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Technical report

Peter Stenumgaard

Radiated Emission Limits to Protect Digital Wireless Communication Systems

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Radiated Emission Limits to Protect Digital Wireless Communication Systems

Abstract (not more than 200 words)

Present international limits for maximum levels of unintentional radiated emission from electronic devices are developed to protect analog communication services. The international standardisation work to develop such limits to protect digital communication services has been slow in progress. One technical difficulty is to decide what measurement detector to use to verify that given limits are met. The difficulty has been to find a measurement detector with a response that is proportional to the disturbance effect on a digital communication system subjected to the measured disturbance signal. Within the VOLGA project the RMS (Root-Mean Square) detector has been proposed, which has created great interest in the international standardisation authority CISPR (International Special Committee on Radio Interference). Therefore, the results from the VOLGA project have been incorporated in the CISPR activity within the area. The problem is important for the Swedish defence since it is necessary to be able to handle emission limits on COTS (Commercial off the Shelf) co-located with digital wireless communication systems.

In this report, a complete proposal of emission limits is put forth for the RMS detector. This is done by considering a number of modern digital communication services as well as developing a co-location scenario where disturbing electronics is located in the vicinity of a modern digital communication system. The emission limits determined falls below the present levels for commercial electronics but above the present limits for military specified electronics.

Keywords
Digital wireless communication, radiated disturbance, emission limit, RMS detector, limits, bit error probability

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Gränsvärden på strålad emission för att skydda digitala trådlösa kommunikationssystem

Sammanfattning (högst 200 ord)

Existerande internationella gränsvärden för maximalt strålad oavsiktlig elektromagnetisk emission från elektronik är anpassade för att skydda analoga kommunikationstjänster. Det internationella standardiseringsarbetet för att utveckla dessa gränsvärden till att skydda digitala kommunikationstjänster har än så länge gått långsamt. En teknisk svårighet är att besluta sig för vilken mätdetektor som skall användas för att verifiera att givna gränsvärden uppfylls. Svårigheten har varit att finna en mätdetektor vars utslag är proportionell mot den störningspåverkan en störningssignal har på ett digitalt kommunikationssystem som utsätts för den uppmätta störningssignalen. Inom projektet VOLGA har Root-Mean-Square (RMS)-detektorn föreslagits vilket väckt stort intresse inom det internationella standardiseringsorganet CISPR (International Special Committee on Radio Interference). Resultaten från VOLGA har därför inkorpererats i CISPR:s arbete inom området. För totalförsvaret är denna fråga väsentlig att lösa för att kunna handskas med emissionskrav på COTS (commercial off the shelf) som samlokaliseras med trådlösa digitala kommunikationssystem

I denna rapport har ett komplett förslag på gränsvärden tagits fram för RMS-detektorn. Detta har gjorts genom att ta hänsyn till ett antal moderna digitala kommunikationsstandarder samt genom att ta fram ett samlokaliseringsscenario där störande elektronik placerats i närheten av ett modernt digital kommuniaktionssystem.

De framtagna gränsvärdena ligger nivåmässigt lägre än dagens befintliga gränsvärden för kommersiell elektronik men över de nivåer som gäller för militära emissionsstandarder.

Nyckelord
Digital trådlös kommunikation, strålad störning, emissionskrav, RMS-detektor, gränsvärden, bitfelssannolikhet

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1 Background

This report summarizes the work performed in part 1 “VOLGA” of the project “VOLGA/EMS 2004-2005”, FMV 272264-LB649849, 2004-04-13. Part 1 consists of the following two tasks:

- Investigation of which types of communication systems/co-location scenarios should have the greatest influence of how radiated emission limits are designed.
- Production of a proposal of radiated emission limits consisting of electric field strength, frequency range and measurement bandwidth, based on the results in task 1.

The problem overview is shown in Figure 1. The goal is to define emission limits when the RMS (Root-Mean Square) detector is used in the measurement system. The RMS detector delivers $\sqrt{\mathrm{E}\left\{n^2(t)\right\}}$, where *n(t)* is the level of the signal at the detector input. (The operator E denotes the mean value.) The emission limit shall guarantee that the bit error probability in the digital radio system will not exceed a specified value. The rationale for this research is that the standard detectors used today do not give a response that is proportional to the disturbance effect in terms of bit error probability on digital radio systems. Earlier research results [3][5][9][10][13] within the VOLGA project show that the RMS detector gives a response that can be related to the disturbance effect on digital radio systems. In order to solve this problem, a set of prioritised digital communication services to be protected must be selected. This is for instance necessary in order to choose relevant measurement bandwidths and frequency bands for future emission standards. These selections are done in Task 1. Based on these selections, emission limits are calculated in Task 2. The report is organized as follows.

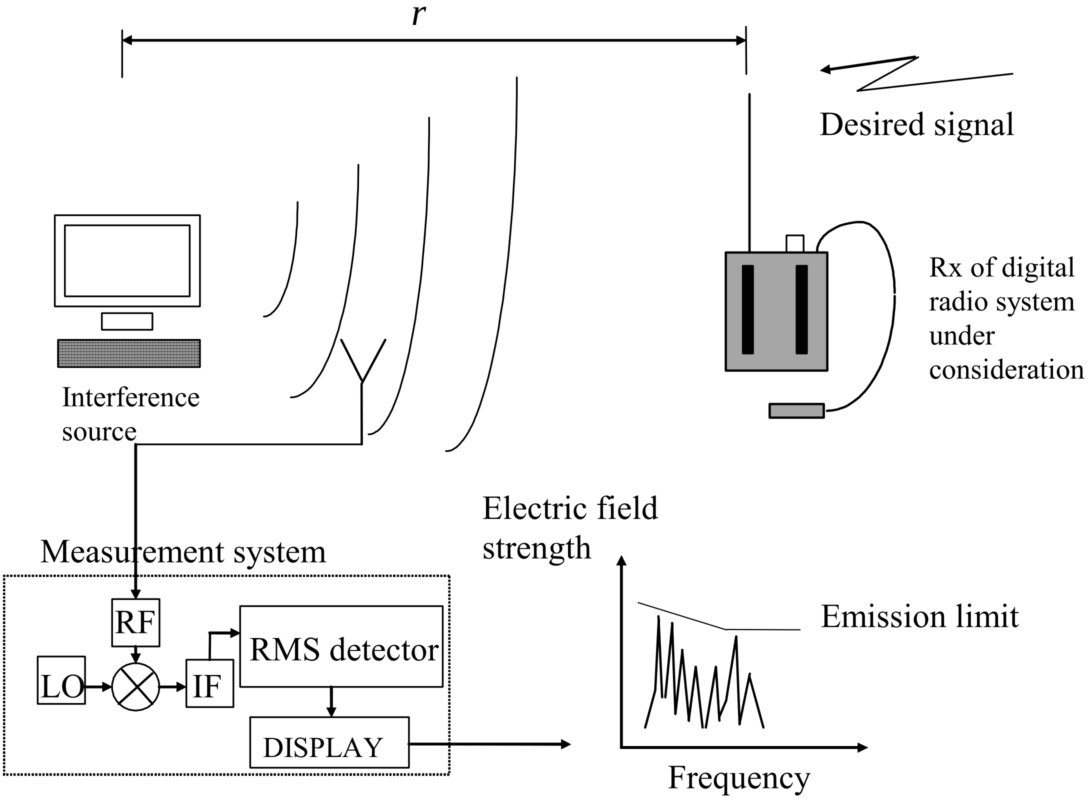

Figure. 1: Problem overview

After an introductory section in Chapter two, the results for the two tasks are presented in Chapters three and four. The emission limit proposed is summarized in chapter five. Conclusions are drawn in Chapter six and suggestions for future research are given in Chapter seven.

