Statistical methods for radio frequency interference when estimating the performance degradation of digital radio receivers

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Abstract

The radiated interference environment can significantly degrade a radio communication system. Since this degradation can give serious consequences, the interference environment needs to be controlled. To foresee the degradation, the interference needs to be quantified and the performance of radio communication systems needs to be analyzed. When estimating the impact from radio frequency interference on digital radio systems, a statistical approach is to prefer. By using the amplitude probability distribution (APD) of an interference source, its impact can be determined. Another successful approach is to use the ordinary Gaussian Approximation (GA) with a correction of the interference power. This concept is based on the impulsiveness correction factor (ICF), which adjust the interference power due to the waveform properies, to avoid serious underestimations of the bit error probability (BEP). These two approaches are suitable methods to achieving accurate performance estimates of a digital radio receiver.

1. Introduction

The rapid technological evolution paves the way for many new wireless applications. A household today consists of many more electrical appliances and more wireless solutions than it did 20 years ago. Cars are equipped with electrical equipment to utilize new facilities. The trend seems to be an ever growing amount of electrical equipment. Electrical equipment generates electromagnetic emission, which can degrade the quality of desired radio signals when received in a communication system receiver. Especially when the interfering sources are located in the vicinity of the radio receiver, the resulting effect can be severe. This disturbance phenomenon is called intersystem interference and is an inevitable problem in reality. As a consequence, the interference will affect the communication system's capacity, robustness, reliability and availability.

Since this degradation can give serious consequences for the user of the communication system, the interference environment needs to be controlled. However, the measurement methods used to quantify the interfering signals today are not suitable as a measure to relate to the degradation of a digital radio communication system. This is a troublesome fact, which for example the C.I.S.P.R. (The International Special Committee on Radio Interference) is aware of in their work with suitable emission requirements [1-3].

For digital receivers, where the bit error probability (BEP) is a quality measure, we need information of the statistical properties of the interference amplitude after the intermediate frequency (IF) filter in the radio receiver. Therefore, the information provided by solely the quasi-peak, peak or root mean square (RMS) detector is not sufficient. For example, the quasi-peak detector is developed to emulate how a human being perceives the interference an analog radio receiver. The peak detector alone is not suitable either, as it only captures the maximum level of the interference signal, which is not of interest when estimating the BEP. Furthermore, the RMS detector, which is commonly used, measures the average interference power and does not capture the waveform properties of the interference signal. With information only from a RMS detector, the additive white gaussian noise (AWGN) approximation (GA) of the interference signal is commonly used when estimating the BEP. However, the GA has shown to result in large underestimations of the BEP, several magnitudes lower that expected [4]. On the contrary, the amplitude probability distribution (APD) of the interference signal captures the statistical properties of the interference and has shown to be useful for performance estimation [5-12]. An APD detector function is available on some spectrum analyzers today and the measurement procedure has been standardized by C.I.S.P.R. [13].

Another way is to use the GA, but correct the interference power, in such a way that no underestimation is introduced. Such correction factor is proposed in [4, 14-16]. It is denoted the impulsiveness correction factor (ICF) and is a rough adjustment for the waveform properties of the interference so that the GA still can be used.

In this paper we will discuss these two approaches. They are both statistical in the sense that the interference signal is treated statistically in the analysis of the radio system. In section 2, the BEP and the GA are discussed. In section 3, the relation between the APD and the BEP is briefly described. In section 4, the concept of the ICF is presented. Finally the paper is concluded in section 5.

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2. Performance measures of digital radio receivers

The conventional performance measure of a digital radio receiver is the BEP. The BEP indicates the probability that a transmitted bit is erroneously detected. In a highly disturbing environment, the BEP will become high. For an error probability of one half, it is equally likely to detect a bit as correct as incorrect. An incorrect decision is generated when the contribution from an interfering signal adds to the desired signal such that the decision variable falls into an incorrect decision region in the detector. The key issue when determining the impact of an interfering signal is to have information about its envelope and phase in the decision device in the detector. As the interference signal can be regarded as uncorrelated to the desired signal, it is reasonable to believe that the phase of the interference signal at the decision instant is uniformly distributed in the interval [0,2π]. As we will discuss later the APD is catching the envelope properties after the IF filter in a receiver, for example in a spectrum analyzer. This is the main reason for why the APD is very suitable as a measurement function of interference signals.

