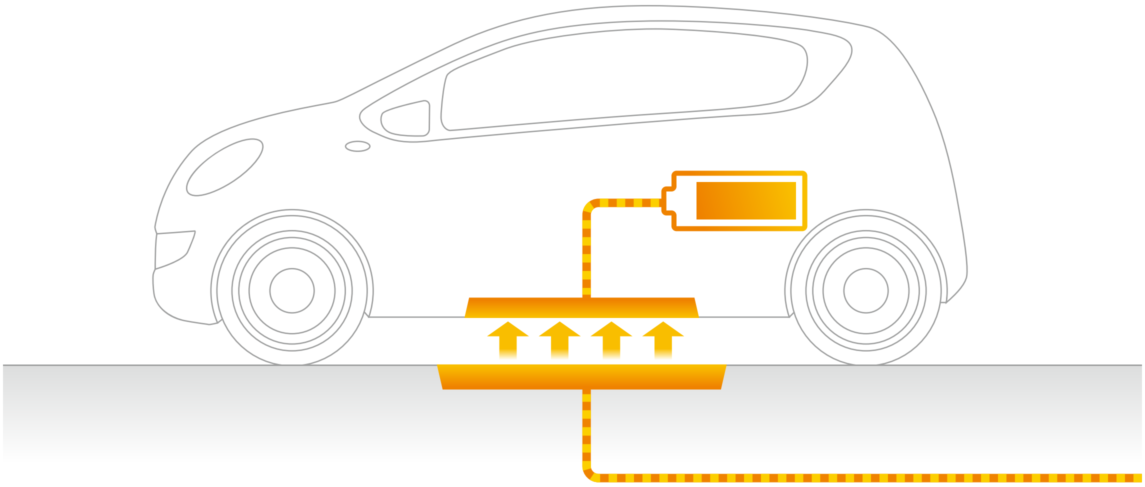
Interference Risks from Wireless Power Transfer for Electric Vehicles

KARINA FORS, SARA LINDER, PETER STENUMGAARD



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Karina Fors, Sara Linder, Peter Stenumgaard

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Sammanfattning

Trådlös laddning av elfordon är en relativt ny tillämpning av trådlös energiöverföring och dess påverkan på andra system är inte helt undersökt. Frekvenserna för trådlös laddning används också av radiokommunikationssystem. Eftersom tekniken är relativt ny pågår det mycket arbete med att utveckla tekniken i sig, men också att undersöka möjliga störningar av andra system och fastställa emissionsgränser. Det finns till exempel en arbetsgrupp inom ITU-R som undersöker trådlös laddnings möjliga påverkan på radiokommunikationstjänster som arbetar på samma eller angränsande frekvenser. Resultaten i denna rapport är ett komplement till arbetet inom den gruppen.

Det finns flera föreslagna frekvensband för trådlös laddning av fordon med olika egenskaper. Från föreslagna emissionsnivåer på dessa frekvenser gör vi jämförelser med bakgrundsbruset och beräknar ett avstånd inom vilket störningen överskrider bruset. Den sammanlagda effekten från flera WPT-EV-system beräknas också. För ett antal radiokommunikationstjänster härleds skyddsavstånd.

Den övergripande slutsatsen är att strålad emission från WPT-EV kan orsaka icke-försumbara störningsproblem för ett antal radiobaserade tjänster vid samlokaliseringsavstånd varierande mellan några tiotals meter upp till tiotals kilometer. Den sammanlagda effekten från flera WPT-EV system kan ge en ökning av brusnivån inom flera hundra kilometer.

Nyckelord: trådlös laddning, eldrivna fordon, interferens, elektromagnetisk emission

Summary

Wireless power transmission (WPT) for electrical vehicle (EV) charging is a relatively new application of wireless energy transfer and its potential impact on other systems has not been investigated in depth. The frequencies for WPT-EV are also used by radiocommunication systems or services. Since WPT-EV is a new technology there is a lot of work going on in the world in evolving the technology itself, but also in investigating interference in other systems and setting emission limits. There is, for example, a working group within the ITU-R that is examining the possible impact of WPT-EV on the radiocommunication services operating in the same or adjacent frequencies. The results in this report are a complement to the work within that group.

There are several proposed frequency bands for WPT-EV with different characteristics. From proposed emission limits, comparisons are made with the background noise and a distance within which the interference power exceeds the noise is calculated. Aggregated effects from several WPT-EV systems are also calculated. For a number of radiocommunication services protection distances are derived.

The overall conclusion is that radiated emission from WPT may cause non-negligible interference impact on radio-based services at co-location distances ranging from a few tens of metres up to the order of tens of kilometres. The combined effect from several WPT-EV systems can result in an increased noise level for distances up to hundreds of kilometres.

Keywords: wireless power transfer, electrical vehicle, interference, electromagnetic emission

Contents

1. Introduction

Technologies to transmit electric power wirelessly have been developed since the 19th century, beginning from induction technology. Since the Massachusetts Institute of Technology innovation on non-beam wireless power technology in 2006, technologies of wireless power transmission (WPT) under development vary widely; e.g. transmission via radio-frequency beam, magnetic field induction, resonant transmission, etc. WPT applications are expanding to mobile and portable devices, home appliances and office equipment, and electric vehicles. Nowadays, resonant WPT technologies are coming out to the consumer market. The automotive industry looks at WPT for electric vehicle (EV) applications in the upcoming future.

There are various WPT applications in use, in experimental, or in implementation phase throughout the world. The frequencies used for WPT for electric vehicle charging (WPT-EV) are used also by radiocommunication systems or services. Since the charging powers can range from a few kW up to the order of 200 kW, the risks for radio interference must be carefully investigated not to harm wireless services. The impact of WPT-EV applications on existent radiocommunication services has not been sufficiently known. In order to examine this possible impact of WPT-EV on the radiocommunication services operating in the same or adjacent frequencies, WRC-15 agreed that ITU-R should study this impact via its Resolution 958 (WRC-15) as one of the urgent studies required in preparation for the 2019 World Radiocommunication Conference (WRC-19).

Studies of coexistence between WPT and radio services have started within the International Telecommunication Union (ITU). In this report, the interference risks from WPT EV are studied for the frequency bands 19-25 kHz, 79-90 kHz and 100-300 kHz. The report is organized as follows. In chapter 2, the basic technical parameters for WPT EV are reviewed. In chapter 3, the methodology, emission levels for WPT systems, models for the calculations are given together with interference criteria. The analyses comparing WPT emissions with atmospheric noise are presented in chapter 4, both for one and several WPT stations. In chapter 5, the possible impact on selected wireless services is investigated. The report is concluded in chapter 6.

2. Technical Parameters of WPT for EV

2.1 Overview of technology of WPT for EV

WPT uses the basic principle from transformer coupling via a magnetic core. A transformer consists of a primary and a secondary side. Each side uses a coil that is wired around a magnetic core. The transformer is electrically fed with a high-frequency power supply at the primary side and the output is used for charging the rechargeable energy storage system (RESS) at the secondary side. In WPT for EV, the transformer is broken up into two pieces, separated by an air gap, see Figure 2.1. The primary side is typically located at the ground and the secondary side is located in the vehicle. The vehicle is positioned over the primary side so that the two sides are electromagnetically connected. Special circuitry is used to match the two sides so that resonance is achieved during the charging process. In Figure 2.2, the equivalent electric circuit for the WPT is shown. In Figure 2.2, C1 and C2 are capacitances, L1 and L2 are inductances and M is the mutual inductance between the two parts of the transformer coupling.

With this solution, an efficiency factor in the order of 80 - 95% is possible to achieve [1], depending on frequency band used. Thus, about 5-20% of the power fed to the primary side will be lost as e.g. heat and radiated power. It is therefore of high importance that the resonance is achieved accurately during charging, not to increase the unintentional radiated electromagnetic interference. The resonance peak is typically narrow with respect to frequency variation. Other physical variations can also affect the electromagnetic properties of the coupling. It is therefore of high importance that this resonance can be monitored and adjusted if needed. As a comparison, the efficiency factor of a transformer coupling without this air gap could be in the order of 99%. Thus, breaking up the circuit and introducing the air gap leads to large losses. These losses can be reduced, but not fully eliminated. This fact also means that WPT is not an optimal technology with respect to power efficiency in general, compared to if e.g. a physical wired connection is used.