2 Introduction

Emission standards date back to the 1920s, when broadcasting services started to reach the general public. Quite soon it became evident that control of the generation of electrical noise and similar man-made disturbances was essential in order to guarantee a good quality of the new broadcasting services. However, imposing limitations on electrical equipment and household appliances could cause trading problems if different countries applied significantly different norms. This problem was soon realized on international level, which led to the foundation of the International Special Committee on Radio Interference (CISPR) in 1934. The International Electrotechnical Commission (IEC) and the International Telecommunication Union (ITU) were cofounders [1]. The first goal was to reach an agreement on measurement procedures. This work was carried out during the 1930s. There after, the work of developing standard emission limits could start. The first standard produced was at a national level when the BS613 (1935) concerning components for radio disturbance suppression devices was published in England. In 1937, the BS727 concerning characteristics of an apparatus for measuring of radio disturbance was published. This standard had a major impact on the standardization work within CISPR. The CISPR Publication No. 1 including the characteristics of a measurement receiver and certain design features was published in 1961. Current measurement procedures and detectors are actually based on the work carried out in the standardization organizations during 1930 – 1939. It was during this time period the quasi-peak detector was defined for the frequency range 160 - 1605 kHz. Thus, present commercial emission standards are developed to protect analog communication services. These standards still use a measurement detector, i. e. the quasi-peak detector, which captures the human perception of electromagnetic (EM) disturbances on analog radio receivers [1]-[2]. However, this detector is not adequate to capture the effect of EM disturbances on digital radio receivers.

An approximate method of estimating the impact on digital communication systems, if the disturbance has been measured with a quasi-peak detector, has been presented in [3] and [4]. This method can be used for system design purposes until new emission standards considering digital communication systems have been developed. The work of developing measurement procedures considering a digital radio receiver as a disturbance victim has started both in CISPR and ITU-R [6]. This work is summarized in [2][11]. This is a very complex problem since there is an ever growing variety of digital modulation and coding schemes to consider as the area of digital communication services undergoes a rapid development. However, to find a solution is necessary in order to protect these services against radiated electromagnetic emission. One approach [2][11][12] is to create a new type of weighting detector, representing the disturbance effect on digital radio receivers. Thus, this approach is similar to the strategy behind the development of the quasi-peak detector. So far, the progress in this work has been slow. An alternative approach is presented in [9][10][14][18] and is based on the idea of using an already existing standard detector, namely the RMS detector. Up to now, the RMS detector has not been used in EMI measurements even if the 2nd edition (1972) of CISPR 1 [8] says that experience has shown that an RMS voltmeter might give a more accurate assessment of the interference effect on analog radio than the quasi-peak detector does.

The results to be presented in this report are based on the same fundamental assumptions that are used in the previous CISPR/ITU work [2]:

- The bit error probability (BEP) is the performance parameter of interest for the digital communication system.
- The repetitive pulsed disturbance is the waveform of particular interest.

- The disturbance pulses have a pulse duration that is short compared to the digital symbols transmitted.

The classical model of a digital communication system is shown in Figure 2.1. The output information from the analog source is coded into binary symbols by the source encoder. In the channel encoder redundancy symbols (error correcting code) are added to allow the receiver to correct a certain amount of errors arisen during transmission on the radio channel. The modulator transforms the digital symbols into analog waveforms appropriate for transmission over the channel. In the receiver the opposite procedures are performed until the user gets the information. The BEP is the probability that the digital receiver makes an error in the decision of what kind of data bit has been received (e. g. whether the transmitted data bit was a “0” or a “1”). In [9][10] a relation between the RMS value of the disturbance signal and the corresponding BEP is presented for digital communication systems that do not use error-correcting codes.

The question of how error-correcting codes should be considered in the development of future emission standards is open. Another way of describing this question is if the BEP at receiver location 1 or 2 in Figure 2.1 should be used as performance measure when emission limits are chosen. There are arguments to consider only the uncoded case (or location 1). Firstly, error-correcting codes are normally designed to handle other disturbance problems than unintentional disturbance from co-located electronic equipment. Such problems could include varying quality of the radio channel such as multipath fading or other wave propagation effects. In military applications jamming could be one of several severe problems to be handled by the error correcting code. The error-correcting code is therefore designed to handle certain

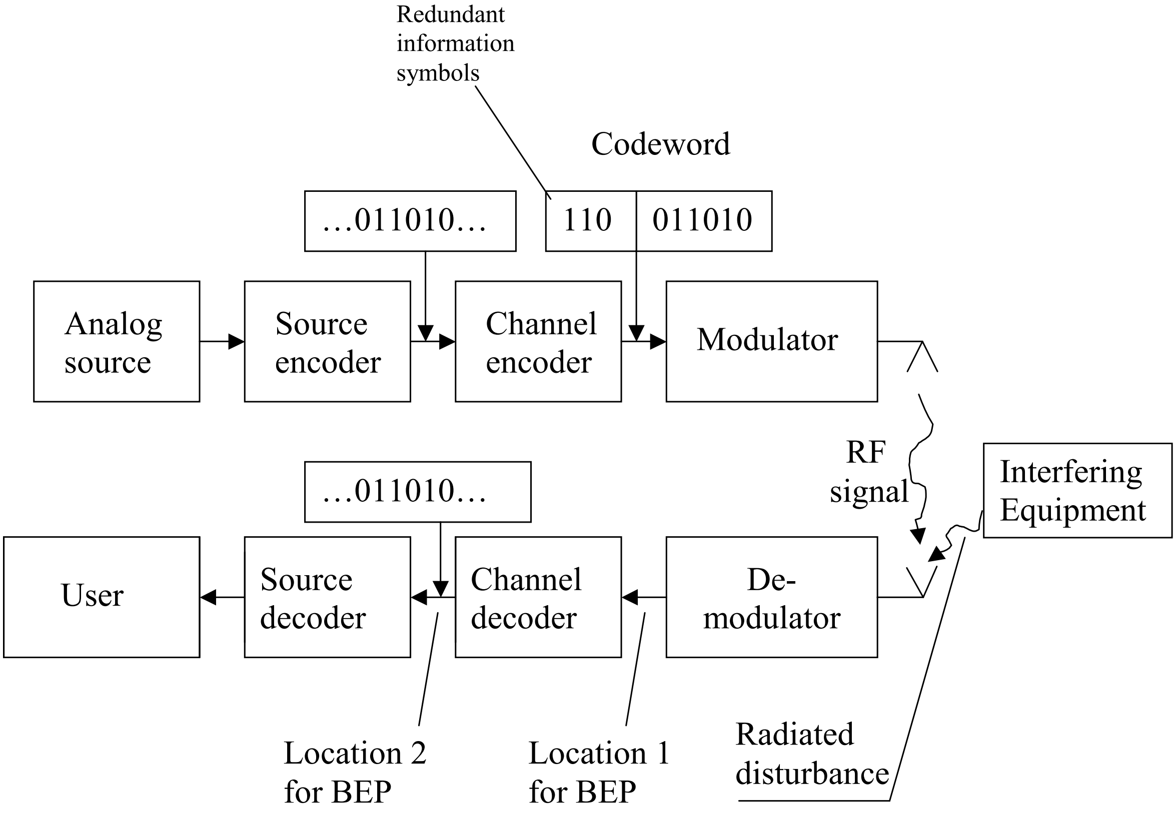

Figure. 2.1: The classical model of a digital communication system.

combinations of disturbance parameters corresponding to the expected most difficult disturbance problem. Therefore, taking error-correcting code capacity into account in the case of protecting the system against unintentional disturbance from co-located electronics is risky. This is because it is unclear how the result should be interpreted as it is not obvious how the degradation of the error-correcting code should be considered. Secondly, if the BEP is measured *after* error correction (location 2), we will not know how much of the code capacity has been used for correcting errors caused by co-located disturbance. This means that even if the BEP for a disturbed system is at an acceptable level, the system performance has been degraded in an uncontrolled manner since an unknown amount of the error correcting capacity has been used. In other words; the “reserve” intended to be used for other disturbances on the radio channel is now already used for co-located interference. A consequence could for instance be that the disturbance from co-located electronics leaves no error-correcting capacity to handle other disturbance problems caused by the varying radio channel.