Traditionally, when estimating impact on digital radio receivers, interference sources have often been modelled as AWGN, for which there exist simple mathematical expressions. On the contrary, performance expressions for receivers in non-Gaussian interference based on a mathematical description of the interference often get very complicated depending on the interference source. The GA of interfering signals is widely used in communication theory problems. It is performed by approximating the interference signal as a zero-mean Gaussian process with equal average power. The rationale for using of this approximation is that the Gaussian distribution is mathematically convenient in performance analysis and that for some signals it leads to good performance estimates. Furthermore, for some applications the central limit theorem also motivates its use. However, in practical applications Gaussian-like interference is not the most common type. For pulse modulated signals and impulsive signals, the approximation have been shown not to be valid. For larger signal-to-interference ratios (SIR), the degradation in terms of BEP can be several orders of magnitude larger that the GA suggests, which for example can be seen in Fig. 1.

3. Amplitude probability distribution

One way to describe an interference signal is to show its statistical properties of the signal envelope. The APD is defined as the part of time the measured envelope of an interfering signal exceeds a certain level [11]. It has earlier been shown that there is a relation between the APD of an interfering signal and the maximum BEP it causes on a coherent radio receiver. In Table I, the relation between the APD and the maximum BEP are shown for several common modulation schemes, *M*-phase shift keying (PSK), *M*-pulse amplitude modulation (*M*-PAM), *M*-quadrature amplitude modulation (QAM) and *M*-frequency shift keying (*M*-FSK) [5].

TABLE I
RELATION BETWEEN THE MAXIMUM BEP AND THE APD

Modulation	Relation between $P_{b,max}$ and APD
2-PSK	$P_{b,max} \approx \mathrm{APD}_R(\sqrt{E_b})$
4-PSK	$P_{b,max} \approx 1/2\,\mathrm{APD}_R(\sqrt{E_b})$
8-PSK	$P_{b,max} \approx 1/3\,\mathrm{APD}_R(0.66\sqrt{E_b})$
16-PSK	$P_{b,max} \approx 1/4\,\mathrm{APD}_R(0.39\sqrt{E_b})$
4-PAM	$P_{b,max} \approx 1/2\,\mathrm{APD}_R(0.63\sqrt{E_b})$
8-PAM	$P_{b,max} \approx 1/3\,\mathrm{APD}_R(0.37\sqrt{E_b})$
16-QAM	$P_{b,max} \approx 1/4\,\mathrm{APD}_R(0.63\sqrt{E_b})$
64-QAM	$P_{b,max} \approx 1/6\,\mathrm{APD}_R(0.38\sqrt{E_b})$
2-FSK	$P_{b,max} \approx \mathrm{APD}_R(0.71\sqrt{E_b})$
4-FSK	$P_{b,max} \approx \mathrm{APD}_R(\sqrt{E_b})$

In the left part of Fig. 1, the average BEPs are shown for several different interference signals. To the right in the same figure, the corresponding APDs are shown. The APD and the BEP are derived from simulations. The interference signals are modelled as Middleton class A with different parameter settings [17] for a binary phase shift keying (BPSK) receiver. As can be seen there is a very good correspondence between the BEP and the APD.

