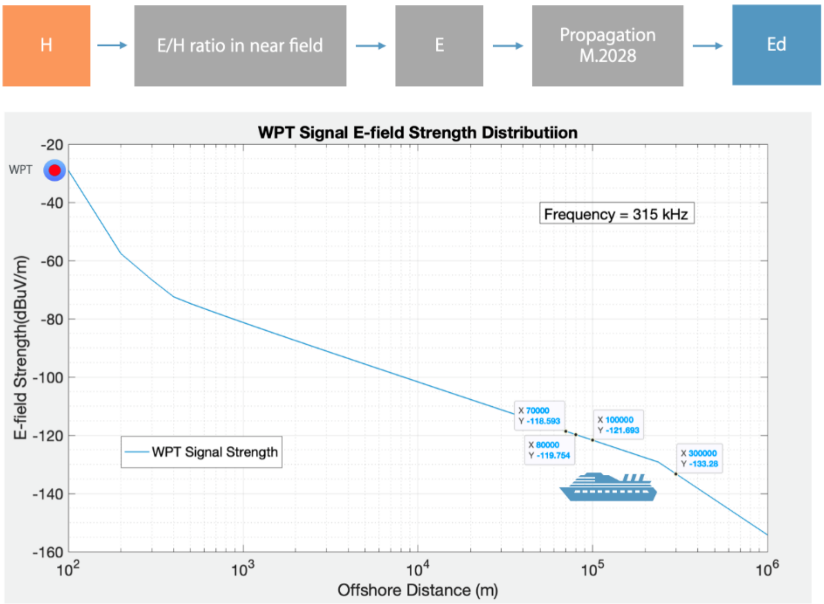


Figure 68 shows the electric field strength distribution from single WPT device. WPT's signal strength received at the vessel corresponds to the coverage. The propagation model used is based on Recommendation ITU-R SM.2028.

FIGURE 68

WPT device's E-field distribution



Distance (km)	WPT signal strength (dBuV/m) - Ed
70	-118.59
80	-119.75
185	-127.04
220	-128.54
225	-128.74
300	-133.28
370	-136.92
400	-138.28
500	-142.16

With respect to both single-entry and aggregate scenarios, the system link budget simulation was carried out with conservative assumptions. The DGNSS stations for China, Korea (Republic of), India, Malaysia, Vietnam, Brazil and Canada were taken into consideration in this study. In the single-entry scenario, it shows there is more than 140 dB margin. For the aggregate scenario as shown in Table 49, the simulation concludes on the number of WPT devices that are aggregated simultaneously at the same frequency and the same phase and that can cause the harmful interference to DGNSS receiver. Furthermore, considering the WPT device density in dense urban and urban area, the area distribution areas are concluded respectively. And the distributed area of dense urban or urban from the simulation is far larger than the coastal city in reality. It means that the aggregated interference could not get to the harmful level in practice.

TABLE 49

DGNSS system link budget simulation

DGNSS parameters	China	India	Viet Nam	Korea (Republic of)	Brazil	Canada
Nominal signal strength (uV/m)	75	100	100	100	20	75
Coverage (km)	300	185	500	80	370	150
Protection ratio (dB)	15	15	15	15	15	15

TABLE 49 *(END)*

DGNSS parameters	China	India	Viet Nam	Korea (Republic of)	Brazil	Canada
Maximum acceptable interfere level (dBuV/m)	22.50	25.00	25.00	25.00	11.02	22.5
WPT signal strength at the coverage (dBuV/m)	–133.28	–127.04	–142.15	–119.75	–136.92	–125.22
Single-entry WPT margin (dB)	155.78	152.04	167.15	144.75	147.94	147.72
Number of aggregated WPT devices (units) to reach margin	61 526 366	39 994 475	227 771 824	17 278 260	24 947 671	24 325 471
Equivalent dense urban area (km^2)	47 476	30 861	175 958	13 332	1 999 581	16 217
Equivalent urban area (km^2)	189 902	12 3444	70 382	53 330	498 953	64 868
Area (km^2)/Coastal city	6 340 (Shanghai)	603 (Mumbai)	2 061 (Ho Chi Minh City)	770 (Busan)	1 521 (Sao Palo)	115 (Vancouver)

Results of WPT devices on the shore

The study shows that both single entry and aggregate do not introduce any harmful interference to maritime DGNSS system operating in Regions 2 and 3. In Region 1, there is no overlap between the WPT frequencies and DGNSS.