On the other hand, in practical applications it is normally very difficult to modify existing systems so that the BEP before error correction can be determined. This speaks for the use of the BEP in location 2 for the design of emission limits. Consequently, it is of great importance if a relationship between the RMS-detector response and the impact, in terms of BEP, on a system using error-correcting codes is known. With this knowledge, emission limits based on the BEP after error correction can be determined. That has therefore been developed in earlier work of VOLGA and is presented in [15][16].

3. Sub part 1: Selection of communication systems/co-location scenarios

All radiated emission standards specify the measurement bandwidths to be used. Current standards specify bandwidths which have been chosen to represent older analog communication systems. Furthermore, all standards are based on a certain co-location scenario where a certain amount of interference has been considered acceptable for the analog service considered. In this section a co-location scenario for electronic devices in the vicinity of digital communication system is chosen as a basis for the coming derivation of acceptable radiated emission limits. By considering the bandwidths of modern digital communication systems, a selection of new measurement bandwidths is proposed. The current measurement bandwidths in the CISPR standard EN55022 are shown in Table 3.1 [17].

Frequency range	**Bandwidth**
30 MHz - 1000 MHz	120 kHz*)
1 GHz - 18 GHz	1 MHz or more**)

Table 3.1: Measurement bandwidths according to EN55022.

*) 6 dB bandwidth [7]
**) Proposed impulse bandwidth (equal to 1.065 times the 6 dB bandwidth) under discussion. EN55022 is not yet extended to measurements at frequencies above 1 GHz.

The choice of measurement bandwidths for the RMS detector is done considering some selected wireless standards presented in Table 3.2. Since the dynamic range in channel bandwidths in Table 3.2 is large, it is not convenient to use only one measurement bandwidth for each frequency range.

Standard	**Frequency range (MHz)**	**Channel bandwidth**	**Peak data rate**
TETRA	380-383, 390-393 for emergency systems in Europe. 410-430 MHz, 870-876 MHz / 915-921 MHz, 450-470 MHz, 385-390 MHz / 395-399.9 MHz for civil systems in Europe	25 kHz, 50 kHz, 100 kHz, 150 kHz.	54 kbit/s 8 PSK/25KHz, 864 kbit/s 64 QAM/150 kHz
DVB-T	175-230 470-802	6 MHz, 7 MHz, 8 MHz	3.73-31.67 Mbit/s
DAB	223-230 (1452-1492)	1.536 MHz	0.6-1.7 Mbit/s
GSM 900	890-915 (uplink) 935-960 (downlink)	200 kHz	14.4 kbit/s 53.6 kbit/s (GPRS) 384 kbit/s (EDGE)
GSM 1800	1710-1785 (uplink) 1805-1880 (downlink)	200 kHz	14.4 kbit/s 53.6 kbit/s (GPRS) 384 kbit/s

			(EDGE)
IMT-2000 3GPP/FDD	1920-1980 (uplink) 2110-2170 (downlink)	5 MHz	2Mbit/s 10 Mbit/s (HSDPA)
Bluetooth	2402-2480	1 MHz	723.3 kbit/s
DECT	1880-1900	1.728 MHz	1152 kbit/s
IEEE 802.11b,g	2400-2483.5	20 MHz	11 Mbit/s (b) 54 Mbit/s (g)
IEEE 802.15.3a (UWB)	3168-4752 or 3100-5150	503.25 MHz, 1368 MHz, 550 MHz	<55 Mbit/s
Hiperlan/2	5000	20 MHz	<54 Mbit/s
IEEE 802.16	10000-66000	28 MHz	134 Mbit/s
JTRS (military)	2-2000	5 MHz	5 Mbit/s

Table 3.2: Channel bandwidths of some standardized wireless services.

If the difference between the measurement bandwidth and system bandwidth is too large, the correlation between the measured result and the corresponding interference impact on the system will be weak. Of course there is always a disadvantage to use more than one measurement bandwidth since it will increase the total measurement time. On the other hand, the usefulness of the measurement increases if at least two sets of measurement bandwidths are used. We should also have in mind that older legacy systems will exist in parallel to all new digital communications systems why the measurements must be useful even for the older systems. Therefore, two sets of measurement bandwidths are proposed for future emission measurements. The two sets are denoted narrow band (NB) and broad band (BB). The proposed bandwidths are shown in Table 3.3.

Frequency range	Bandwidth NB	Bandwidth BB
30 MHz - 230 MHz	200 kHz	1 MHz
230 MHz - 1.9 GHz	200 kHz	5 MHz
1.9 GHz - 18 GHz	1 MHz	20 MHz

Table 3.3: Proposed measurement bandwidths.

The shift at 1.9 GHz is due to the allocated frequencies for GSM and UMTS. The co-location scenario is chosen according to Figure 3.1 and 3.2. The interference source is located in a structure without any electromagnetic shielding effectiveness. The co-location distance is chosen to 10 m as reference distance for the emission limits. This distance is chosen so that the results can be compared to the current limits in EN55022 since the latter are defined for 10 m. We assume that the radio communication system has a BEP of approximately 10^{-5} in the undisturbed case (Figure 3.1). The radiated disturbance is allowed to increase the BEP to approximately 10^{-3} (Figure 3.2). We use the modulation scheme *binary phase shift keying* (BPSK) as a reference scheme for our calculations. The BEP is measured after decoding for low interference pulse repetition frequencies but before decoding for high interference pulse repetition frequencies, see Chapter 4.

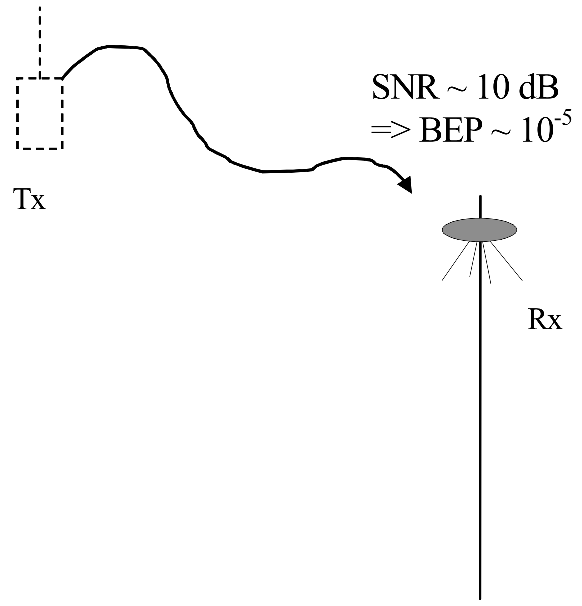

Figure 3.1: Co-location scenario without radiated emission from COTS.

