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An impulsiveness correction factor for multiple Middleton Class A sources

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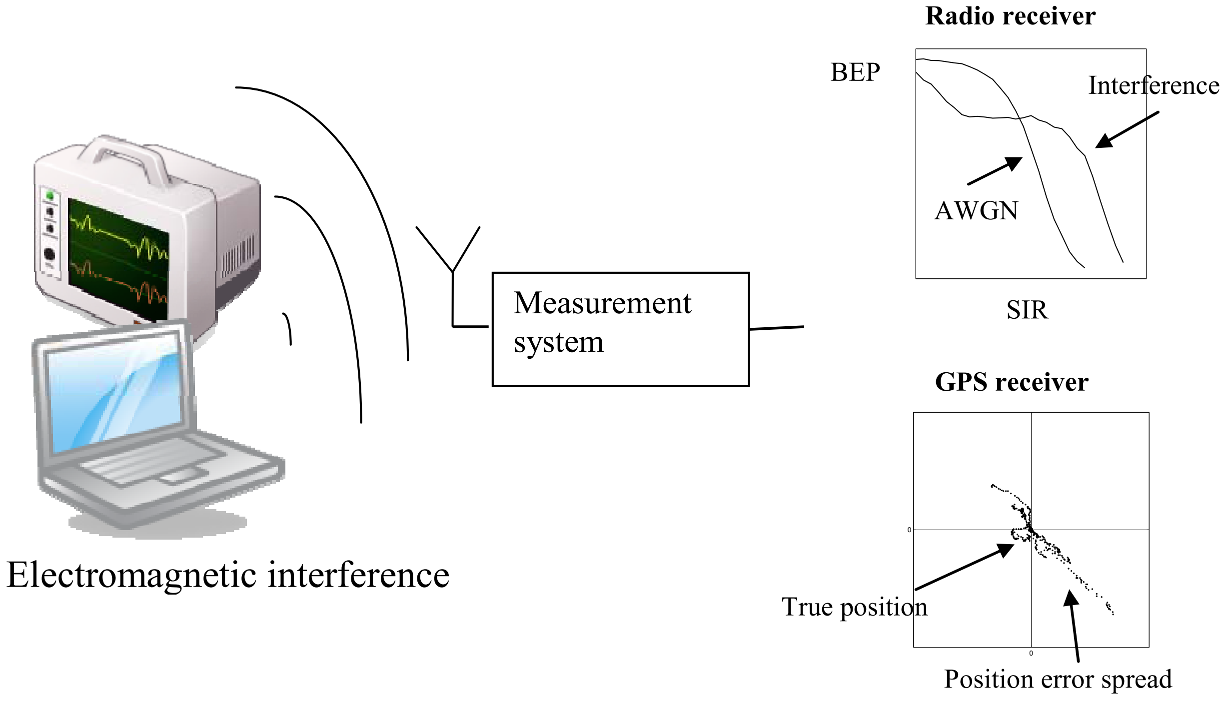

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Karina Fors, Kia Wiklundh

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Sammanfattning

För att kunna förebygga kritisk prestandapåverkan hos digitala kommunikationssystem, är det nödvändigt att analysera situationer där elektrisk utrustning och radiosystem är samlokaliserade. I sådana analyser är det nödvändigt att kunna använda förenklade matematiska modeller. För detta ändamål, är det brukligt att använda den Gaussiska approximationen för interferenser. Dock, speciellt för pulsmodulerade signaler, har approximationen visat sig kunna ge mycket stora fel. För höga signal interferens förhållanden kan bitfelshalten bli mycket högre än vad den Gaussiska approximationen ger. I tidigare arbete, har en s.k. korrektionsfaktor (*ICF*) föreslagits kunna användas på den Gaussiska approximationen för att minska felet. Korrektionsfaktor har undersökts för ett binärt fasskiftsmodulerat (BPSK) system. Korrektionsfaktorn har tidigare även undersökts för två varianter av interferenser. En interferens bestående av flera pulsmodulerade AWGN-signaler och en bestående av multipla störkällor i form av en pulsmodulerad AWGN-signal samt en BPSK-modulerad signal. För dessa fall visade sig korrektionsfaktorn inte fungera lika bra som för fallet med bara en pulsmodulerad AWGN-signal. Därför har en flexibel brusmodell (Middleton Class A) undersökts här. Den undersökta brusmodellen kan parametersättas så att en stor variation av signalegenskaperna kan modelleras.