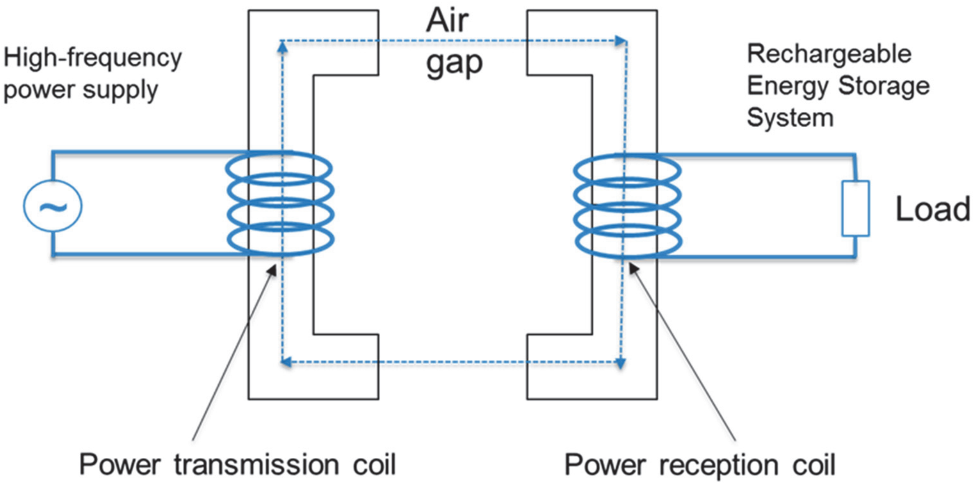

Figure 2.1: Schematic picture of the principal technology for WPT for EV. The transformer is divided into two parts, separated by an air gap.

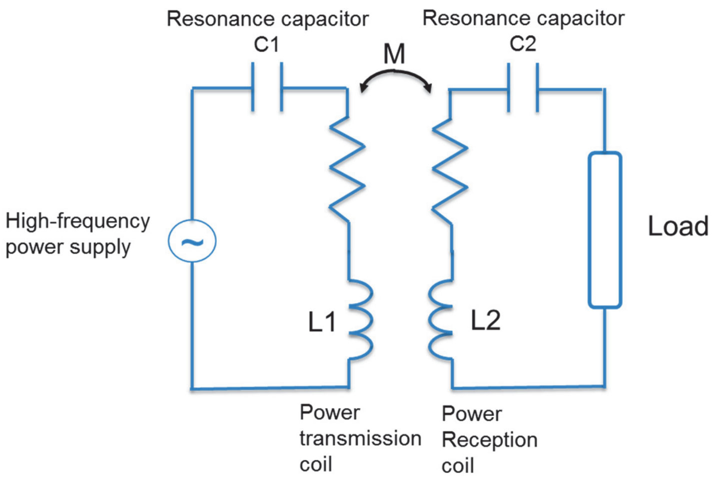

Figure 2.2: Equivalent electric circuit for WPT.

2.2 Technical parameters and frequency bands

In Table 2.1, proposed power levels and frequency bands are shown for different kinds of applications [1]. The values are not decided on, and other proposals exist. In table 2.2, some predictions over future use of WPT are shown [1].

Table 2.1: Technical parameters for WPT [1].

Categories	**Power level**	**Frequency band**	**Applications**
High power WPT	22 kW – 200 kW 11 kW – 22 kW	19 – 21[1] kHz 59 – 61 kHz	Heavy-duty vehicle (Bus, Tram, Truck, ATV)
Medium power WPT	7.7 kW – 11 kW 3.7 kW – 7.7 kW	79 -90 kHz	Passenger car
Small power WPT	Less than 50 W	100 – 300 kHz 6 765 – 6 795 kHz	Mobile devices

Table 2.2: Predictions over the future use of WPT [1].

Year	**Worldwide number of vehicles, EV+PHEV [millions]**	**WPT deployment rate**	**Worldwide number of WPT equipped vehicles [millions]**
Number of vehicles in 2020	5	--	0
Increase 2021 → 2025	50	15%	7.5
Increase 2026 → 2030	100	30%	30
Total Number of vehicles in 2030	150	approx. 50%	approx. 40

[1] The upper limit is often 25 kHz.

3. Models and assumptions

The interference from WPT in other radio systems are investigated in this report and the analysis consists of several parts. In this chapter, the underlying scenario and input data for the analyses are described. The emission limits for radiated emission from WPT-systems are reviewed, followed by a description of the model for the attenuation of the electromagnetic field from the WPTsource. Lastly, the interference criteria used in this report are given.

3.1 Interference scenario and method

The physical scenario is illustrated in Figure 3.1, which shows a WPT system emitting an electromagnetic field that is received by an antenna at a distance *r*. The WPT device is regulated by standards, which limit the maximum power used and the maximum allowed field strength at a certain distance (or at several distances) for different frequencies. The emission limits are described further in the next section. Since the antenna at the victim receiver can be located at other distances than the one specified in the standard, a conversion is needed. The interference level is converted to other distances by applying the appropriate field attenuation for the frequency of interest. The standards, do not discriminate between different polarizations of the radiated field. The polarization of the field depends on the design and orientation of the source and may differ in different directions. For ground wave propagation, the vertical polarisation of the electrical field propagates more easily. Therefore, we assume that maximum permitted limits are related to the vertically polarized electrical field from a magnetic dipole.

The field strength of the interference is converted to a corresponding noise factor in the wireless receiver and finally compared to the noise figure caused by the atmospheric background noise according to the ITU-level. Alternatively, the field strength is compared to the protection criteria for specific radio services.

3.2 Radiated emission levels from WPT

Emission limits regulate the maximum values of an electromagnetic field at a certain distance (or at several distances) at different frequencies. For WPT systems there are several standards that may apply. Besides the specific standards for wireless power transfer systems, there are standards for short-range devices (SRD) including inductive loop systems. There is also an ongoing work within CISPR with a standard for different classes of WPT systems for vehicles.

Within Europe, there are two ETSI harmonized European standards that treat WPT-systems, one for wireless power transmission systems [2] and one for short-range devices including inductive loop systems [3]. Both standards treat general systems for wireless power transfer systems used also for other purposes than vehicle charging. Hence, the limits are probably going to be revised to include high-power WPT systems. The ETSI-limits for WPT-systems [2] are shown in Table 3.1. In the ETSI-

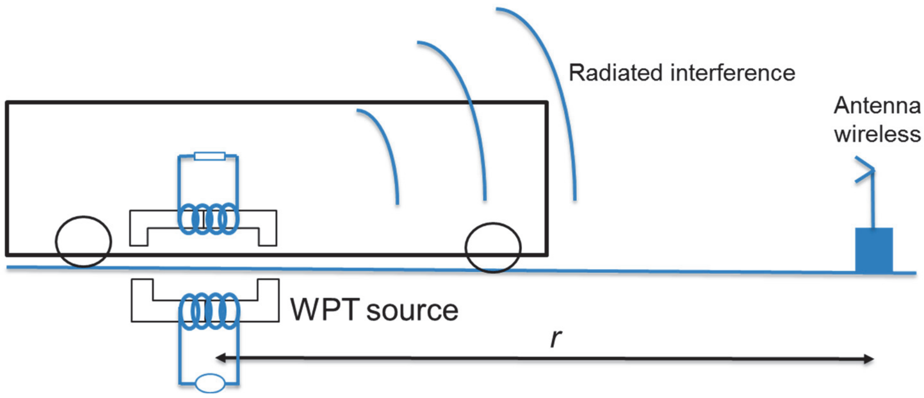

Figure 3.1: The interference scenario with a WPT system and an antenna receiving an interference signal.

standard for SRD systems [3], the H-field limit at 10 metres for the frequency band 9-90 kHz is 72 dBµA/m, descending 3 dB/octave above 30 kHz, or 42 dBµA/m at specific spot frequencies (see further details in the standard).

Within CISPR, there is an ongoing work to develop radiated emission limits for WPT-EV. When this report was written, the work with the emission limits was not finalized and the proposed limits were used. These limits for CISPR 11, are shown in Table 3.2 for Class A systems and in Table 3.3 for Class B systems. Class A limits apply to WPT equipment with a rated a.c. main power > 22 kW that are intended to be connected to a dedicated power transformer or generator, but not to low voltage (LV) overhead power lines. For WPT equipment not intended to be connected to a user specific power transformer, the limits for ≤ 22 kW apply (Class B). The proposed limits are from the work in ITU [1].

Table 3.1: H-field limits for WPT-systems according to ETSI EN 303 417 [2] within the specified operating frequencies.

Frequency range [MHz]	H-field strength limit [dBµA/m at 10 m]	Comments
0,019 ≤ f < 0,021	72	
0,059 ≤ f < 0,061	69,1 descending 10 dB/dec above 0,059 MHz	See note 1
0,079 ≤ f < 0,090	67,8 descending 10 dB/dec above 0,079 MHz	See note 2
0,100 ≤ f < 0,119	42	
0,119 ≤ f < 0,135	66 descending 10 dB/dec above 0,119 MHz	See note 1
0,135 ≤ f < 0,140	42	
0,140 ≤ f < 0,1485	37,7	
0,1485 ≤ f < 0,30	-5	
6,765 ≤ f < 6,795	42	

NOTE 1: Limit is 42 dBµA/m for the following spot frequencies: 60 kHz ± 250 Hz and 129,1 kHz ± 500 Hz.
NOTE 2: At the time of preparation of the present document the feasibility of increased limits for high power wireless power transmission systems to charge vehicles [i.4] was prepared. New specific requirements for such systems (e.g. higher H-field emission limits in the 79 - 90 kHz band) will be reflected within a future revision of the present document.