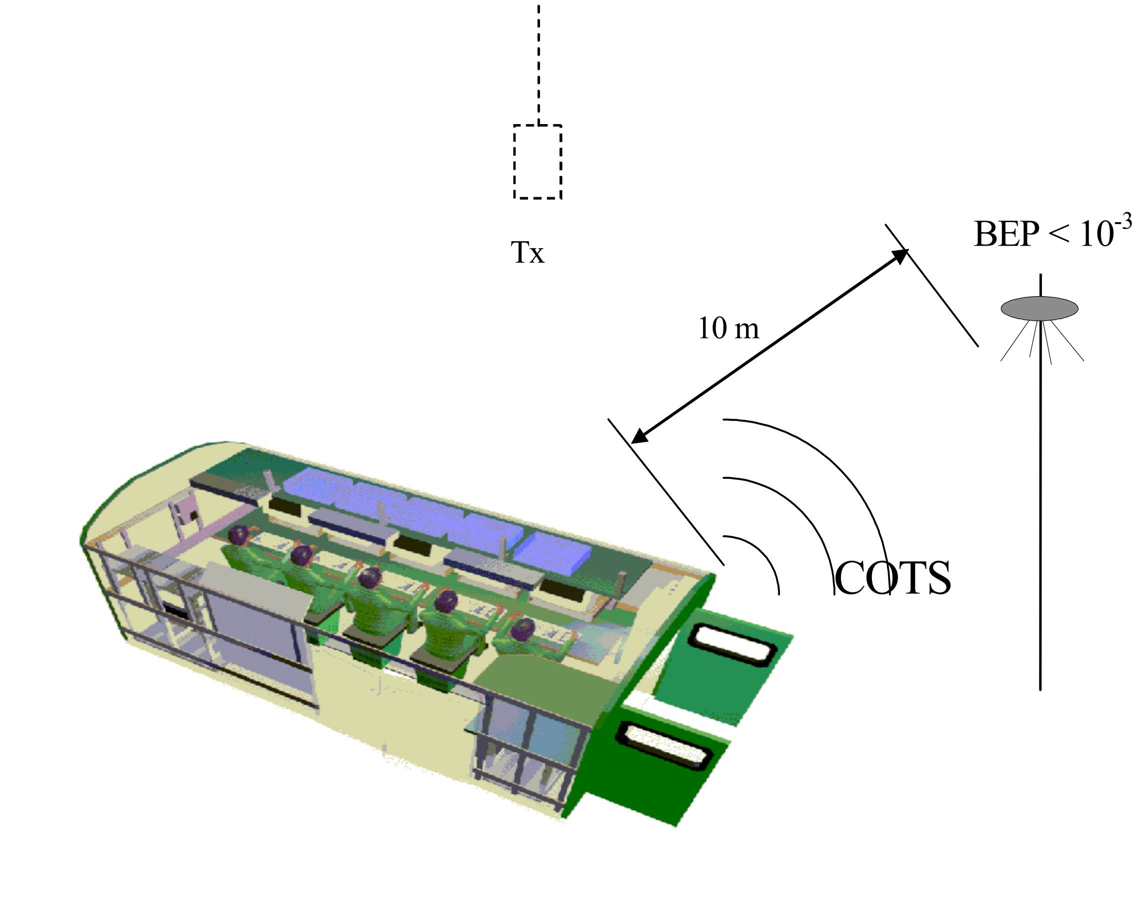

Figure 3.2: Co-location scenario with radiated emission from COTS.

4. Sub part 2: Emission limits for the RMS detector

Earlier research has shown [16] that the performance of digital communication systems, which are well protected with error-correcting codes, is related to the RMS value of a repetitive pulsed signal (Figure 4.2). Furthermore, this relation is very simple as the RMS value corresponding to a certain BEP, p_0, is approximately constant with respect to the pulse repetition frequency $1/T_P$ of the disturbance signal (for pulse repetition frequencies exceeding the symbol rate R_S of the digital radio system), see Figure 4.1. For pulse repetition frequencies $> R_S$, the RMS level is approximately the same as for additive white Gaussian noise (AWGN) ande sine-wave interference. This relation has been shown to be valid for several digital modulation schemes [9]. Thus, it is possible to determine the maximum allowed electric field strength, caused by repetitive impulsive signals, such that the BEP does not exceed a certain requirement. With this knowledge it is possible to amend present radiated emission standards to consider digital communication systems.

As mentioned above, whether the emission limit should be based on the coded or uncoded case is an open question. If we consider the coded case we can choose a constant emission limit according to Figure 4.3. This gives a safety margin (see the indicated margin area in Figure 4.3) for pulse repetition frequencies *below* the symbol rate of the communication system. If we choose to base a constant limit on the uncoded case according to Figure 4.4 this will result in a safety margin for pulse repetition frequencies *above* the symbol rate of the communication system. In Figure 4.5 a trade off between the uncoded and coded case is shown.

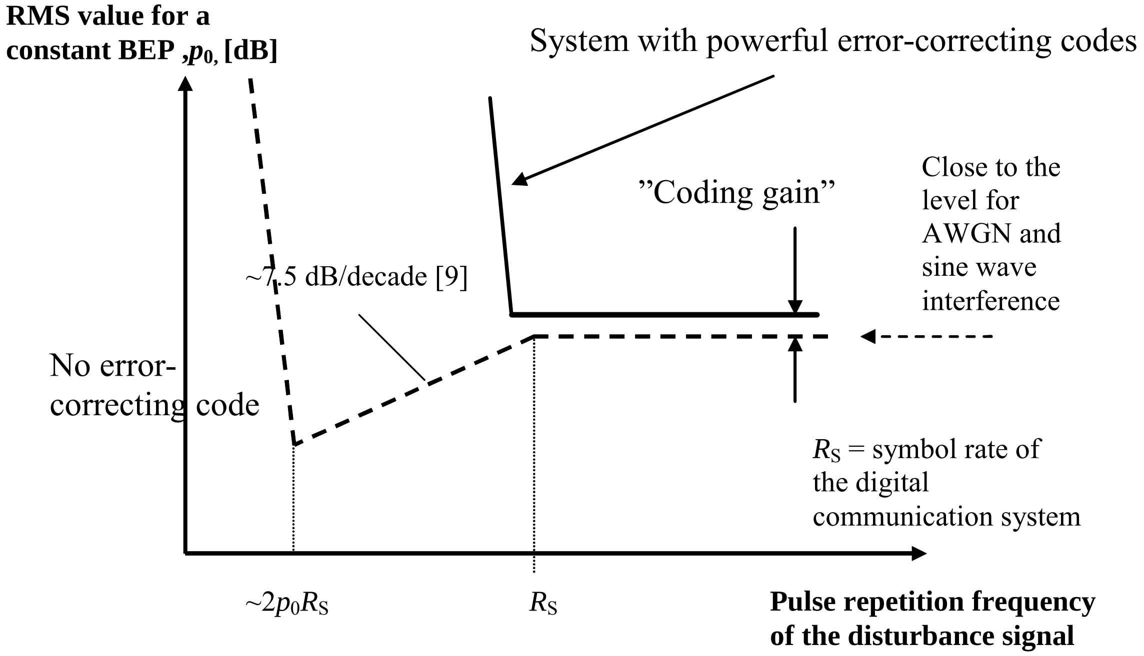

Figure 4.1: The principal relation between the RMS value, for constant bit error rate, and the pulse repetition frequency of the disturbance signal.

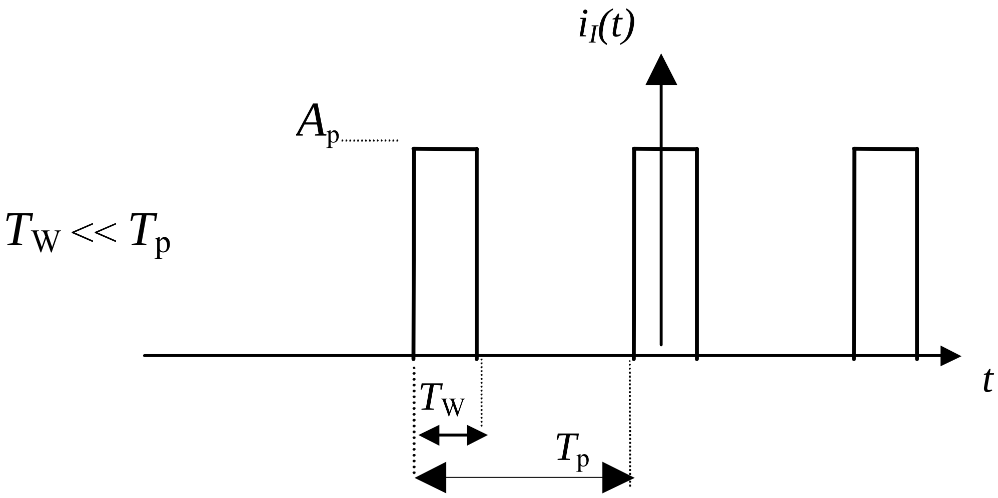

Figure 4.2: The pulsed repetitive disturbance signal (bandpass representation).