I det här arbetet har *ICF* undersökts för interferensmiljöer vilka innehåller en eller multipla störkällor. Analysen visade att korrektionsfaktorn är starkt korrelerad till den använda brusmodellens parametrar vilket innebär att felen orsakade av Gaussapproximationen kan korrigeras. Därutöver har en ny metod tagits fram för fallet med multipla störkällor. Metoden baseras på fallet med en dominant störkälla. Slutsatsen från arbetet är att ICF-måttet är mycket användbart på ett brett spektra av olika interferenssignaler.

Nyckelord: Gauss approximation, felsannolikhet, BEP, interferensmiljö, impulsiveness correction factor, *ICF*, telekonflikt

Summary

To prevent crucial degradation of a communication system, it becomes necessary to analyze co-location situations of electrical equipment and radio systems. For such analyses, it is essential to have appropriate simplified methods to get computationally tractable expressions for the interference impact. For this, the Gaussian approximation of interfering signals is widely used. However, especially for pulse modulated signals the approximation has been shown not to be valid. For high signal-to-interference ratios the degradation can be several magnitudes or orders larger that the Gaussian approximation suggests. In previous work, a so-called impulsiveness correction factor (*ICF*) was suggested to be used on the Gaussian approximation. This was demonstrated for binary phase shift keying (BPSK) modulation. This relation has also been investigated for an interfering signal consisting of several pulse modulated AWGN and for an interfering signal mixed with one pulse modulated AWGN and a BPSK modulated signal. For these cases the correction factor was not as good as for the pure case with one pulse modulated AWGN signal.

For the work in this report Middleton Class A is studied. The correction factor has been investigated for interference consisted of one or several signal sources (also called mixed interference environment). The *ICF* showed a strong correlation to used interference model parameters which gives the possibility to adjust for the errors caused by the Gaussian approximation. Furthermore, for multiple interference sources environment a new method has been derived. The method is used to calculate a new *ICF* based on the case with one dominant interference signal. The conclusion is that the concept of *ICF* is applicable for a large variety of interfering signals.

Keywords: Gaussian approximation, bit error probability, BEP, interference environment, impulsiveness correction factor, *ICF,* intersystem-interference

Table of contents

1 Introduction

To prevent crucial degradation of a communication system, it becomes necessary to analyze co-location situations of electrical equipment and radio systems. Such analyses could be performed in advance before the equipment is used, on-line or on demand when problems appear, very much depending on the situation. For such analyses, it is essential to have appropriate simplified methods to get computationally tractable expressions for the intersystem interference. Although the intersystem-interference analysis is based on approximations, the analysis may become very complex and time consuming. Hence, a computer-aided tool is often necessary. Several analysis tools exist, and the most established ones consider shared antenna sites for platform integration of systems. Among the earliest shared site interference analysis software was the CO-Site Analysis Model (COSAM) [3], which was developed for naval shipboard applications at the request of the Department of Defence, USA. Since that, several further developments have been presented mainly intended for military use. In most tools, a so-called Gaussian approximation of the interference source is implemented, which can entail large underestimations of the receiver degradation [1]. Furthermore, the tools are usually developed for analog radio systems, often with a modification to include also digital radio systems. For most digital radio systems, these modifications are not sufficient to model the properties of a digital receiver. For these reasons, new analysis tools are needed [2]. The development of such a tool (named NTK) has begun within the Swedish Armed Forces at the request of the Swedish Defence Material Administration