Table 3.2: Proposed limits CISPR 11, Class A [1].

Frequency range [kHz]	Limits for a measuring distance *D* in m, class A (≤ 22 kW) b			Limits for a measuring distance *D* in m, class A (> 22 kW) a,b		
	D = 30 m	*D* = 10 m	*D* = 3 m	*D* = 30 m	*D* = 10 m	*D* = 3 m
	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]
9 - 19	18,0 - 14,8	42,0 - 38,8	66,5 - 63,3	18,0 - 14,8	42,0 - 38,8	66,5 - 63,3
19 - 25	**73,0**	**97,0**	**121,5**	**83,0**	**107,0**	**131,5**
25 - 36	13,6 – 12,1	37,6 – 36,1	62,1 - 60,6	13,6 – 12,1	37,6 – 36,1	62,1 - 60,6
36 - 40	**72,2**	**96,2**	**120,7**	**82,2**	**106,2**	**130,7**
40 – 55	11,6 - 10,3	35,6 - 34,3	60,1 - 58,8	11,6 - 10,3	35,6 - 34,3	60,1 - 58,8
55 – 65	**70,4**	**94,4**	**118,9**	**80,4**	**104,4**	**128,9**
65 – 79	9,6 - 8,7	33,6 - 32,7	58,1 - 57,2	9,6 - 8,7	33,6 - 32,7	58,1 - 57,2
79 - 90	**68,8**	**92,8**	**117,3**	**78,8**	**102,8**	**127,3**
90 – 130	8,2 - 6,6	32,2 - 30,6	56,7 - 55,1	8,2 - 6,6	32,2 - 30,6	56,7 - 55,1
130 – 135 c	**66,0**	**90**	**114,5**	**76,0**	**100,0**	**124,5**
135 - 150	6,4 – 6,0	30,4 – 30,0	54,9 - 54,5	6,5 – 6,0	30,4 – 30,0	54,9 - 54,5

At the transition frequency, the more stringent limit shall apply. On a test site, class A equipment may be measured at a nominal distance of 3 m, 10 m or 30 m. A measuring distance less than 10 m is allowed only for equipment which complies with the definition given in 3.17.

Where the limit varies with the frequency, it decreases linearly with the logarithm of the increasing frequency.

National authorities may request additional suppression of emissions within specific frequency bands used by sensitive radio services at designated installations, for example by imposing the limits in Table E.2.

a These limits apply to WPT equipment with a rated a.c. main power > 22 kW and intended to be connected to a dedicated power transformer or generator, and which is not connected to low voltage (LV) overhead power lines. For WPT equipment not intended to be connected to a user specific power transformer the limits for ≤ 22 kW apply. The manufacturer and/or supplier shall provide information on installation measures that can be used to reduce emissions from the installed equipment. In particular it shall be indicated that this equipment is intended to be connected to a dedicated power transformer or generator and not to LV overhead power lines.

b Selection of the appropriate set of limits shall be based on the rated a.c. power stated by the manufacturer.

c This frequency range should be limited to use for in-plant transportation systems.

Table 3.3: Proposed limits CISPR 11, Class B [1].

Frequency range [kHz]	Limits for a measuring distance *D* in m					
	class B (≤ 1 kW) [a]		class B (> 1 kW to ≤ 7,7 kW) [a]		class B (> 7,7 kW) [a]	
	D = 10 m	*D* = 3 m	*D* = 10 m	*D* = 3 m	*D* = 10 m	*D* = 3 m
	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]	Magnetic Field Quasi-Peak [dB(µA/m)]
9 - 19	27 – 23,8	51,5 – 48,3	27 – 23,8	51,5 – 48,3	27 – 23,8	51,5 – 48,3
19 - 25	**57**	**81,5**	**72**	**96,5**	**72**	**96,5**
25 - 36	22,6 - 21	47,1 – 45,5	22,6 - 21	47,1 – 45,5	22,6 - 21	47,1 – 45,5
36 - 40	**56,2** [b]	**80,7** [b]	**71,2** [b]	**95,7** [b]	**71,2** [b]	**95,7** [b]
40 – 55	20,6 - 19,3	45,1 - 43,8	20,6 - 19,3	45,1 - 43,8	20,6 - 19,3	45,1 - 43,8
55 – 65	**54,4** [b]	**78,9** [b]	**69,4** [b]	**93,9** [b]	**69,4** [b]	**93,9** [b]
65 – 79	18,5 - 17,7	43 - 42,2	18,5 - 17,7	43 - 42,2	18,5 - 17,7	43 - 42,2
79 - 90	**52,8**	**77,3**	**67,8** ~~b~~	**92,3** ~~b~~	**82,8** ~~c~~	**107,3** ~~c~~
90 –150	17,2 – 15	41,7 – 39,5	17,2 – 15	41,7 – 39,5	17,2 – 15	41,7 – 39,5

At the transition frequency, the more stringent limit shall apply. Where the limit varies with the frequency, it decreases linearly with the logarithm of the increasing frequency.

On a test site, class B equipment may be measured at a nominal distance of 3 m or 10 m. A measuring distance less than 10 m is allowed only for equipment which complies with the definition given in 3.17.

National authorities may request additional suppression of emissions within specific frequency bands used by sensitive radio services at designated installations, for example by imposing the limits in Table E.2.

a Selection of the appropriate set of limits shall be based on the rated a.c. main power stated by the manufacturer.

b In some countries, these bands are not available.

3.2.1 Spurious emissions

Limits for spurious emissions from WPT-systems are specified in two ETSI harmonized European standards, one for wireless power transmission systems [2] and one for short-range devices including inductive loop systems [3].

The radiated emissions in the spurious domain shall at 10 metres distance not exceed the specified H-field limits. For frequencies between 9 kHz and 10 MHz, the limits are 27 dBµA/m at 9 kHz and descending 3 dB/oct [3] (alt. 10 dB/dec [2]) for an operating system. There are also limits for systems in standby mode. For frequencies between 10 MHz and 30 MHz, the limit is -3.5 dBµA/m [2, 3].

It is possible that these limits will be adjusted for WPT-EV applications and permit higher values.

3.3 Radiated fields from WPT

The attenuation of the radiated interference from a certain WPT source depends on the frequency, the antenna properties of the source, the height above ground, and other physical properties. The problem is complicated by the fact that the analysis has to be done in the near field region of the WPT source. In practice, this means that the rates by which the electric and magnetic fields are attenuated change with frequency.

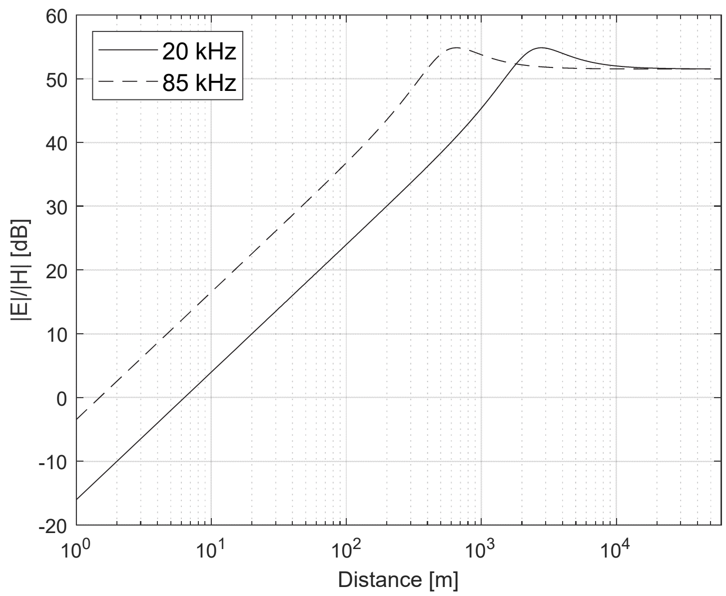

Figure 3.2: *E*/*H* ratio in dB as a function of distance for 20 kHz and 85 kHz [4].

Since the primary emitting source is a magnetic coil, the magnetic field will dominate for short distances. The E/H ratio for a small loop is shown in Figure 3.2. In the far field, the E/H ratio is equal to the free space impedance $Z_0 = 377\ \Omega$. For the magnetic loop antenna, the ratio of the field's magnitudes can be expressed as [4]

$$\frac{|E|}{|H|} = Z_0 \left| \frac{1 + \frac{1}{ikr}}{1 + \frac{1}{ikr} + \frac{1}{(ikr)^2}} \right|, \tag{4.1}$$

where i is the imaginary unit, $k = 2\pi/\lambda$, where λ is the wavelength and r is the distance from the source.