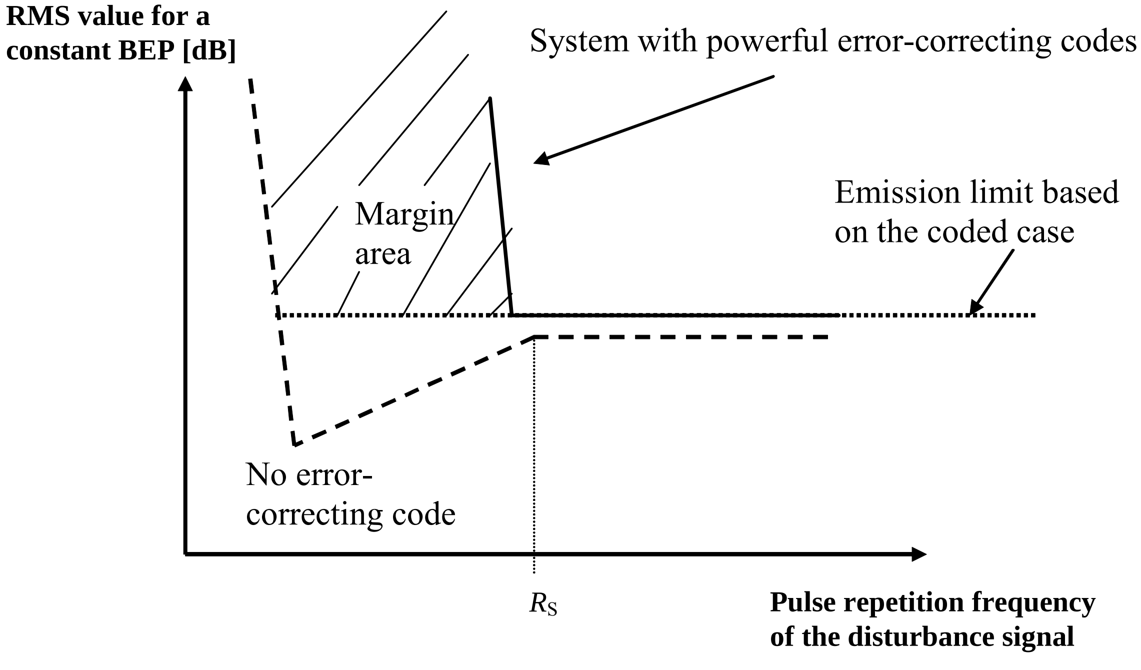

Figure 4.3: A possible choice of constant emission limit based on the system performance with error-correcting codes.

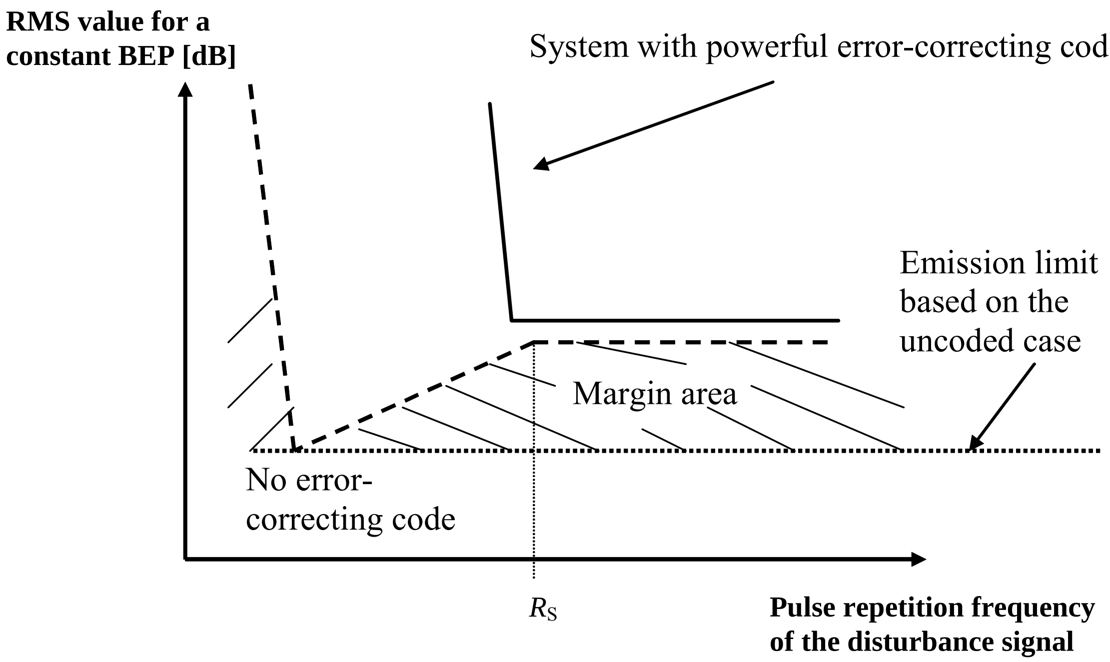

Figure 4.4: A possible choice of constant emission limit based on the system performance without error-correcting codes.

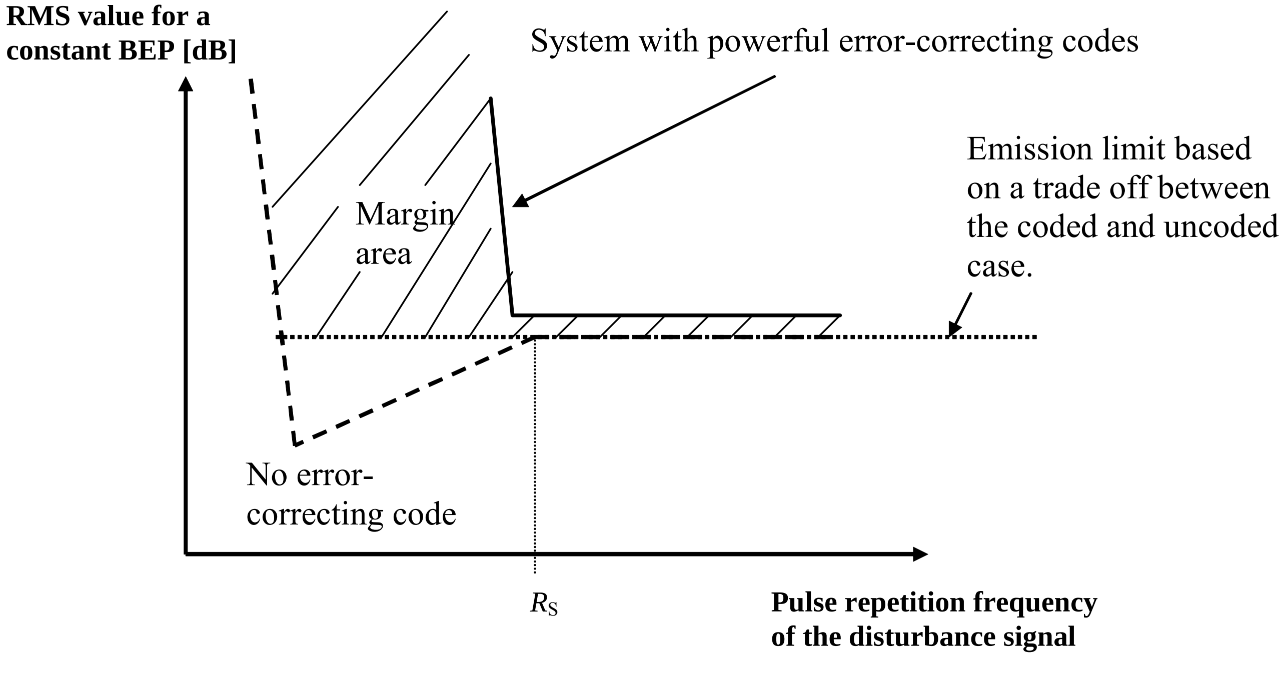

Figure 4.5: A possible choice of constant emission limit based on a trade off between the uncoded and coded case.