In the single-entry scenario, there is a minimum 144 dB margin for Korea DGNSS and bigger margins for the system in other countries.

In the aggregate scenario, all WPT devices are assumed to operate at the same frequency and the same vector phase (worst case). In reality, the charging frequency varies, and the devices should be with random vector phases. The results would result in less interference. Also, antenna discrimination was not applied. The distributed area of dense urban or urban from the simulation is concluded to be far larger than the coastal city in reality, meaning that the aggregated interference could not get to harmful level in practice.

11.3.4 Aggregate Study 2: Scenario of WPT device on the vessel

This scenario mainly addresses WPT devices on board vessels, e.g. cruise vessel. The WPT devices are charged inside the cabins and evenly distributed within the rectangular area. EM Modelling was used for near field propagation. The vector summation is applied to evaluate the aggregated interference using the Monte Carlo methodology.

The number of active devices is calculated as described in Table 50.

TABLE 50

Activity factor of WPT devices

Scenario	Frequency penetration (%)(1)	Wireless charging method ratio (%)(2)	Charging period (%)(3)	Activity factor (%) during charging peak charging time(4)
Wireless high usage	30	60	25	4.5
Wireless low usage	30	15	25	1.13

(1) 100-148.5 kHz dominates the frequency usage now. It is expected that 315-400 kHz will take a share of the market with 100-148.5 kHz in the future. 30% penetration rate is expected.

(2) Wireless charging penetration is expected to be up to 34% in 2025.

(3) The charging period is almost equal to 8 hrs. One-time charging is done within 2 hours.

(4) Main Charging time is between 11 pm and 7 am (across 8 hours).

A large cruise ship is used as the basis for the analysis. The AIDA Nova was selected as shown in Fig. 69.

FIGURE 69

AIDA Nova (*https://en.wikipedia.org/wiki/AIDAnova)*

A model is developed based on the Layout of the ship. See Figs 70 and 71.

FIGURE 70

Ship geometric model (part 1)

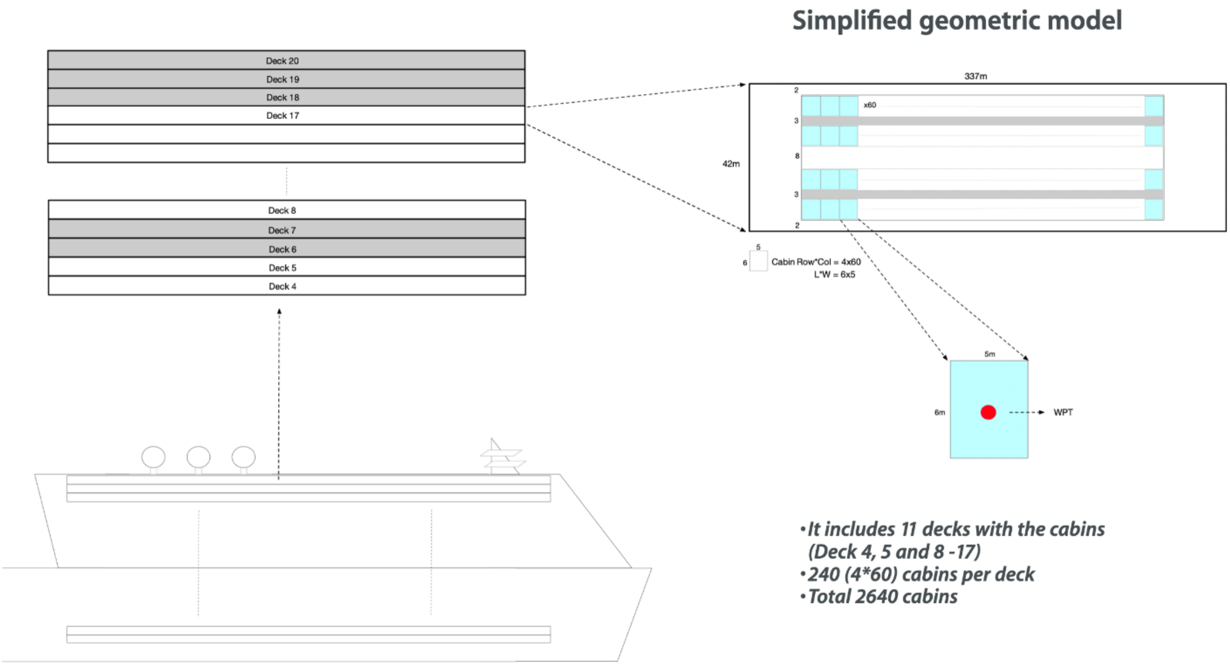
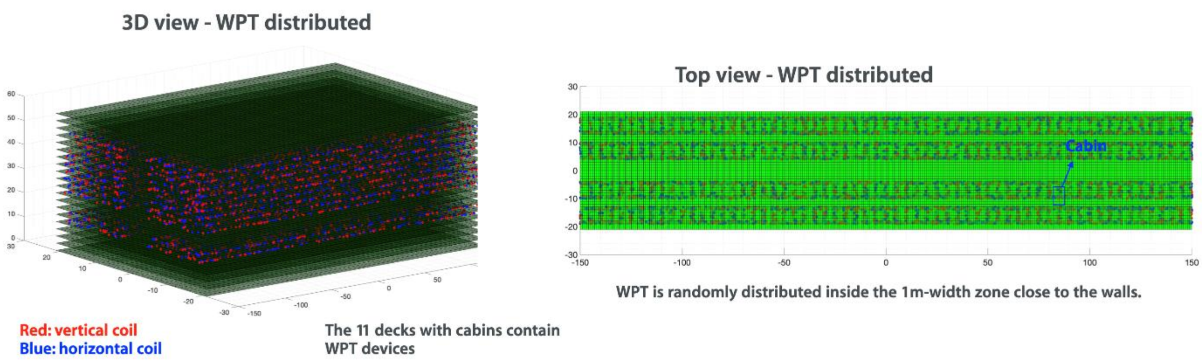