The attenuation of the magnetic field is assumed to be 60 dB/dec in the near field and 20 dB/dec in the far field. The limit between near and far field depends on the wavelength and is often set as $1/k = \lambda/2\pi$. This is an approximation of the attenuation of the magnetic field assuming free-space.

3.4 Interference criteria

As a basic criterion for where the radiated fields from WPT might interfere with wireless services, the received interference level from the WPT source is compared to the interference level caused by atmospheric noise. The atmospheric noise is always present at the receiver of a wireless service and can thus be regarded as a base level of existing interference. The distance from which the atmospheric noise level in the receiver is exceeded by the interference from the WPT has therefore been determined for each frequency region of interest and for different emission limits defined for WPT equipment.

Additionally, the received interference level is compared to the protection criteria for specific radio services. The radio services analysed are working at different frequency bands in the VLF, LF and MF bands. The analysed radio services are the Standard frequency and time signal (SFTS), Loran-C, non-directional beacon (NDB) and differential transmissions for global navigation satellite systems (DGNSS). The protection criteria for the different systems are found in Chapter 5, together with the analysis.

4. Interference compared to noise

In this chapter, the interference from WPT systems are compared to atmospheric noise. First, the analysis is performed for a single WPT source and later several sources are aggregated. The analysis is performed for two frequencies since the results are frequency dependent. We chose the frequency 20 kHz, that is in the frequency band proposed for heavy duty vehicles, and 85 kHz in the frequency band proposed mainly for passenger vehicles.

The atmospheric noise is described in an ITU recommendation on radio noise [5] as a noise factor. For the atmospheric noise, two levels are considered. The minimum and maximum values of the hourly medians of the external noise figure (F_a (dB)) expected to be those values exceeded 99.5% and 0.5% of the hours. At 85 kHz, the minimum atmospheric noise is about the same as man-made noise at a quiet receiving site [5]. At 20 kHz, no value for man-made noise is given, but the trend for higher frequencies indicates that the man-made noise is much lower than the atmospheric noise. In this analysis, the emissions from WPT-systems are compared to the minimum noise level. From the noise factor, the electric field strength in a receiving antenna can be calculated.

The interference from the WPT is attenuated with distance. For the electric field, the attenuation in the near field is assumed to be 40 dB/dec. In the far field region, the attenuation is assumed to be 20 dB/dec up to a transition point where the attenuation is larger. For long distances, the attenuation of the electric field of the ground wave is modelled in [6]. For low frequencies (<100 kHz), this transition point occurs for distances longer than 100 km, for most conditions.

The limit between near and far field is often set as $\lambda/2\pi$, with corresponds to a distance of 2 387 m for 20 kHz and 562 m for 85 kHz.

The emission standards give limits on the magnetic field strength at specific distances, often at 10 metres distance. The electric field strength of the field can be calculated for a magnetic loop according to the method described in section 3.3 and also calculated at other distances using the attenuation model described above.

4.1 Results from one WPT source

The emission standards have a limit on the magnetic field strength at 10 metres distance from the WPT system. For a frequency of 20 kHz, the highest limit is 107 dBµA/m for Class A and 72 dBµA/m for Class B, according to the proposed CISPR 11 standard (see Table 3.2 and Table 3.3). The highest emission levels are for the WPT systems with the highest power. The emission limits are converted to electric field strength with equation (4.1). The field strength is then calculated for other distances from the WPT source with the attenuation model described above.

The electric field strength of the atmospheric noise is calculated for the measurement bandwidth in the standards (200 Hz for frequencies from 9 kHz to 150 kHz).

Figure 4.1 shows the electric field strength as a function of distance from the WPT for the frequency 20 kHz and for the maximum limits from the proposed CISPR 11 standard. The atmospheric noise is shown for the minimum value (red line) and maximum value (black line).

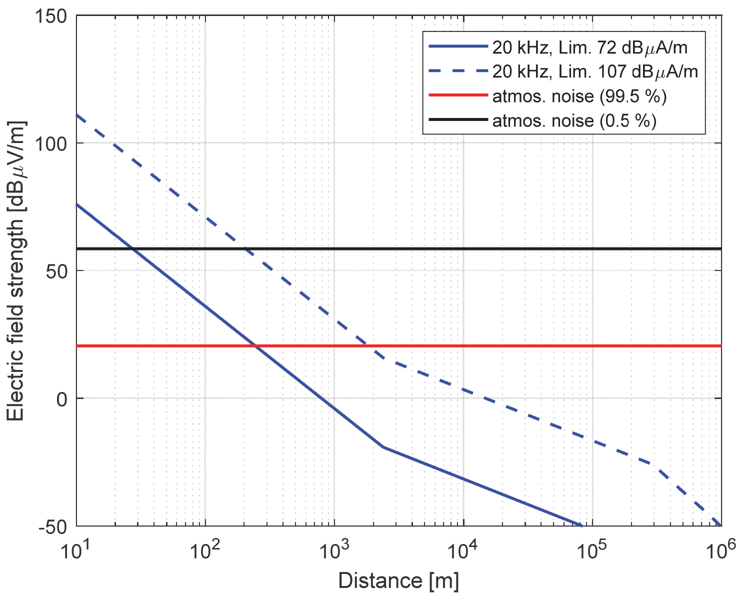

Figure 4.1: Electric field strength at 20 kHz calculated from the proposed CISPR 11 limits.

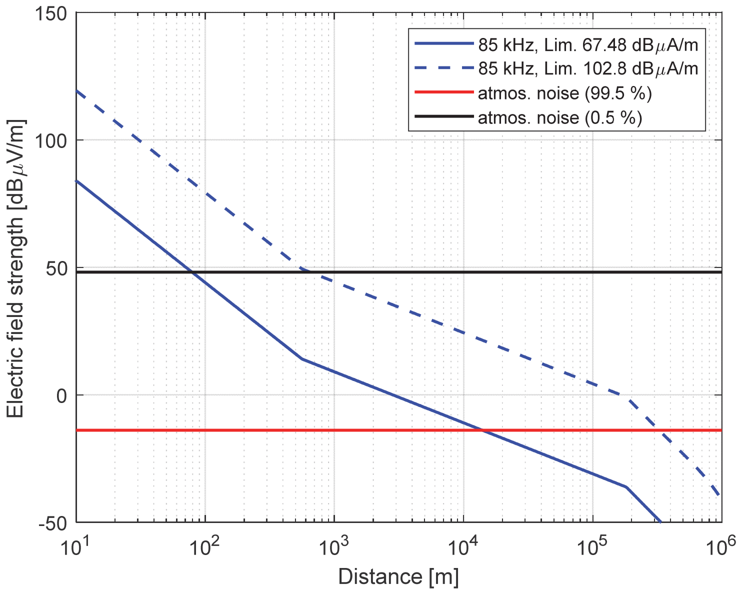

Figure 4.2: Electric field strength as a function of distance for the frequency 85 kHz.

The change of attenuation model for the near- and far field is seen at a distance of approximatively 2 km. The more rapid decrease of the field strength for very long distances is also visible. The levels of the atmospheric noise at 20 kHz is also shown in the figure. For distances shorter than about 27 m for Class B and 200 m for Class A, the emissions from the WPT exceeds the maximum value of the atmospheric noise under the assumptions used. For the minimum atmospheric noise level, the emissions from WPT exceeds the noise for distances shorter than 250 m for Class B and 2 km for Class A. At 20 kHz the distance for the low noise level is about ten times longer than the high level distance.

Figure 4.2 shows the corresponding results for 85 kHz. The emission limits are lower at 85 kHz than for 20 kHz, but the atmospheric noise (0.5 % and 99.5 %) is also lower at higher frequencies. Also, the near field limit is also shorter for higher frequencies. The WPT interference exceeds the noise for distances up to about 80 m and 15 km for Class B and 600 m and 300 km for Class A. The electric field from the WPT-source will experience different propagation attenuation in the near field, far field or at very long distances.

The results show that the emissions from WPT systems can increase the noise and interference in a receiver near a WPT system substantially. The interference decrease with distance but long distances are required for the emissions not to exceed the noise.

4.1.1 High-Frequency band

The spurious emissions from a WPT-systems may disturb communication systems operating at much higher frequencies, therefore is emissions in the High-Frequency (HF) band compared to noise levels. The spurious emissions are given in section 3.2.1 from [2]. For frequencies between 150 kHz and 30 MHz, the measurement bandwidth is 9 kHz [3]. The standards might be adjusted for WPT-EV applications and permit higher values.

In the HF band, there are several different noise environments defined in [5] as median values. These noise levels are shown in Figure 4.3 together with the limit for spurious emissions from a WPT-system. Compared to the highest noise level, City, the emissions can be higher for distances shorter than about 900 m for 5 MHz and 700 m for 10 MHz. For the quiet rural category, the noise level is exceeded up to 10 km for both frequencies. This analysis assumes free space propagation, which is valid for sea water and reasonable for brackish water for 10 km distance [6]. A similar analysis can be found in [7] for 10 and 20 sources.