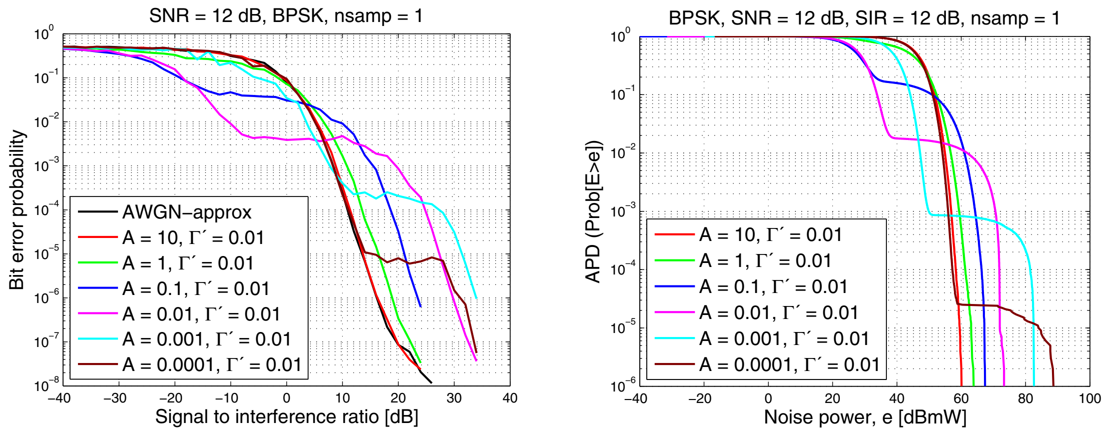

Figure 1: Comparison between the BEP of a BPSK system and the APD of the interference signal

4. Impulsive correction factor

In general, the bit error probability P_b for AWGN can be derived as

$$P_b = f\left(\frac{E_b}{N_0 + N_I}\right) \quad , \tag{1}$$

where E_b is the signal energy per bit [W/Hz], N_0 is the power spectral density [W/Hz] for the receiver noise and N_I is the power spectral density for the interference signal approximated as AWGN within the receiving bandwidth of the radio receiver of interest. The BEP according to (1) can result in estimation errors in the order of several magnitudes for pulsed interference. This is evident in Fig. 1, where we can see that impulsive interference signals and AWGN results in very different BEP for a certain SIR. By using the *ICF*, the error that can occur in the energy-based method can be significantly reduced but in the same time maintain the usefulness of the AWGN approximation. By use of the ICF, the corrected BEP $P_{b,corr}$ can be obtained as [4]

$$P_{b,corr} = f\left(\frac{E_b}{N_0 + ICF \cdot N_I}\right). \tag{2}$$

In Fig. 2, a graphic interpretation of the *ICF* is shown for two of the interference signals. The figure shows the BEP as a function of the SIR, defined as E_b/N_I . Furthermore, in the BEP estimation also a signal-to-noise ratio (SNR) is assumed, defined as E_b/N_0 . Thus, the *ICF* is simply the horizontal shift of the BEP curve as a function of SIR from the AWGN-approximated curve. In this figure, the interference signals are modelled as Middleton class A with different parameter settings for a BPSK receiver. The parameter setting A=1 and Γ=0.1 is an interference signal which is quite similar to a Gaussian distributed signal. It is slightly more impulsive. However, the interference signal with A=0.01 and Γ=0.001 is very impulsive. Notice, that the necessary correction may be quite large. For the interference signal with the parameters A=0.01 and T=0.001, the interference power needs to be increased with approximately 23 dB.

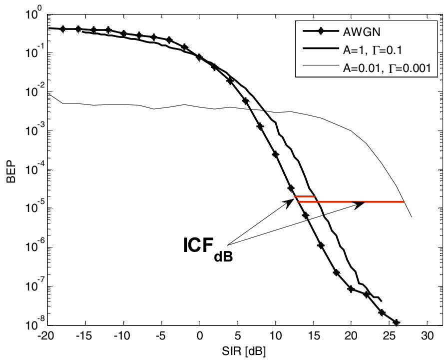

Fig. 2: Example of simulated BEP curves as a function of SIR for a class A interference with the parameter sets (A, Γ)=(1, 0.1) and (A, Γ)=(0.001, 0.001). For these signals the ICF_{dB} is estimated to 2.5 and 22.7 dB, respectively.

5. Conclusion

For digital radio systems, the probability of bit errors is an essential quality measure. Furthermore with several performance enhancing functionality often inherent in the system, such as error correction and interleaving, the average performance is of main interest. For these issues, it is convenient to have a statistical approach when analyzing the performance. Hence, the receiver performance may preferably be statistically determined in terms of eg average probability of bit errors and the interference can be treated in a statistical manner.

The APD, which describes the statistical distribution of the interference envelope, has shown to be a suitable measurement function to be used in performance estimations. Another method, where waveform properties are considered, is with the correction factor ICF. The ICF is adjusting the interference power to avoid the risk for large underestimations of the BEP. Both approaches treat the interference as in a statistical manner, which yields an average performance of the digital radio receiver

7. References

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