To clarify how Figures 4.1-4.5 are related to a certain BEP requirement, this relation is briefly shown below. The measured RMS-value V_{RMS} can be related to the electric field strength E_{R} of the interference by knowing the antenna and receiver properties of the measurement system. If the interference source is electrically small, far field antenna theory can be used. The received interference power, S_{I}, at the radio receiver input can then be estimated as

$$S_{\mathrm{I}} = \frac{\lambda^2}{4\pi Z_0} pqG_{\mathrm{R}} E_{\mathrm{R}}^2(r)\,, \tag{2}$$

where

λ	wavelength [m];
G_{R}	antenna gain of the radio receiving antenna in the direction to the interfering source;
p	polarization matching factor $0 < p \leq 1$;
q	matching factor between radio antenna impedance and load impedance, $0<q \leq 1$;
$E_{\mathrm{R}}(r)$	electrical field strength [V/m] of the radiated interference at the receiving radio antenna;
Z_0	wave impedance for free space (= 377 Ω);
r	separation distance between the undesired interference source and the radio receiver.

Knowing the receiver impedance it is possible to compute a relation $V_{\mathrm{RMS}}(S_{\mathrm{I}})$, since $V_{\mathrm{RMS}}(S_{\mathrm{I}}) \cong \sqrt{S_{\mathrm{I}}}$. The connection to the corresponding bit error probability is then established through standard equations. As an example we show how this connection is outlined for binary communication systems. It has been shown [4] that for pulsed interference, the bit error rate $P_{\mathrm{b}}(\gamma)$ is a function of

$$P_{\mathrm{b}}[\gamma] = P_b\left[\frac{E_{\mathrm{b}}}{N_{\mathrm{I}} + N_0}\right] = P_{\mathrm{b}}\left[\frac{E_{\mathrm{b}}}{\frac{1}{R_{\mathrm{b}}} S_{\mathrm{I}} + N_0}\right] = P_{\mathrm{b}}\left[\frac{E_{\mathrm{b}}}{\frac{1}{R_{\mathrm{b}}}\frac{\lambda^2}{4\pi Z_0} pqG_{\mathrm{R}} E_{\mathrm{R}}^2(r) + N_0}\right], \tag{3}$$

where E_{b} is the energy per data bit and N_0 is the single-sided power spectral density [W/Hz] of the internal noise level in the receiver. If the internal noise consists of thermal noise only, N_0 will be equal to kT, where k is Boltzmanns constant (=1.38×10^{-23} J/K) and T is the temperature in Kelvin. The bit rate of the communication system is R_{b} [bits/s], and the receiver bandwidth is approximately R_{b}. Furthermore, we define

$$P_b\left[\frac{E_{\mathrm{b}}}{N_{\mathrm{I}} + N_0}\right] = P_{\mathrm{b}}\left[\frac{E_{\mathrm{b}}}{\frac{1}{SIR} + \frac{1}{SNR}}\right] = P_{\mathrm{b}}\left[\frac{SIR \cdot SNR}{SIR + SNR}\right] \tag{4}$$

Parameter	**Value**
Noise figure [dB]	15
SNR [dB] (E_b/N_0) without radiated interference	≈10
SIR [dB] (E_b/N_I) with radiated interference	≈10
BEP with radiated interference	10^{-3}
Selected modulation	BPSK

Table 4.1: Selected system parameters for the calculated emission limits.

Thus via Equation (3) we can connect V_{RMS} to P_b. The function $P_b(\gamma)$ is the bit error probability for interference with additive white Gaussian noise (AWGN) without any error correcting codes. As an example Equation (5) shows $P_b(\gamma)$ for the modulation scheme BPSK.

$$P_b(\gamma) = \frac{1}{2} erfc\left(\sqrt{\gamma}\right). \tag{5}$$

Thus, γ is replaced with the expression inside the brackets in equation (3) if we want to consider the mix of thermal and radiated interference. The selected system parameters are shown in Table 4.1.

In Figure 4.6, the present emission limits are shown for EN55022 and RE102 (MIL-STD-461 D) at a distance of 10 meters from the electronic device under test (DUT). The emission levels in RE102 have been converted from 1 m to 10 m by assuming an $1/r$ -decay [3], where r is the distance from the disturbance source. For EN55022, the field levels for frequencies above 1 GHz are from [19][20]. In Figures 4.8-4.9, the maximum allowed electric field strength has been calculated for the measurement bandwidths (Table 3.3) and system parameters (Table 4.1). This field strength is compared to the present levels in Figure 4.6. As can be seen, the calculated limit for the RMS detector is somewhere between the levels in EN55022 and RE102. The emission limit is based on the uncoded case for large pulse repetition frequencies, which corresponds to the coded case without taking any advantage of the “coding gain”. In Figure 4.7, it is shown how the emission limit has been chosen for the calculated results. In Figure 4.10, the electric field strength has been calculated for the RMS detector using the current measurement bandwidths specified in EN55022. As seen, the result is comparable with the proposed for the NB case.

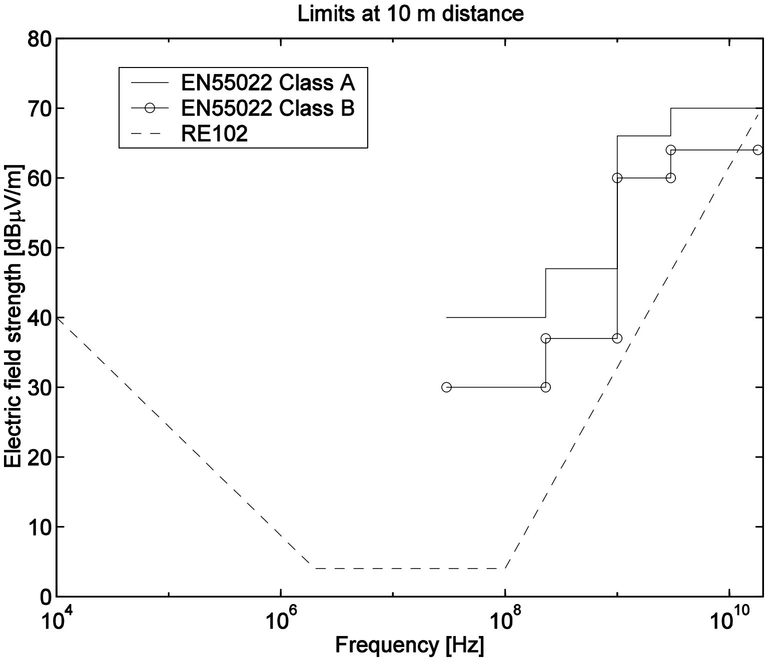

Figure 4.6: Standard radiated emission limits at 10 m distance.

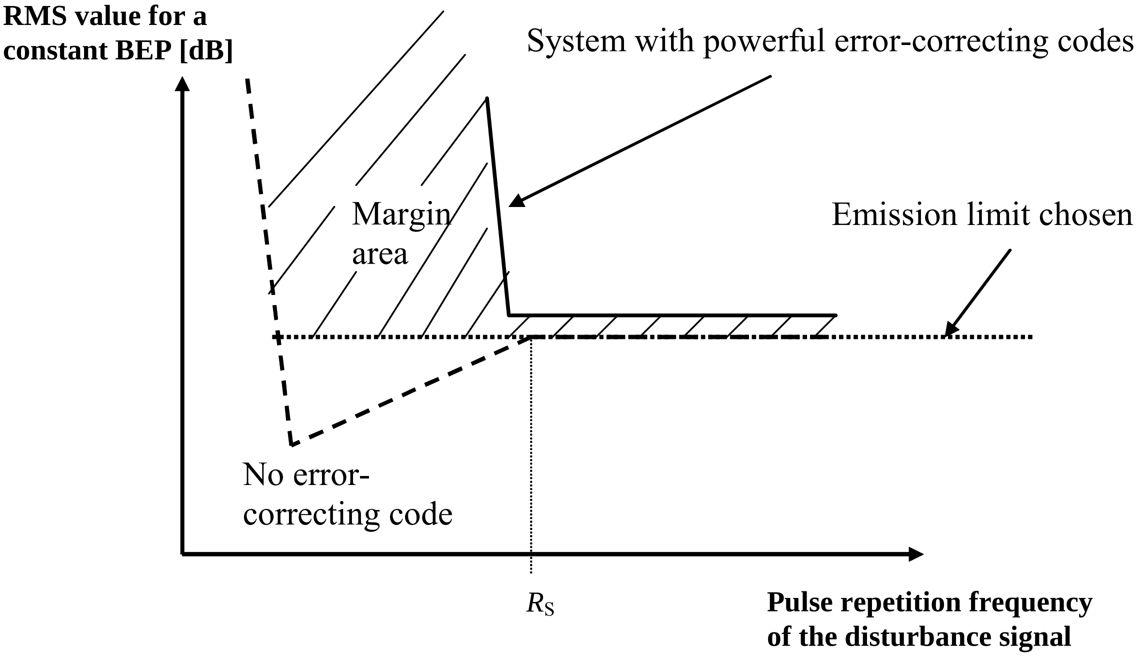

Figure 4.7: Emission limit choice for the calculated results.