4.2 Results from several WPT sources

It is reasonable to assume that several WPT systems will be active at the same time, leading to an increase of the emissions. There are several prognoses made for the growth of WPT systems, see also Chapter 2.2. It is however difficult to foresee the amount of WPT systems in an area and it is also expected that there will be a large variation in different countries, cities and environments. Therefore, different number of WPT systems are evaluated in order to show the effects on the results, from one source up to 500 sources. Here, we assume that the emitted signals from the WPT systems have random phase compared to each other and hence, that the power of the signals is summed together. Figure 4.4 shows the results for 20 kHz and a Class B system according to the highest proposed CISPR 11 limit. The distances where the emissions are higher than the noise range from about 250 metres for one source to 1.1 km for 500 sources. The results for Class A systems at 20 kHz are shown in Figure 4.5. Here the distances are longer since the emission limit is higher. In this scenario, there are situations where the emissions in the far field are higher than the noise, resulting in even longer distances as the attenuation lower than in the near field. The required separation distances for Class A and Class B at 20 kHz and 85 kHz for one and several WPT-sources are shown in Table 4.1.

For the case with several WPT-sources only the minimum value of the atmospheric noise is considered.

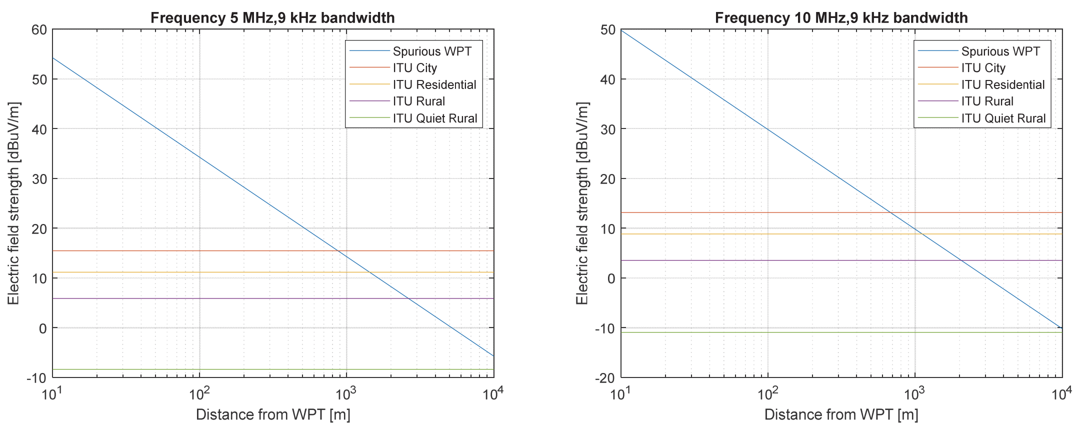

Figure 4.3: Electric field strength as a function of distance for 5 and 10 MHz.

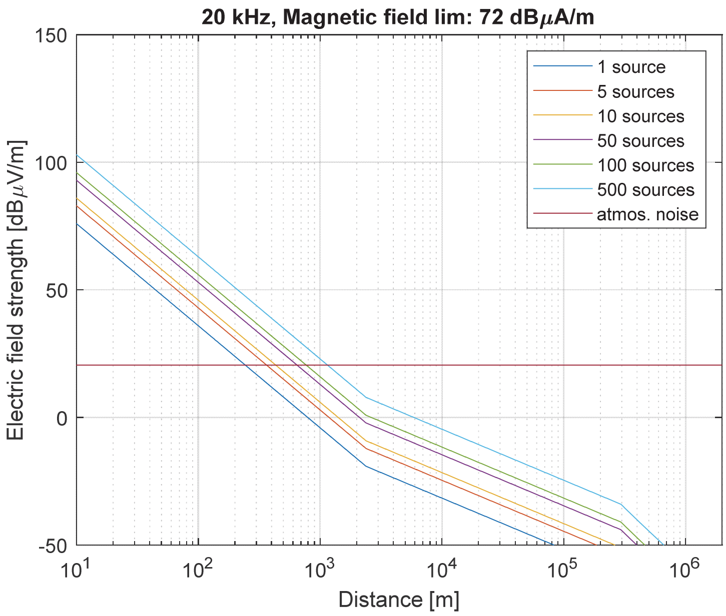

Figure 4.4: Electric field strength as a function of distance for CISPR 11 Class B at 20 kHz.

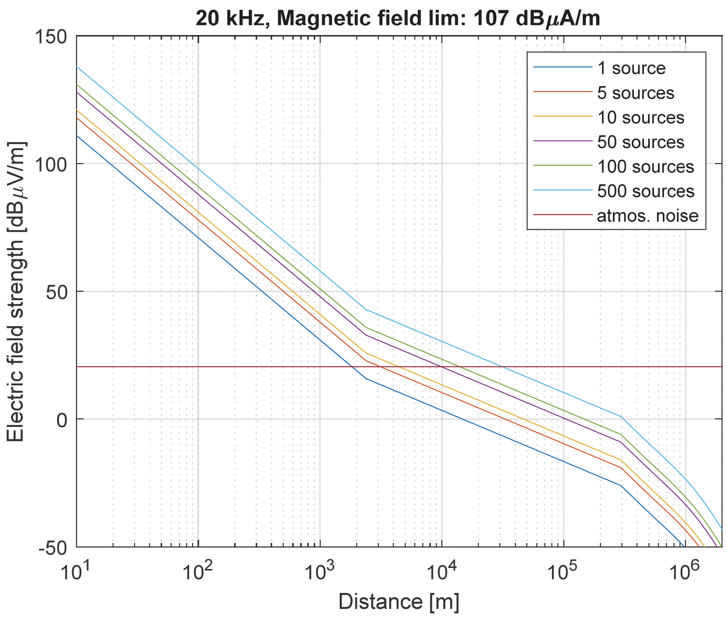

Figure 4.5: Electric field strength as a function of distance CISPR 11 Class A at 20 kHz.

The emission results at 85 kHz are shown in Figure 4.6 and Figure 4.7 for limits according Class B and Class A, respectively. At 85 kHz, both the emission limit and the atmospheric noise level are lower than at 20 kHz, but the emission levels exceed the noise at longer distances than at 20 kHz. This is an effect of not only the different emission and noise levels but also that the transition from near field to far field occur at a shorter distance for the higher frequency.

For Class A systems, the required distances in order to avoid an exceedance of the background noise are hundreds of kilometres.

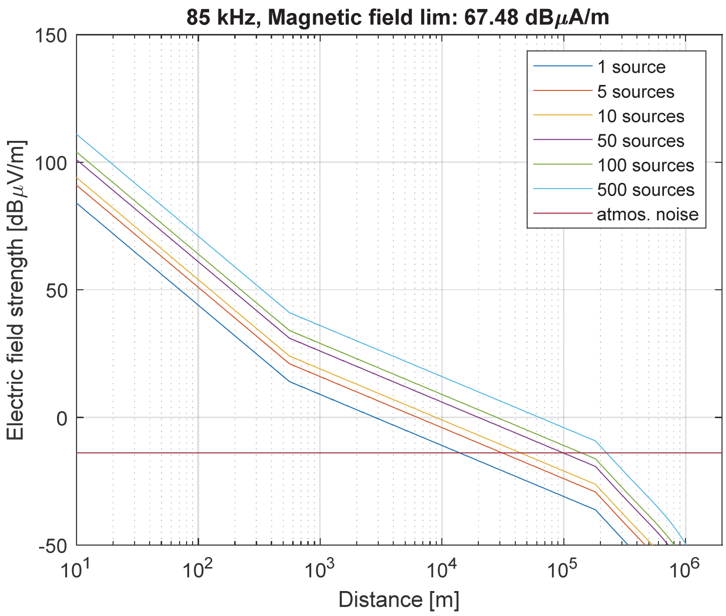

Figure 4.6: Electric field strength as a function of distance CISPR 11 Class B at 85 kHz.

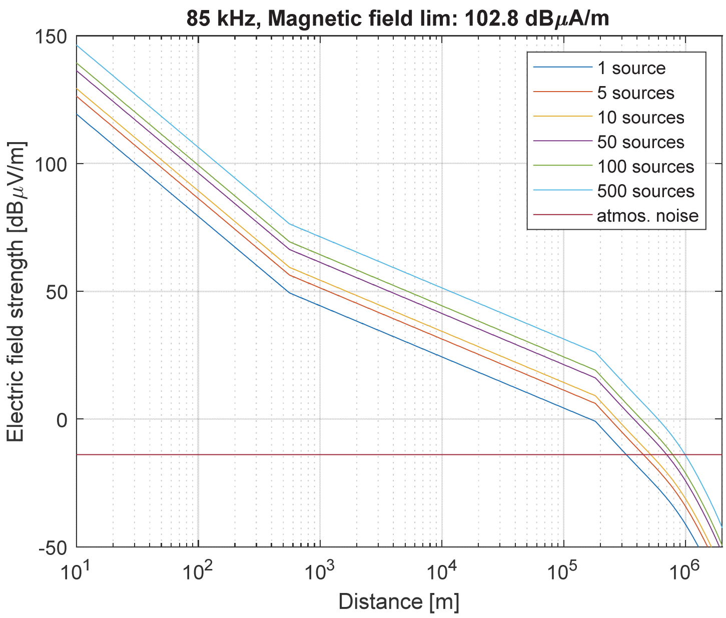

Figure 4.7: Electric field strength as a function of distance CISPR 11 Class A at 85 kHz.