FIGURE 71

Ship geometric model (part 2)



Two different Scenarios were studied which covers either one or two WPT devices per cabin.

Cruise ships are largely made from metal structures which have a large impact on the magnetic fields of formed by WPT chargers. Measurements as shown in Table 51 indicate the following level of impact can happen (orange frame).

TABLE 51

Field attenuation caused by various (building) materials

Ref	Item	Spacing (mm)	Loss (dB)	Further Details
1	Post Room wooden door	500	0	
2	Post Room brick wall, 280 mm thick	300	0	
3	Double-thickness wood composition board (chipboard) (50 mm)	500	0	
4	Steel panel, 600 ×1000 mm	475	2	Panel 100 mm behind generator
5		475	10	Panel between generator and receiver
6	Aluminium panel, 480 ×2000 mm	500	11	Panel horizontal
7		500	15	Panel vertical
8	GTEM-cell, through wall	500	>34	Door needs to be fully closed.

Field attenuations due to metal structures lead to a reduction of the field of more than 10 dB. The attenuation value is considered as a randomized variable, which is in the range of 10-30 dB.

Considering different DGNSS antenna type, E-field antenna and H-field antenna, the studies were respectively carried out. Tables 52 and 53 summarize the aggregate results.

TABLE 52

Results summary of WPT devices on the vessel- H-field DGNSS antenna (using a constant E/H factor)

Cabins	Area (m*m)	WPT per cabin	WPT density (/km^2)	Aggregated E-field (99.8% probability)		Permissible max. interference level (dBμV/m) (R1/R2/R3)
				1.1% AF	4.5% AF	
4x60x11	42*337	1	186520	–13.83	–6.53	18.89/11.02/17.04
4x60x11	42*337	2	373039	–11.23	–2.08	18.89/11.02/17.04

TABLE 53

Results summary of WPT devices on the vessel- E-field DGNSS antenna (using a distance dependent E/H factor)

Cabins	Area (m*m)	WPT per cabin	WPT density (/km^2)	Aggregated E-field (99.8% probability)		Permissible max. interference level (dBμV/m) (R1/R2/R3)
				1.1% AF	4.5% AF	
4x60x11	42*337	1	186520	–27.65	–17.96	18.89/11.02/17.04
4x60x11	42*337	2	373039	–23.61	–12.93	18.89/11.02/17.04

Results of WPT devices on the vessel

The simulation concludes that WPT devices on the vessel do not introduce the harmful interference to maritime DGNSS receiver installed on the vessel. Considering the actual permissible maximum interference there is still a more than 13 dB margin in all Regions and all cases.