The Gaussian approximation of interfering signals is widely used. It is performed by approximating the interference signal as a Gaussian process with equal average power as the interference signal. The motivation for the usage of this approximation is that the Gaussian distribution is mathematically convenient in performance analysis and that it for some signals leads to good performance estimates. However, especially for pulse modulated signals the approximation has been shown not to be valid [1]. For larger signal-to-interference ratios (SIR) the degradation can be several magnitudes or orders larger that the Gaussian approximation suggests. In [1], it was suggested to still use the Gaussian approximation for its advantages but correct it according to a correction factor, a so-called impulsiveness correction factor (*ICF*). This was demonstrated for binary phase shift keying (BPSK) modulation. The simple relation between the *ICF* and the impulsiveness ratio (*IR*) was shown to be valid for the case with one interfering signal consisting of pulse modulated additive white Gaussian noise (AWGN). In [4], the relation was investigated for an interfering signal consisting of several pulse modulated AWGN and for an interfering signal mixed with one pulse modulated AWGN and a BPSK modulated signal. For these cases the correction factor was not as good as for the pure case with one pulse modulated AWGN signal. To conclude, the *ICF* has been investigated for a pulse modulated AWGN signal and several pulse modulated AWGN signals. The case with one pulse modulated AWGN signal has a character to either interfere or not, which differs from the continuously transmitted interference and might be of interest. For this reason it would be interesting to analyze how the correction factor should be expressed for a more general interfering signal expressed in terms of its amplitude statistics. For such interference model the occurrence of the interference samples in time is not important. Furthermore, it would be interesting to analyze how the correction factor is related to the impulsiveness of the interference, as the work in [1] showed a direct relation between the *ICF* and the *IR*. Finally, it is important to investigate how the *ICF* should be considered for a mixture of several interference signals since this is often the case in real applications. For this issue Middleton's Class A interference model is studied. This interference model is flexible with a possibility to vary the interference parameters from arbitrary impulsive to near Gaussian. It is defined as the amplitude probability density function (pdf) of the interfering signal at the output of the intermediate frequency (IF) filter of the measurement receiver.

In this work, the concept of *ICF* is investigated for two different cases:

1. One class A interference source

2. One dominant class A interference source and a sum of several class A interference sources (also called mixed interference environment)

In both cases also a thermal receiver noise is assumed to be present, which is modelled as AWGN. The first case may correspond to the case where a total interference environment is considered and under evaluation of its effects. The second case is applicable when several interference sources are put together and constituting a whole interference environment.

The chapters are organized as follows. In chapter 2, the system model and the concept *ICF* are described. In chapter 3, the *ICF* for one interfering signal is studied. In this chapter it is shown that the *ICF* is dependent on the SNR and the specific parameter of the interference model used. This interference model is highly flexible and can be used as a model for most interfering sources. The parameters are possible to estimate from measurements of the interfering signal. This relation opens up for using a look-up table to deliver the *ICF*. In chapter 4, the *ICF* is approximately derived for several interfering signals of the same kind. A theoretical relation is proposed to determine the *ICF*, based on the individual *ICF* of the dominant interference part. In chapter 5, the applications of these results are described. All together the *ICF* seems to be very promising as a concept for the discussed applications. Finally, discussion and conclusions are presented in chapter 6 and further work is proposed in chapter 7.

2 System model

This chapter starts with a simple description of the measure *impulsiveness correction factor* (*ICF*). Then, Middleton's Class A interference model used in simulations is described. Finally, the used radio simulation model is illustrated.