Table 4.1: Distance where the emission equals the atmospheric noise.

Number of sources	Distance (metre)			
	20 kHz		85 kHz	
	Class A	Class B	Class A	Class B
1	1 820	243	327 000	14 000
5	3 120	363	451 000	31 300
10	4 410	432	518 000	44 300
50	9 850	646	701 000	99 100
100	13 900	769	786 000	140 200
500	31 200	1 150	992 000	224 900

In [7], the interference impact is analysed for the frequency 80 kHz and for ten sources. A magnetic dipole model is used for converting the emission limits to other distances. The results show that the interference from WPT-emission will be equal to the atmospheric noise for distances of about 2000 metres. The distance is shorter than those shown in Figure 4.6. The difference can be explained by that man-made noise extrapolated for the ITU-category City is used in [7] and that a different model is used for attenuation of the field.

Figure 4.8: Scenario with 500 WPT systems located at Gotland with emissions at 20 kHz and 85 kHz.

As an illustration of the distances, these are shown on a map with 500 WPT sources located on Gotland in Figure 4.8. The smallest circle (dot) has a radius of 1.1 km and represents Class B systems at 20 kHz. The next circle with a radius of 31 km is for Class A at 20 kHz. The two largest circles with radii 225 km and 992 km are for Class B and Class A systems at 85 kHz. For a case with 500 high power WPT systems at 85 kHz located at Gotland, a large part of Scandinavia, the Baltic countries and central Europe may experience an increased noise level due to the emission.

However, the distance indicates when the emissions from the WPT-systems exceed the low noise level (that is exceeded 99,5% of the time). Moreover, for the longest distances another wave propagation model might be more suitable [9].

Compared to the long distances for 85 kHz, the distances for systems at 20 kHz may appear small. In Figure 4.9, a circle with a radius of 31 km is drawn around Malmö, showing that emission from Class A systems may pose a problem also at the lower frequency.

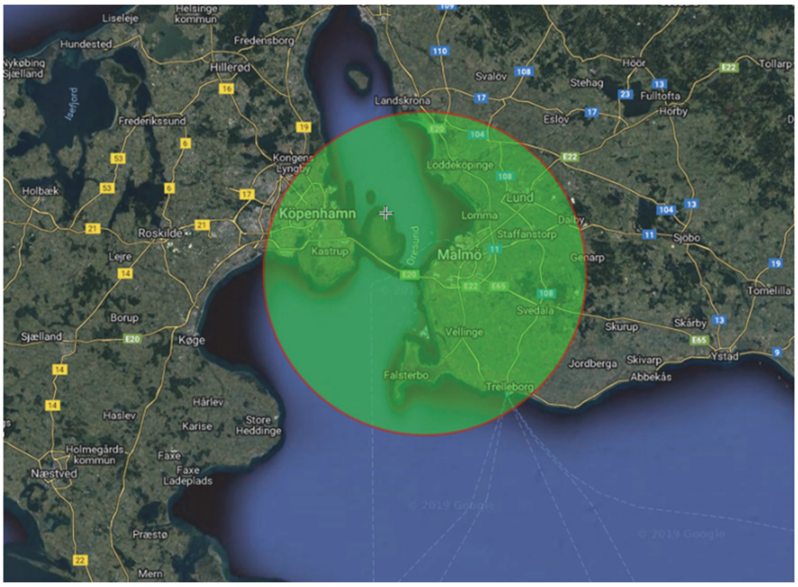

Figure 4.9: Scenario with 500 WPT systems according to Class A at 20 kHz.

5. Interference analyses for radio services

In this chapter, the effects of interference from WPT systems on different radio services are analysed. The services analysed are working at different frequency bands in the VLF, LF and MF bands. The analyses are based on the emission limits (described in chapter 3) for the WPT-system and protection criteria for the radio services.

5.1 Standard frequency and time signal

The standard frequency and time signal (SFTS) service provide accurate and precise atomic time over large areas, serving tens of millions of users. There are several frequency bands allocated for the transmission of standard frequency and time signals. In Europe, the following frequencies under 100 kHz are of interest [8]

- 19.95 kHz - 20.05 kHz – Primary
- 72 kHz - 84 kHz – Secondary, 77.5 kHz DCF time signal

ITU Working Party 7A provided information about SFTS to the WPT work [10]. There are additional bands used for SFTS:

- 14-19.95 kHz
- 20.05-70 kHz
- 72-84 kHz – Region 1
- 86-90 kHz – Region 1

The minimum usable field strength for the SFTS service is 100 µV/m (40 dBµV/m) [1], which in the far field region corresponds to a magnetic field strength of -11.5 dBµA/m. There are also two different levels of protection of the SFTS service. A basic protection of 25 dB and a stricter protection criterion, including imperfections, of 31 dB. Moreover, depending on the frequency separation to the SFTS, different protection criteria are applied. The minimum usable field strength and protection criteria for SFTS are given Tables A1.1-6 and A.1-7 on page 25-26 in [1] and summarized in Table 5.1.

The proposed CISPR limits, described in Section 3.2, give a limit of 107 dBµA at 10 metres for the most powerful WPT system working in the frequency region 19-25 kHz. Figure 5.1 shows the magnetic field strength for emissions from a WPT system at different distances. The maximum permissible interference signals for SFTS are also shown in the figure. Both the basic protection criteria and the protection criteria including imperfections are shown for frequency separations of 0, 1 and 10 kHz, see Table 5.1. The near field region for a frequency of 20 kHz is about 2.4 km. The required separation distance when the two systems work at the same frequency is 5 km for the strictest protection criteria. For a frequency separation of 10 kHz and the basic protection criteria, the required separation distance is about 900 m.

Table 5.2 gives the required separation distances to fulfil the protection criteria including imperfections for SFTS, when interfered by different types of WPT systems. The emissions from the WPT system are set according to the proposed CISPR limits [1], see also Section 3.2, for WPT systems using the frequency range 19-25 kHz for Class A and Class B systems. The protection distances are a few hundred metres even for the less powerful WPT systems and with a frequency separation of 10 kHz. For the most powerful systems, the distances are a couple of km.

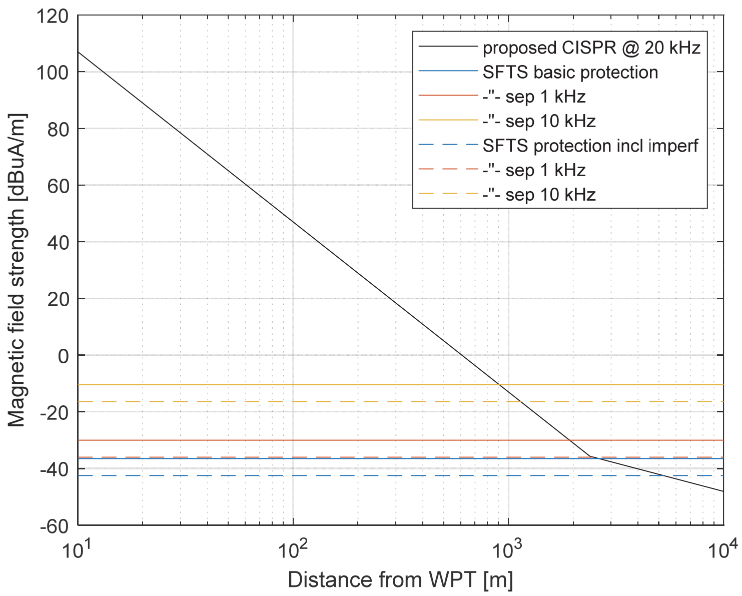

Figure 5.1: WPT emission level at 20 kHz, compared to protection criteria for SFTS.

Table 5.1: Adjacent frequency protection criteria for SFTS.

Frequency separation [kHz]	0	1	2	3	4	5	6	7	8	9	10
Max field strength basic protection [dBμA/m]	−36.5	−30.16	−25.03	−21.75	−19.38	−17.54	−16.04	−14.77	−13.68	−12.72	−11.86
Max field strength incl. imperfections [dBμA/m]	−42.5	−36.16	−31.03	−27.75	−25.38	−23.54	−22.04	−20.77	−19.68	−18.72	−17.86

Table 5.2: Required separation distances for WPT systems in the frequency range 19-25 kHz for SFTS protection criteria including imperfections.