Further mitigating factors are not considered which would reduce the impact such as the impact of the metallic base structure of the ship which may reduce the filed by up to 40 dB and the antenna pattern of the DGNSS receiver. The highest WPT levels will be below the DGNSS antenna while the useful signal will arrive horizontally.

11.4 DGNSS for port approach

One remaining one use case for DGNSS that was not explicitly studied is the improved accuracy when a vessel is entering or leaving a harbour. For the largest port in the countries studied above, the locations of the nearest DGNSS stations were checked. In every case there is a DGNSS stations in direct proximity to those ports and with a field strength level well above the minimum.

11.5 Summary of the results

The simulation has shown that the E-field of WPT devices for mobile and portable devices do not impact the reception of DGNSS.

For the scenario where the WPT devices are located on shore, the number of the aggregated WPT devices is calculated so that the aggregated interference is compared to the permissible interference level. The resulting number of WPT devices, for different coastal cities, is far larger than what is expected to be deployed in reality.

For the scenario where the WPT devices are on board vessel, for the aggregated interference there is at least 13 dB margin in all Regions. Furthermore, the study does not take additional losses into account caused by the design and material choice of the ship structure. The antenna discrimination of DGNSS is not applied as well which would reduce even further the aggregated interference level.

For the scenario of DGNSS used for port approach, the location of the DGNSS transmitter is chosen to provide significant margin to avoid any interference risk from WPT.

12 Maritime mobile service in relation with GMDSS

There is a need to ensure protection of maritime mobile services for safety of life services as listed in Appendix **15** of the RR which are in particular 490 kHz, 518 kHz and 2 187.5 kHz. WPT operating in the frequency ranges 315-405 kHz, 1 700-1 800 kHz and 2 000-2 170 kHz do not overlap with these frequency ranges or have uneven harmonics falling onto those.

13 SFTS in 3 995-4 005 kHz in Region 3

No studies were carried out. A potential solution is to restrict WPT to frequencies above 2 005 kHz and avoid a potential 2nd harmonic falling into the range use by the SFTS in 3 995-4 005 kHz.

14 Impact study of non-beam WPT for mobile and portable devices in 1 700-1 800 kHz range on systems of radiolocation service

No studies have been carried out.

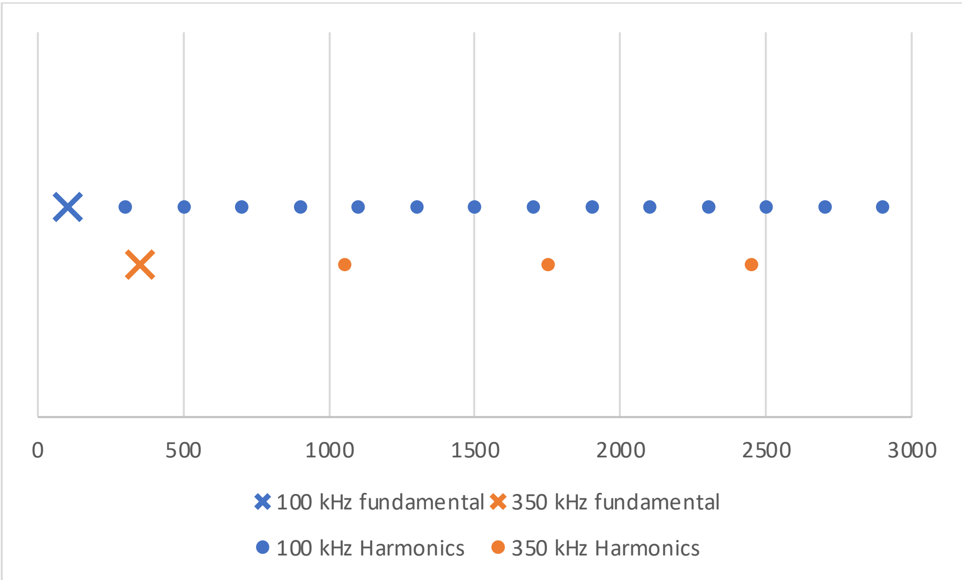
15 Comparison WPT charging impact between 100-148.5 kHz and 315-405 kHz

Two elements are relevant here: first the difference in "frequency" of the harmonics and secondly the difference in actual levels of emissions.