2.1 Impulsiveness Correction Factor (ICF)

The *ICF* is defined as the maximum SIR difference, between the interfering signal and AWGN. The figure 2-1 shows one example of the *ICF*. In [1] the impulsiveness ratio *IR* is shown to be correlated to the *ICF* for pulse modulated signals. The *IR* is defined as

$$IR = 20\log\frac{V_{\mathrm{RMS}}}{V_{average}}, \text{ [dB]} \tag{1}$$

where V_{RMS} and V_{average} are the root-mean square and time average values of the interference. It should be noted that both the *ICF* and *IR* measurements should be done with the same bandwidth as the digital communication system of interest uses. In [1] it has been shown that *ICF* can be approximated as

$$ICF \approx ICF_{\mathrm{offset}} + \frac{3}{4}IR, \text{ [dB]} \tag{2}$$

where the ICF_{offset} is a offset factor which depends on which modulation scheme used by the digital communication system.

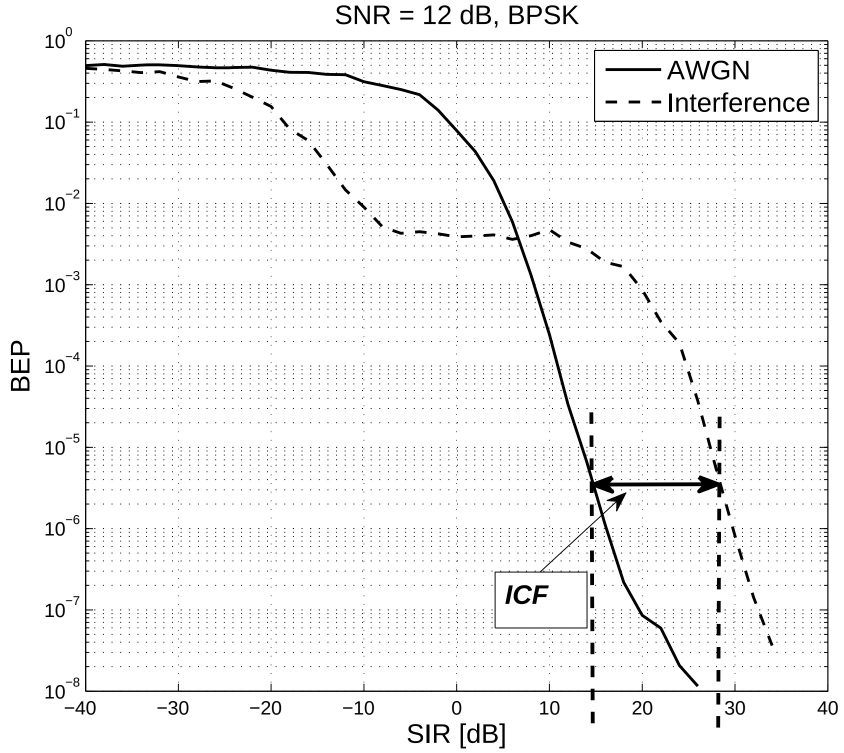

Figure 2-1 The measure *ICF* is defined as the SIR difference for the same BEP between the interfering signal and the AWGN.

In this work, a BPSK system is studied and therefore the ICF_{offset} is set to -4 dB. Additional description of the measure *ICF* together with a derivation of the equation can be read in [1].

2.2 Interference model

For the investigation, Middleton's Class A model and AWGN are used as interference models. Middleton's interference model is based on the assumption that the total received interference waveform consists of several interference sources each Poisson-distributed in time and space [5]. In general, a narrowband noise $x(t)$ is represented by its envelope $r(t)$ and phase $\phi(t)$ as

$$x(t) = r(t)\cos(2\pi f_c t + \phi(t)), \tag{3}$$

where f_c is the centre frequency of the noise. The Class A pdf of the amplitude X normalized to the root mean square (rms) value, is defined as [5]

$$p_X(x) = e^{-A}\sum_{m=0}^{\infty}\frac{A^m}{m!\sqrt{2\pi\sigma_m^2}}e^{-\frac{x^2}{2\sigma_m^2}}, \tag{4}$$