Frequency difference [kHz]	0	1	2	3	4	5	6	7	8	9	10
Max field strength [dBuA/m]	-42.5	-36.16	-31.03	-27.75	-25.38	-23.54	-22.04	-20.77	-19.68	-18.72	-17.86
Class A < 22 kW, 97 dbuA/m	2 113	1 657	1 361	1 200	1 096	1 021	964	918	880	849	821
Class A > 22 kW, 107 dbuA/m	5 238	2 525	1 998	1 761	1 608	1 499	1 415	1 347	1 292	1 245	1 205
Class B < 1 kW, 57 dbuA/m	455	357	293	259	236	220	208	198	190	183	177
Class B 1-7.7 kW, 72 dbuA/m	810	635	521	460	420	391	369	352	337	325	315
Class B > 7.7 kW, 72 dbuA/m	810	635	521	460	420	391	369	352	337	325	315

Table 5.3 gives the separation distances for a WPT system in the frequency range 79-90 kHz. For most WPT systems, the limits are lower for the higher frequency. However, the near field distance is shorter and the attenuation is lower in the far field, so the required separation distances are long. For the most powerful WPT system and no frequency separation, the distance is almost 60 km.

In Europe there is a SFTS radio station DCF77 operating at 77.5 kHz. As an example, a WPT system using the frequency 80 kHz is analysed. This gives a frequency separation of 2.5 kHz. The maximum permissible interfering signal, for 2 kHz separation, is -31.03 dBμA/m for protection of SFTS, which would require a separation distance of 15 km for a high power Class A WPT system, and 1.5 km for a powerful Class B system. These distances are long for a service that is used by the public in their homes where WPT-systems could be expected quite close to a SFTS receiver.

Table 5.3: Required separation distances for WPT systems in the frequency range 79-90 kHz for SFTS protection criteria including imperfections.

Frequency difference [kHz]	0	1	2	3	4	5	6	7	8	9	10
Max field strength [dBuA/m]	-42.5	-36.16	-31.03	-27.75	-25.38	-23.54	-22.04	-20.77	-19.68	-18.72	-17.86
Class A < 22 kW, 92.8 dbuA/m	18 448	8 891	4 926	3 376	2 570	2 079	1 750	1 512	1 333	1 194	1 081
Class A > 22kW, 102.8 dbuA/m	58 338	28 116	15 576	10 677	8 127	6 576	5 533	4 780	4 217	3 775	3 419
Class B < 1 kW, 52.8 dbuA/m	388	304	250	220	201	187	177	168	161	156	151
Class B 1-7.7 kW, 67.8 dbuA/m	1 037	540	444	391	357	333	314	299	287	277	268
Class B > 7.7 kW, 82.8 dbuA/m	5 834	2 812	1 558	1 068	813	658	559	532	511	492	476

The distances are calculated for the magnetic field. Since the magnetic field dominates the electric field in the near field around the source, the separation distances would be shorter when calculated for the electrical field. For distances in the far field, the results are similar independent of which field they are calculated with.

5.2 Loran-C

Loran-C is a radio navigation system with a large coverage area that uses the frequency range 90 – 110 kHz. Loran-C is an old system and were to be upgraded to enhanced-LORAN (eLoran). However, the system is not widely used anymore and is replaced by other navigation systems. In Europe, most of the transmitters were shut down in 2015 and the system is also shut down in US and Canada. However, there may be an active use of Loran-C/eLoran in other parts of the world. There is an ongoing discussion of the future of the system, since it is more robust to jamming than for example GPS. Even if the status and future of the system is unclear, an analysis is still included in this report.

In [11] the technical characteristics of Loran-C are given and the unwanted field strength at the Loran-C receiver may have to be below 23 dB(µV/m) to prevent interference. This corresponds to a magnetic field strength of -28.5 dBµA/m in the far field.

For the frequency interval 90-130 kHz, the maximum permissible interference at 10 metres distance is 32.2 dBµA/m for the proposed CISPR limits [1].

The required separation distance in order to be under the permissible interference limit for Loran-C is about 100 metres, see Figure 5.2.

5.3 Non-directional beacon (NDB)

Non-directional beacon (NDB) is used for navigational aid and a radio signal is transmitted by a transmitter at a known location. NDB provides a way to guide aircrafts and is a complement to other instrument landing systems working at a higher frequency, such as VOR, ILS etc. Due to the low frequency, the range of the system is often longer than for other navigation systems at fixed positions.

Working party 5B in ITU has provided information about the NDB systems [12] as an input to the groups working with WPT in ITU. The frequency range for NDB systems is 130-535 kHz and the permissible interference limit is 21.9 dBuV/m. The corresponding magnetic field strength, in the far field, is -29.6 dBµA/m.

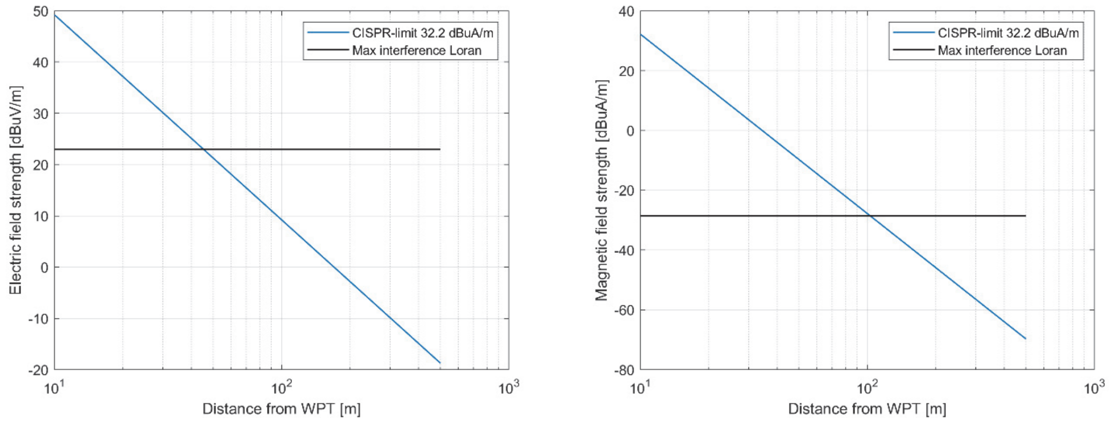

Figure 5.2: Permissible interference for Loran-C and emission from WPT from proposed CISPR limit.

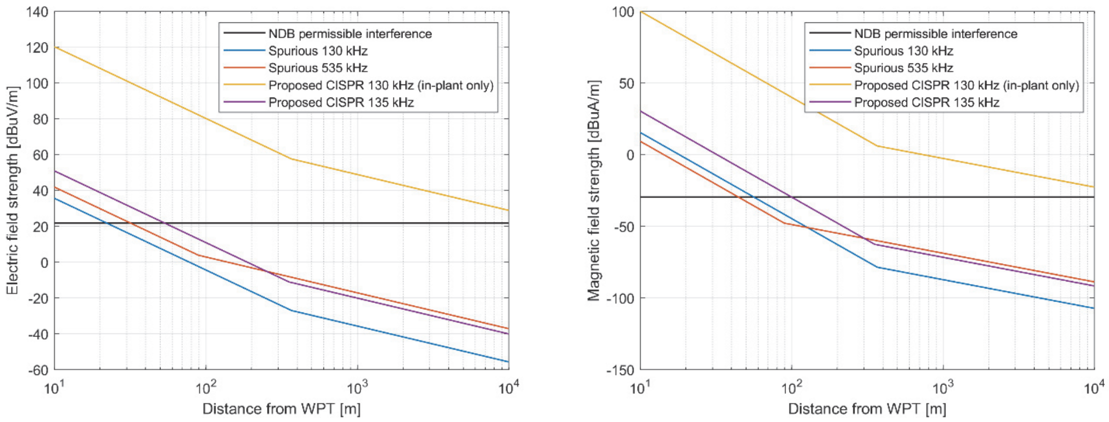

Figure 5.3: Permissible interference for NDB and interference from WPT systems fulfilling different standards.

For WPT systems using a frequency below 100 kHz, the frequency band for NDB is in the spurious domain for a WPT system. The maximum emissions are given in [2, 3] and described in Section 3.2.1. Since the limit varies with frequency, the limits are calculated for the highest and lowest frequency in the NDB-band. The limit is set for a distance of 10 metres from the WPT system.

The frequency range 130-135 kHz is proposed to be used for in-plant transportation systems. In the proposed new version of CISPR 11 [1], the level is 100 dBµA/m in that band at 10 metres distance, for a Class A system with high power. For 135-150 kHz, the limit is 30.4-30.0 dBµA/m.