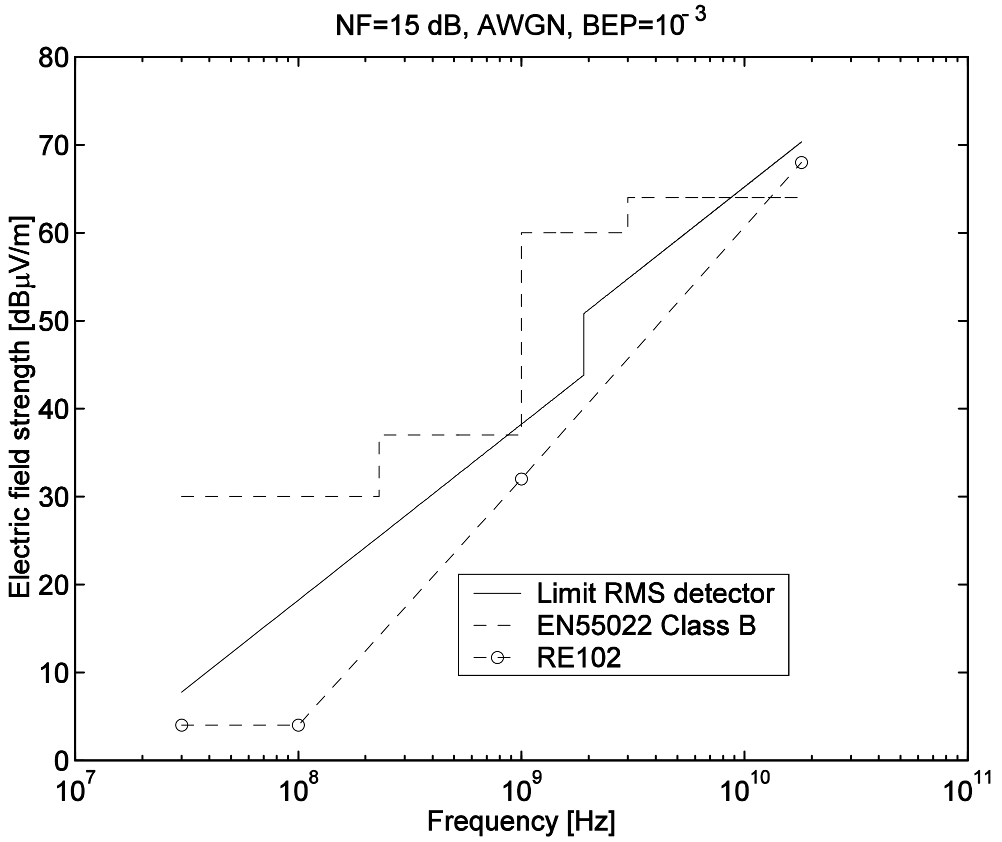

Figure 4.8: Emission limit for the NB case at a distance of 10 m.

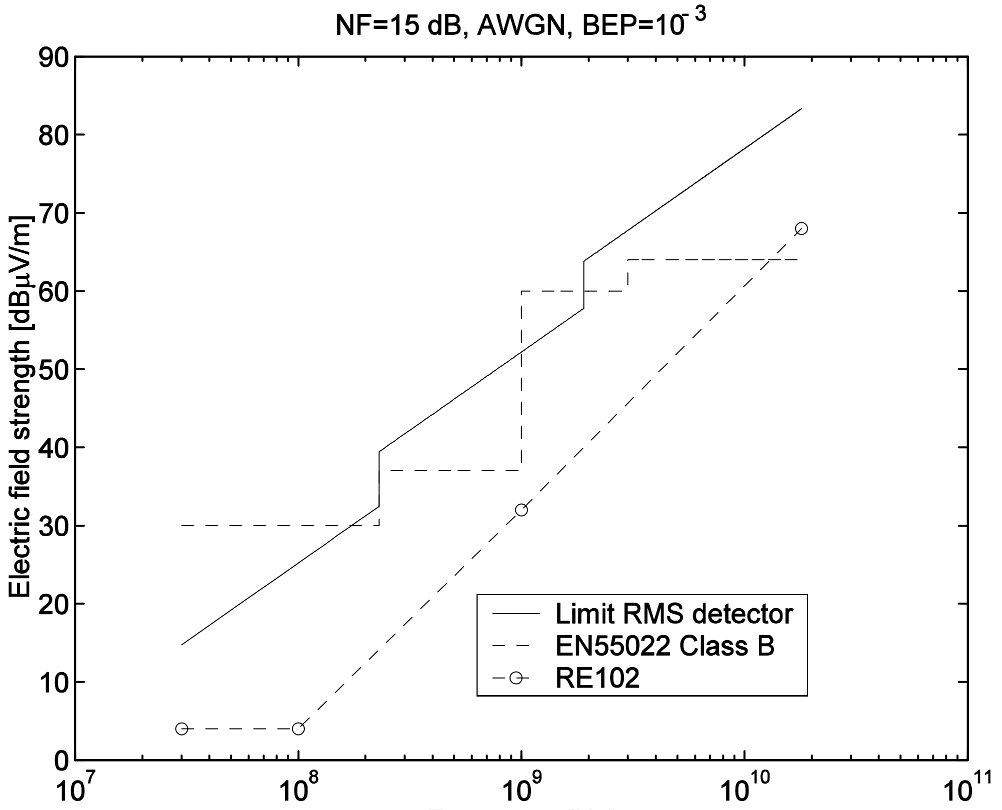

Figure 4.9: Emission limit for the BB case at a distance of 10 m.