Figure 72 depicts a comparison of an example of a WPT device operating on 100 kHz and one on 350 kHz creating odd harmonics. The WPT device operating at 100 kHz has 14 harmonics below 3 MHz, while the WPT device operating at 375 kHz has only three harmonics. In such a case it is four to five times more likely that a radio service is affected when the WPT device operates in the lower range.

FIGURE 72

"Frequency" of occurrence of harmonics below 3 MHz



The fundamental emissions limit of WPT devices in 100-148.5 kHz can be up to 37.7-42 dBµA/m while the emissions of WPT devices in 315-405 kHz will not exceed −15 dBµA/m (at 10 m distance).

In real life, WPT devices for portable and mobile charging may not reach the levels as suggested by Fig. 72 above. Nevertheless, they can be very significant. As shown in § 6.3.7, actual levels of some chargers operating in 100-148.5 kHz exceed −15 dBµV/m at their 3rd harmonic.

These levels comply with the existing regulatory framework in many countries but show significantly higher harmonics than those coming from a WPT charger operating with a fundamental limit of −15 dBµA/m.

WPT chargers in 315-405 kHz are a significantly lower risk to Radio Services. Overall, the occurrence of harmonics is much lower. But especially due to the lower level of emissions at the fundamental level, their harmonics are also much lower.

16 Conclusion

Emissions modelling and measurements were used to analyse the impact from WPT for mobile and portable devices on radiocommunications services. The Report analysed the interference impact on AM Broadcasting, Amateur Radio and Aeronautical Radionavigation (ADF/NDB) and a service agnostic study analysing the effects of WPT on the man-made noise floor.

16.1 AM broadcasting in 525-1 700 kHz

WPT devices for charging mobile and portable devices require adequate separation distance from radiocommunication service receivers in order not to cause interference.

For AM broadcasting and WPT devices operating in the 100-148.5 kHz frequency range one study found that the required separation distance was 2.3 m while the other study indicated that the required separation distance may be significantly larger.

For AM broadcasting and WPT devices operating in 315-405 kHz one study found that the required separation distance was 1.5 m in most cases when the operating frequency of WPT device is chosen to be 360 kHz and the fundamental emission level is between −25 to −35 dBμA/m at 10 m (−15 dBμA/m in ETSI EN300 330), that is much less than 100-148.5kHz. The study covered the sensitivity analysis on different orientations of the WPT devices and AM broadcasting receivers. One of the measurements found one charger that required 2.3 m separation distance, which shows the separation distance will increase due to the frequency offset of 500 Hz between the harmonic and the AM broadcasting channel centre. The worst case frequency offset from channel centre is 1.6 kHz. Further calculation shows that when the frequency offset is 1.6 kHz instead of 500 Hz, the protection distance increases to 2.7 m. However, further measurements could be needed to verify this calculation in order to avoid potential harmful interference to AM broadcasting systems caused by WPT.

AM broadcasting is significantly less affected by WPT devices operating in 315-405 kHz compared to 100-148.5 kHz. Administrations are advised to verify that the situation is satisfactory in accordance with their national requirements.

16.2 Radio Amateur Service in 135.7-137.8 kHz

WPT devices for charging mobile and portable devices operating in the 100-148.5 kHz frequency range require adequate separation distance from radiocommunication service receivers in order not to cause interference. For the Amateur Radio service this distance was between 15.3 m and 51.3 m depending on the scenario. Nevertheless, there could likely be multiple WPT devices within range of the single receiver since the protection distances are large for an urban area.

16.3 Aeronautical Radionavigation related to WPT in 100-148.5 kHz and 315-405 kHz

The studies for aeronautical radionavigation (ADF/NDB) found that the required separation distances were much less than the minimum safe flying altitudes.

16.4 Generic impact analyses of WPT on radio communication services (e.g. Fixed and Mobile) from WPT in 315-405 kHz, 1 700-1 800 kHz and 2 000-2 170 kHz

16.4.1 Aggregated Monte Carlo Study

The Monte Carlo study analysed the amount of interference that falls inside a receiver's bandwidth by comparing it to a man-made noise level. It shows that the envisaged deployment density of WPT devices in both frequency ranges (i.e. in 315-405 kHz, 1 700-1 800 kHz and 2 000-2 170 kHz) leads only in very dense urban areas, to a noise increase above the median level predicted in Recommendation ITU-R P.372 between 1.2 und 2.1 dB 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 dB to 0.7 dB, respectively, for the three frequency ranges. For all other environments (urban and residential) the increase of the median noise is less than 0.4 dB, 0.6 dB or 0.8 dB, depending on the frequency.