The attenuation as a function of distance is described in Section 3.3. In the near field we assume that the H-field attenuates 60 dB/dec. For the far field, the attenuation is assumed to be 20 dB/dec. The transition from near field to far field depends on the frequency.

Figure 5.3 shows the different emission limits at 10 metres distance and the decay with distance. The permissible interference limit for NDB protection converted to magnetic field strength is also shown. If the interference is a spurious emission from a WPT system at a frequency below 100 kHz, the distance from the WPT should be over 60 metres. For a WPT system working in the frequency band 130-135 kHz, and a NDB system within the same frequency range, a much larger separation distance is needed (over 10 kilometres). If the NDB use a frequency outside the in-plant WPT band, a separation of 100 metres is sufficient. If the WPT system is inside a plant, there might be additional attenuation from the building etc.

5.4 Differential transmissions for global navigation satellite systems from maritime beacons – DGNSS

Differential Global Positioning Systems (DGPS) are enhancements to the Global Positioning System (GPS), which provide improved location accuracy. The service is recognized as a safety service by the ITU [13].

In Recommendation ITU-R M.823-3 (page 16-17) [14] the technical characteristics of the system are given. The receiver frequency range is 283.5 – 325 kHz and the receiver dynamic range is 10 – 150 uV/m. The protection ratio is 15 dB for no frequency separation (table 5 page 17 in [14]).

The reception of the DGNSS signal can be assumed to be in the far field. The lowest E-field captured by the most sensitive receiver is 10 µV/m, corresponding to a magnetic field strength of 0.0265 µA/m (−31 dBµA/m). With a protection ratio of 15 dB, the maximum allowed magnetic field strength of an interfering signal is −46 dBµA/m.

The frequency band for DGNSS is the spurious domain for a WPT system. The maximum emissions are given in [2, 3] and described in Section 3.2.1. Since the limit varies with frequency, the limits are calculated for the highest and lowest frequency in the DGNSS band. The difference is however small.

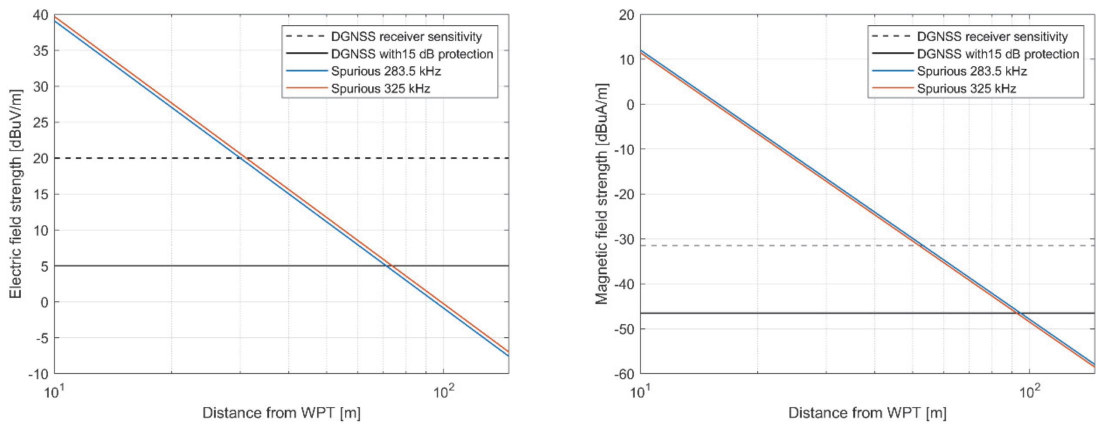

Figure 5.4: Magnetic field strength for spurious emissions as a function of distance from WPT. Limits for DGNSS are also shown.

The limit is set for a distance of 10 metres from the WPT system. In the near field we assume that the H-field attenuates 60 dB/dec. For a frequency of 325 kHz, the near field limit ($\lambda/2\pi$) is 146 metre.

The magnetic field strength of the spurious emissions as a function of the distance to the WPT is shown in Figure 5.4. At a distance shorter than 50 metre there is a risk that the spurious emissions are stronger than the receiver sensitivity. When the protection criteria for DGNSS is applied, there is a risk that the level is exceeded for distances shorter than 100 metre.

5.5 Military communications in the VLF and LF bands

The frequency band 15-45 kHz is used for long range military communications. The frequency band 19-25 kHz is proposed to be used for WPT-systems with high power levels [1]. Therefore, emissions from these WPT-systems may disturb the reception.

6. Summary and conclusions

In this report we evaluated the effects of emissions from WPT-EV systems. As a base for the analyses, we assumed that the WPT systems just fulfil the various emission requirements. However, these standards might still be adjusted for WPT-EV applications and permit higher values. First the interference level from one or several Class A and B WPT-systems was compared to the level of atmospheric noise. Then the effects of interference from WPT systems on different radio services were analysed.

For atmospheric noise the necessary propagation distance to attenuate the emission from sources placed at a certain geographical position is derived. For example, if 500 high power sources using 85 kHz are placed in the middle of Gotland, then a large part of Scandinavia, the Baltic countries and central Europe may experience an increased noise level due to the emission. For 20 kHz with 500 sources placed in Malmö an increased noise level can be expected in Copenhagen and from Falsterbo to Löddeköpinge. Table 6.1 shows the distance where the emission from different WPT sources equal the atmospheric noise for 1, 10 and 500 sources.

Table 6.1: The distance when the emission from WPT equals the atmospheric noise level (see chapter 4).

Number of sources	Distance (metre)			
	20 kHz		85 kHz	
	Class A	Class B	Class A	Class B
1	1 820	243	327 000	14 000
10	4 410	432	518 000	44 300
500	31 200	1 150	992 000	224 900

For the spurious emissions in the HF-band, the distance needs to be 500-1000 m for the emission from one WPT-EV source to equal the noise level for the ITU category with the highest man-made noise (i.e., City) for frequencies 5-10 MHz. For the quiet rural category, the distances are over 10 km long.

The effects of interference from WPT systems on different radio services were studied. To determine the interference distance, the range outside in which no harmful interference will occur was used. The analyses are based on proposed or existing emission limits for the WPT-system and protection criteria for the radio services. This level depends on the minimum signal level that an affected radio service can handle.

For the strictest protection criteria, a high WPT Class A source at 20 kHz must be located at least 5 km from the SFTS service when the systems use the same frequency. However, when the WPT interferes at a frequency 10 kHz from the SFTS service then the needed distance is about 900 m. The same situation for 85 kHz, and a high power WPT, gives a much harder situation, which requires an interference distance of almost 60 km when using the same frequency and 3.4 km when the WPT interferes at a frequency 10 kHz from SFTS. In Europe one of the SFTS signals, DCF77, operates in 77.5 kHz. As an example, a WPT system using the frequency 80 kHz is analysed. This gives a frequency separation of 2.5 kHz for protection of SFTS and a distance of 15 km would be necessary for a high power Class A WPT system, and 1.5 km for a powerful Class B system. These distances are long for a service that is used by the public in the homes where WPT-systems could be used quite close to a SFTS receiver.

Another analysed radio service is Loran-C, which is a radio navigation system with a large coverage area. The system is not widely used today and in many countries replaced by other navigation systems. Even if the status and future of the system is unclear an analysis is still included in this report, because it is more robust to jamming than for example GPS. The required separation distance for the interference to be under the permissible interference limit for the Loran-C system is about 100 metres in the frequency band 90-130 kHz.

NDB is used for navigational aid and a radio signal is transmitted by a transmitter at a known location. NDB provides a way to guide aircraft and is a complement to other instrument landing systems working at a higher frequency, such as VOR, ILS etc. Due to the low frequency, the range of the system is often longer than for other navigation systems at fixed positions. The frequency range for NDB systems is 130-535 kHz. For WPT systems using a frequency below 100 kHz, the frequency band for NDB is in the spurious domain for a WPT system. For such interference, the separation distance to the WPT should be just over 60 metres. If WPT is working in the frequency band 130-135 kHz (for in-plant WPT) and a NDB system uses the same frequency, then a large separation distance is needed (over 10 kilometres). If the NBD uses a frequency outside of the in-plant WPT band, then a separation distance of 100 m is sufficient.

DGPS is an enhanced GPS service, which provides improved location accuracy. The frequency band for DGNSS (283.5 – 325 kHz) is the spurious domain for a WPT system. At a distance shorter than 50 metre there is a risk that the spurious emissions are stronger than the receiver sensitivity, and when the protection criteria for DGNSS is applied there is a risk that the level is exceeded for distances shorter than 100 metre.

The frequency band 15-45 kHz is used for long range military communications and emissions from WPT-systems may disturb the reception.

The overall conclusion is that radiated emission from WPT may cause non-negligible interference impact on radio-based services.

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FOI
Defence Research Agency
SE-164 90 Stockholm

Phone: +46 8 555 030 00
Fax: +46 8 555 031 00

www.foi.se