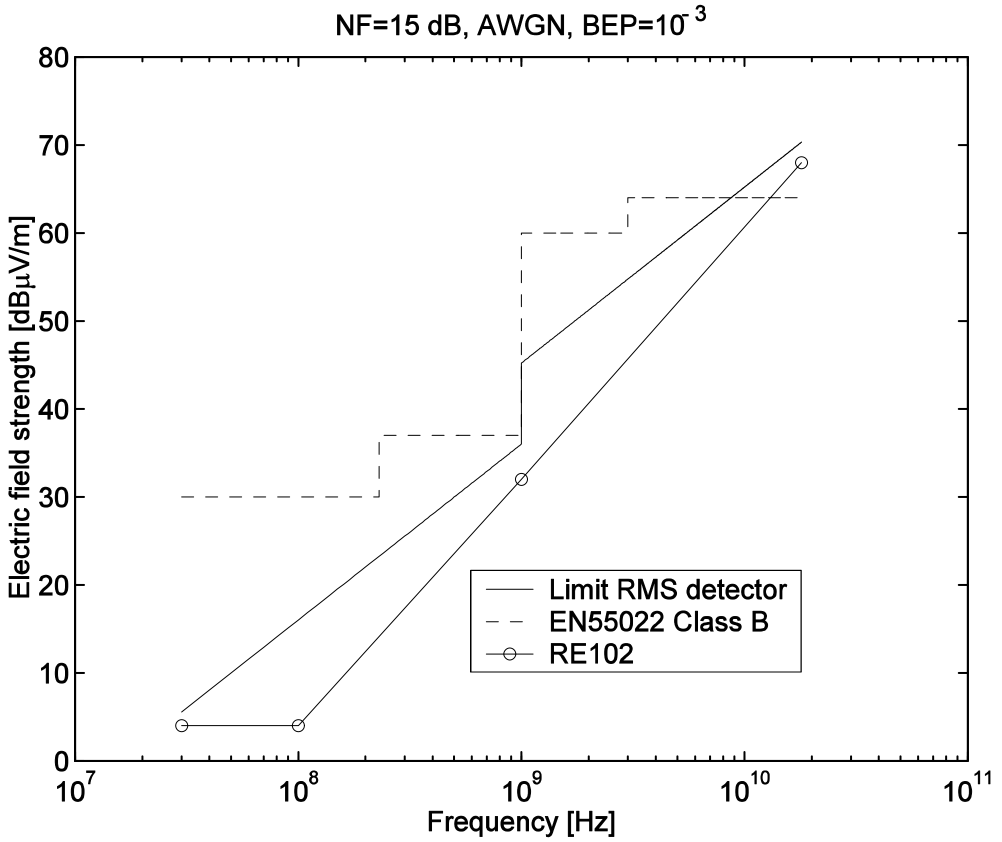

Figure 4.10: Emission limit for CISPR bandwidths at a distance of 10 m.

5 Summary of proposed emission limits

The proposed limits for the RMS detector are defined for two sets of measurement bandwidths, denoted narrowband (NB) and broadband (BB). The corresponding levels of the electric field strengths are shown in figure 5.1.

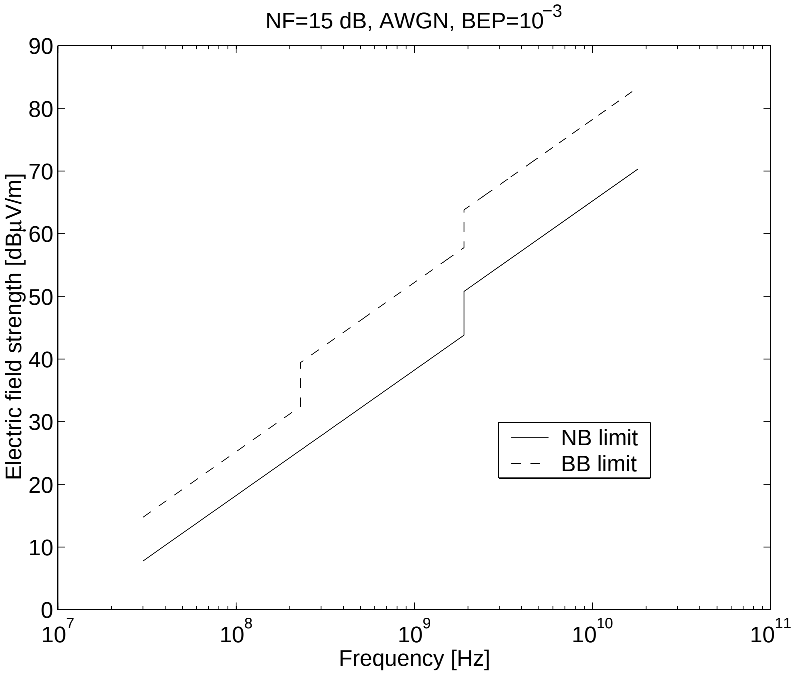

Figure 5.1: Proposed emission limits for the RMS-detector at a distance of 10 m.

Frequency range	Bandwidth NB	Bandwidth BB
30 MHz - 230 MHz	200 kHz	1 MHz
230 MHz - 1.9 GHz	200 kHz	5 MHz
1.9 GHz - 18 GHz	1 MHz	20 MHz

Table 5.1: Proposed measurement bandwidths.

These proposed values for these two sets of measurement bandwidths are defined according to table 5.1 The choice of emission limit has been according to the strategy summarized in figure 5.2 which means that for pulse repetition frequencies below the symbol rate of the digital radio system, a safety margin is automatically incorporated. For pulse repetition frequencies above the symbol rate of the digital communication system, no coding gain is accounted for to obtain the desired BEP.

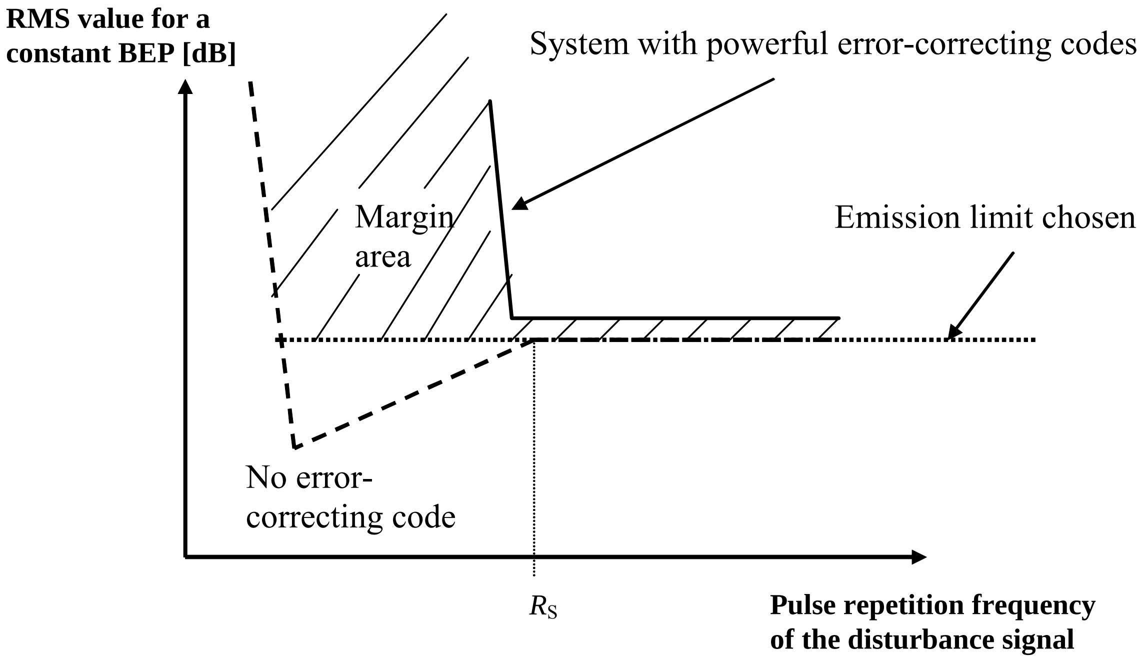

Figure 5.2: Emission limit choice for the calculated results.

6. Conclusion

Since the dynamic in channel bandwidths for modern digital wireless services is large, it is not convenient to use only one bandwidth for each frequency range. Therefore, two sets of measurement bandwidths (denoted NB and BB) are proposed for future emission measurements. In general, the proposed NB limits for the RMS detector have lower levels of electric filed strengths than the present limits in EN55022 but higher than the limits in RE102. The BB limits exceeds the limits in EN55022 in some frequency regions.

7. Suggested topics for further research

Radiated disturbance measurements

To support the theoretical work with the RMS-detector, measurements on a real interference scenario would be of great importance. This could be done with measurements (with an RMS detector) of the radiated emission from selected disturbance sources. A wireless digital communication system would be exposed to the radiated disturbance and the bit error rate should be recorded and compared to result with the radiated emission spectrum.

Characterization of typical radiated emission sources

The radiated emission from different types of personal computers has earlier been measured within the VOLGA project for the frequency region 30 MHz - 1 GHz. Since those measurements were performed oscillator frequencies in personal computers has increased tremendously and which increases the need for new measurements with the frequency region extended to > 1GHz. These measurements need to be updated and extended in frequency for more recent types of computers.

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