where $\sigma_m^2 = (m/A + \Gamma)/(1+\Gamma)$, with Γ as the mean power ratio of the Gaussian noise component to the non-Gaussian noise component [6]. Furthermore, A is the impulsive index, i.e. the product of the received average number of impulses per unit time and the duration of an impulse [6]. It is known that for A approaching 10 or larger, the Class A pdf is very close to a Gaussian distribution [5]. For A and Γ lower than 1 the amplitude pdf gets very heavy tails and the interference can be regarded as very impulsive. By varying the parameters, the pdf can be made arbitrary impulsive or close to a Gaussian distribution. For example, the interference from a switching-type micro-wave oven has been demonstrated to be modeled well with $A \approx 5\cdot 10^{-3}$ and $\Gamma \approx 9$ [7].

2.3 Radio system model

For this work, an uncoded coherent BPSK system is studied. In figure 2-2, the used radio simulation model for the BPSK signal is illustrated. This system is analyzed under the influence of interference and thermal receiver noise. The thermal receiver noise is modeled as AWGN with the single-sided power spectral density N_0. The used interference model is described in section 2.2. Hence, the received signal r consists of the complex signal, the thermal noise n and the impulsive interference u. The bit error probability (BEP) was estimated by comparing the received bit sequence with the transmitted.

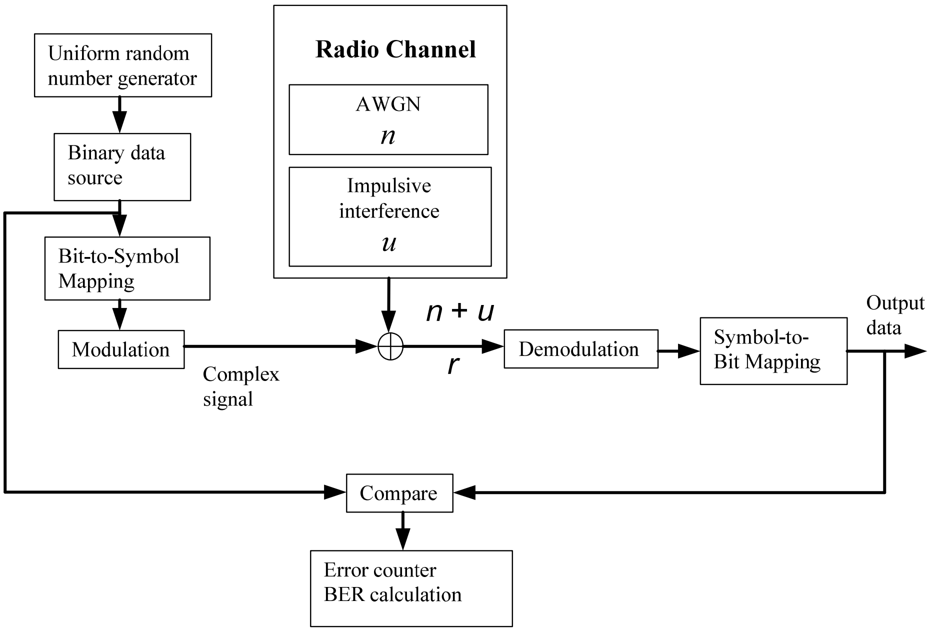

Figure 2-2 The radio system simulation model for illustrative. The received signal *r* contains the signal of interest, the thermal noise *n* and the impulsive interference *u*.

If the received interference in a radio receiver can be approximated as Gaussian noise, the BEP can be calculated relatively easy for different modulation schemes. The theoretical BEP is a function of the SNR γ where γ is defined as E_b/N_0. The E_b denotes the bit energy of one information bit. If the digital communication system is subjected to interference which can be approximated as Gaussian noise, γ can be replaced by γ' defined as

$$\gamma' = \frac{E_b}{N_0 + N_I} \tag{5}$$

where N_I is the single-sided power spectral density of the for the interference within the BPSK system bandwidth.