These levels represent peak charging times which typically 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 man-made noise levels that were used in this study. 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 information on man-made noise levels for that case.

16.4.2 Single-entry Monte Carlo Study

The 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. It shows that when modelling the varying alignment of the WPT charger from the receiver coils (varying from best to worst emissions), the distances where the WPT charger emissions drop below the median man-made noise level depending on the frequency range:

– In cities between 11 m and 14 m compared to the median level predicted in Recommendation ITU-R P.372 and between 7 and 9 m compared to the level from actual measurements of radio noise in the Netherlands.

– In residential areas between 15 m and 18 m compared to the median level predicted in Recommendation ITU-R P.372 and between 9 m and 13 m compared to the level from actual measurements of radio noise in the Netherlands.

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 and there is perfect alignment of the receive antenna with the field created by the WPT device.

The actual noise environment at less than 10 m distance from the WPT device can be higher or lower than the man-made noise levels that were used in this study. 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 information on man-made noise levels for that case.

16.5 Impact of non-beam WPT for mobile and portable devices in 100-148.5 kHz and 315-405 kHz on Maritime Radionavigation / Differential Global Navigation Satellite Systems (DGNSS)

The first single entry study result shows that, for single entry of non-beam WPT for mobile and portable devices, protection distance for DGNSS can reach 47-51 m for the third harmonic of WPT devices operating in the range 100-148.5 kHz at the unwanted emissions limits and 17 m for the fundamental emissions of WPT devices operating in the range 315-405 kHz at the fundamental limit.

It also shows 7 m to 17 m for the third harmonic of WPT devices operating in the range 100-148.5 kHz and 8 m to 11 m for the fundamental emissions of WPT devices operating in the range 315-405 kHz at actual measured emissions levels. WPT devices for portable and mobile devices operating in 315-405 kHz have a lower interference impact on DGNSS compared to harmonics from WPT devices in 100-148.5 kHz.

The second single entry study shows that, for a single entry of non-beam WPT for mobile and portable devices, protection distance for DGNSS is 21 m without considering mitigating factors, i.e. the WPT devices should be 21 m away from the DGNSS receiver.

The required separation distances should be taken into account by administrations when planning the usage of 100-148.5 kHz and 315-405 kHz band for WPT, especially avoiding interference caused by WPT to the DGNSS receivers both ashore and onboard.

The first aggregate study has shown that the WPT devices on the shore do not impact the reception of DGNSS onboard a vessel.

The second aggregate study has shown that the H-field and E-field of WPT devices on a large cruise ship operating in the range 315-325 kHz do not impact the reception of DGNSS.

16.6 Maritime Mobile Service in relation with GMDSS

The protection of maritime mobile services for safety of life services as listed in Appendix **15** of the RR is ensured. Those are, in particular 490 kHz, 518 kHz and 2 187.5 kHz. WPT operating in the frequency ranges 315-405 kHz, 1 700-1 800 kHz and 2 000-2 170 kHz do not overlap with these frequency ranges or have uneven harmonics falling onto those.

16.7 Comparison WPT charging impact between 100–148.5 kHz and 315-405 kHz

Compared to WPT chargers in 100-148.5 kHz, WPT chargers in 315-405 kHz present a lower risk to Radio Services. Overall, there are fewer harmonics. But especially due to the lower level of emissions at the fundamental level, the harmonic emissions are also much lower.

Annex 1

References

ITU-R Document and number	ITU-R Document title
GE75 Regional Plan Agreement	
Recommendation ITU-R P.368-7	Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz
Recommendation ITU-R P.372	Radio noise
Recommendation ITU-R BS.468	Measurement of audio-frequency noise voltage level in sound broadcasting
Recommendation ITU-R BS.498	Ionospheric cross-modulation in the LF and MF broadcasting bands
Recommendation ITU-R P.532	Ionospheric effects and operational considerations associated with artificial modification of the ionosphere and the radio-wave channel
Recommendation ITU-R BS.559	Objective measurement of radio-frequency protection ratios in LF, MF and HF broadcasting
Recommendation ITU-R BS.560	Radio-frequency protection ratios in LF, MF and HF broadcasting
Recommendation ITU-R BS.561	Definitions of radiation in LF, MF and HF broadcasting bands
Recommendation ITU-R M.589	Technical characteristics of methods of data transmission and interference protection for radionavigation services in the frequency bands between 70 and 130 kHz
Recommendation ITU-R BS.638	Terms and definitions used in frequency planning for sound broadcasting
Recommendation ITU-R BS.639	Necessary bandwidth of emission in LF, MF and HF broadcasting
Recommendation ITU-R BS.703	Characteristics of AM sound broadcasting reference receivers for planning purposes
Recommendation ITU-R M.823	Technical characteristics of differential transmissions for global navigation satellite systems from maritime radio beacons in the frequency band 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3