The simulated BEP for the used radio simulation model is studied as a function of the SIR determined for the case when the interference is a Class A interference and AWGN respectively. The SIR is defined as E_b/N_I. The simulations are performed for Class A interference with different combinations of A and Γ. The results presented in chapter 3 are based on simulations performed for the case with one Middleton Class A interference signal present. Additionally, in chapter 4 the simulations are done with a mixed signal source produced by adding a number of transmitting signal sources together. From the simulations, the *desired ICF* is determined from the simulated BEP as the largest SIR exceeding difference achieved from the BEP determined for AWGN. Further description of the measure *ICF* can be read in section 1.2. The *desired ICF* is used to correct the SNR in (5) so that

$$\gamma'' = \frac{E_b}{N_0 + icf \cdot N_I} \tag{6}$$

where *icf* is the non-logarithm of the *desired ICF*. With equation (6), the estimated BEP for an uncoded coherent BPSK system subjected to Class A interference with specific A and Γ is obtained as

$$P_b^{AWGN}(\gamma'') = \frac{1}{2} erfc\left[\sqrt{\frac{E_b}{N_0 + icf \cdot N_I}}\right]. \tag{7}$$

To quantify the amount of interference that originates from Class A interference in the simulations, the SIR is used. The interference level is adjusted to obtain the correct SIR value. In all simulations also a thermal receiver noise is present which is generated from a SNR of 12 dB.

In the simulation used for this report two different simulation setup of A and Γ values have been analyzed. First, a fixed A parameter together with different Γ are investigated. Secondly, different values on A but with fixed Γ are analyzed. The simulations to derive the *desired ICF* are done in Matlab.

3 ICF for one Middleton Class A source

In this chapter the estimated *desired ICF* are approximated for the case when the digital communication system are subjected to interference from one signal source. The interference source consists of one Middleton Class A interference signal source described in section 2.2.

3.1 Received interference signal

The total received interference signal for one Class A source plus the internal noise in the receiver are expressed as

$$i(t) = n(t) + u(t) = n(t) + c(t), \tag{8}$$

were each interference source is

n(t) the internal AWGN noise in the receiver,

c(t) a pure Class A interference signal with specific A and Γ.

The interference signal *i(t)* in (8) are used to estimate the influence on the simulated BEP for a uncoded BPSK modulated radio system.

3.2 *Desired ICF* for one Class A source

For pulse modulated interference, there is a direct relation between the *ICF* and the *IR* according to (2). To avoid confusion in this work, a distinction between the used measure *ICF* and the *desired ICF* must be made. The measure *ICF* is derived in [1] and can be approximated as (2). The *desired ICF* originate from the simulated BEP figures and is measured as the largest SIR exceeding difference achieved from the BEP determined for AWGN. The results in this report originate from simulated BEP figures.

In [4], it is indicated that the relation in (2) is not applicable for sums of pulse modulated signals. One reason for this is that the relation is based on the pulse modulated character of the assumed interference signal. For this reason this relation might not be appropriate when the interference deviate from a pure pulse modulated signal to a more continuous-like signal. Hence, we will investigate the measure *ICF* for a more generally described interfering signal which is described by its amplitude statistical properties. For such kind of interference model the information about pulse duration and time between pulses become irrelevant. With a statistical description of the amplitude, the interference amplitude samples are assumed to come in random order.

The received interference signal is described in section 3.1. The total power level P_{total} for the interference signal *c(t)* in (8) is

$$P_{\text{total}} = P. \tag{9}$$

The power of *n(t)* in (8) is used in the simulations together with the received signal bit energy to give the correct level on the signal-to-noise ratio (SNR). Then, the power of *c(t)* together with the SNR are used to correct the level on the signal-to-interference ratio (SIR). Based on the simulation model described in figure 2-2, the BEP is simulated.