ITU-R Document and number	ITU-R Document title
Recommendation ITU-R SM.1056	Limitation of radiation from industrial, scientific and medical (ISM) equipment
Recommendation ITU-R P.1147	Prediction of sky-wave field strength at frequencies between about 150 and 1 700 kHz
Recommendation ITU-R P.1321	Propagation factors affecting systems using digital modulation techniques at LF and MF
Recommendation ITU-R BS.1348	Service requirements for digital sound broadcasting at frequencies below 30 MHz
Recommendation ITU-R BS.1386	LF and MF transmitting antennas characteristics and diagrams
Recommendation ITU-R BS.1387	Method for objective measurements of perceived audio quality
Recommendation ITU-R BS.1514	System for digital sound broadcasting in the broadcasting bands below 30 MHz
Recommendation ITU-R M.1732-2	Characteristics of systems operating in the amateur and amateur-satellite services for use in sharing studies
Recommendation ITU-R BS.1895	Protection criteria for terrestrial broadcasting systems
Recommendation ITU-R SM.1896	Frequency ranges for global or regional harmonization of short-range devices (SRDs)
Recommendation ITU-R SM.2028	Protection distance calculation between inductive systems and radiocommunication services using frequencies below 30 MHz
Recommendation ITU-R SM.2103	Global harmonization of SRD categories
Recommendation ITU-R P.2109	Prediction of building entry loss
Recommendation ITU-R SM.2110	Frequency ranges for operation of non-beam Wireless Power Transmission (WPT) systems
Recommendation ITU-R SM.2129	Guidance on frequency ranges for operation of non-beam wireless power transmission systems for mobile and portable devices
Report ITU-R BS.401	Transmitting Antennas in LF, MF, and HF broadcasting
Report ITU-R BS.458	Characteristics of systems in LF, MF, and HF broadcasting
Report ITU-R SM.2057	Studies related to the impact of devices using ultra-wideband technology on radiocommunication services
Report ITU-R SM.2153	Technical and operating parameters and spectrum requirements for short-range devices
Report ITU-R SM.2154	Short-range radiocommunication devices spectrum occupancy measurement techniques
Report ITU-R SM.2179	Short-range radiocommunication devices measurements
Report ITU-R SM.2180	Impact of industrial, scientific and medical (ISM) equipment on radiocommunication services
Report ITU-R SM.2210	Impact of emissions from short-range devices on radiocommunication services
Report ITU-R SM.2303	Wireless power transmission using technologies other than radio frequency beam

Other references

[1] Measurement Methodology and Results of Measurements of Man-Made Noise Floor on HF in The Netherlands, T.W.H. Fockens, A.P.M. Zwamborn, F. Leverink, IEEE Transactions on EMC, Vol 61, No. 2, April 2019

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[6] ERC Recommendation 74-01: https://docdb.cept.org/document/1001

[7] ERC Report 69: https://docdb.cept.org/document/637

[8] ECC Report 67: https://docdb.cept.org/document/177

Annex 2

Abbreviations

Term	Explanation
ADC	Analogue digital converter
ADF	Automatic direction finder
AM	Amplitude modulation
BBC	British Broadcasting Corporation
BW	Bandwidth
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
ISM	Industrial, scientific, and medical (applications)
LF	Low frequency
NDB	Non-directional beacon
RR	Radio Regulations
SCN	Single carrier noise
TR	Technical report
WGN	White gaussian noise
WPT	Wireless power transmission

Annex 3

Propagation model for WPT emissions

The propagation loss is based on the propagation model is used according to Recommendation ITU-R SM.2028 with Ground Type 9. 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. After the far field, ground wave propagation is assumed. The model was programmed to output dBµA/m directly. It is set directly to produce −15 dBµA/m at 10 m.

FIGURE 73

Example propagation loss at 2 MHz