In figure 3-1, the simulated BEP is plotted as a function of the SIR determined for a Class A interference and the AWGN, respectively. In this figure, the BEP is studied for a fixed *A* and varying *Γ*. The estimated *desired ICF* is shown in table 3-1. When the figure is inspected a threshold level on the BEP curve can be seen. This threshold level depends mostly on the interference impulsive index *A* and can be approximated to *A*/2. For example, for *A*=0.01 the threshold level is in the order of $5 \cdot 10^{-3}$. The *Γ* also influence the BEP horizontally. For the part of the BEP curve below the threshold level, the BEP-curve is approximately translated 10 dB to left when *Γ* decrease with a factor of 10. Also, the *desired ICF* can be identified in the figure as the largest SIR difference between the BEP of AWGN and the Class A interference. From the figure it can also be observed that the *desired ICF* is dependent on the parameter *Γ*. Large *Γ*, as e.g. *Γ*=10, requires least *desired ICF* while lower *Γ* implies larger *desired ICF*. When *Γ* decreases, the interference becomes more impulsiveness. However, the *desired ICF* seems to approach a maximum for *Γ* around 0.1 and does not seem to increase when *Γ* becomes smaller.

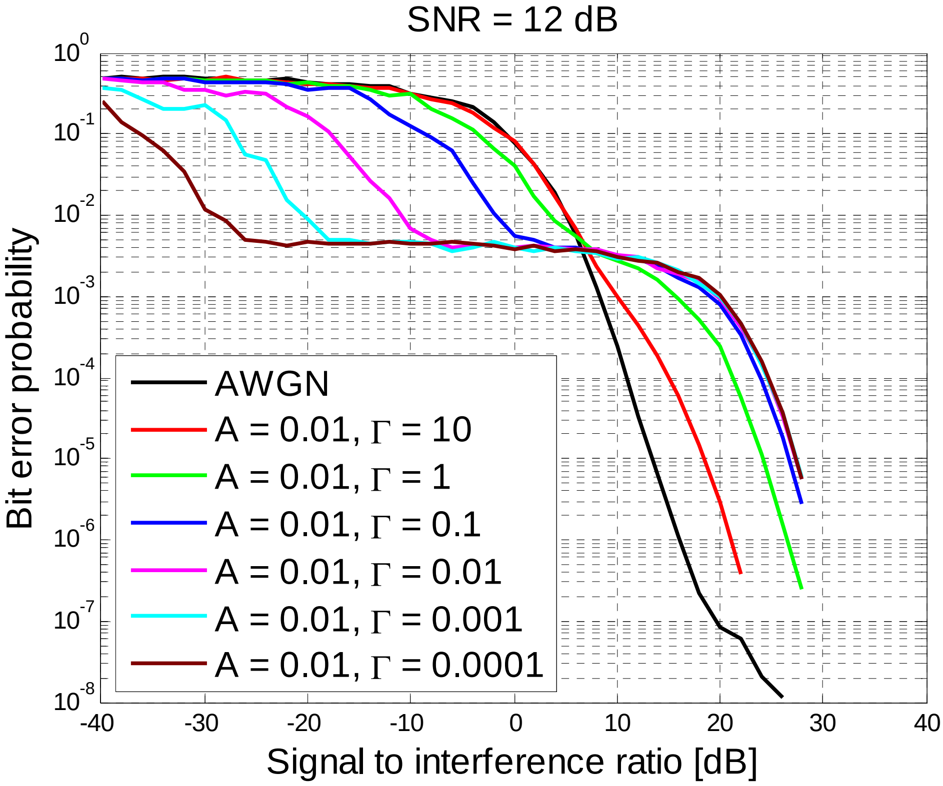

Figure 3-1 The BEP as a function of the SIR for a Class A interference with *A*=0.01 and a varying *Γ*.

In figure 3-2 the simulated BEP is plotted as a function of the SIR determined for Class A interference when *A* varies and *Γ* is kept fixed. The estimated *desired ICF* is shown in table 3-2. In this case, the threshold level in the simulated BEP differs when *A* varies, e.g. with *A*=0.0001 and *A*=0.1 we get the threshold levels $5 \cdot 10^{-5}$ and $5 \cdot 10^{-2}$. Also, with increasing *A* the interfering signal approaches to an AWGN signal. This can be seen in the simulated BEP, e.g. with *A*=10 the simulated BEP almost completely follows the BEP for the AWGN signal. Furthermore, when *A* decrease the signal get more impulsive and the *desired ICF* increase. Another case, when *A*=0.0001 the simulation BEP follows the BEP for the AWGN for SIR under 14 dB but still the *desired ICF* is required to be around 14 dB for SIR over 14 dB. This result supports the need of using a correction factor to correct the BEP especially for high SIR.

3.2.1 *Desired ICF* and IR according to (2)

In order to achieve the ICF, the *IR* was suggested in (2) for pulse modulated signals. Here, we have investigated the relation between the *IR* and the *desired IC*F for all the simulations with all combinations of *A* and *Γ*. In this analysis the *IR* is calculated solely on the Class A interference *c(t)* in (8). Those simulation results indicated that there exist no obvious relation between the calculated *IR* and the *desired ICF* regardless of *A* and *Γ*. Consequently, the relation in (2) was also shown to fail for this kind of interference.

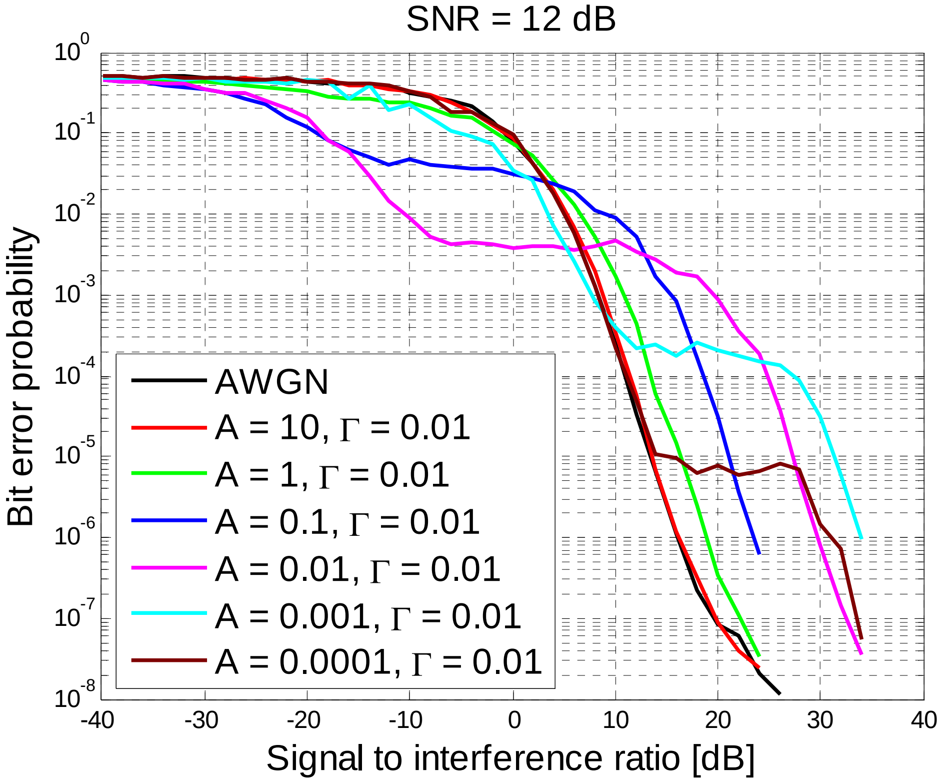

Figure 3-2 The BEP as a function of the SIR for a Class A interference with varying *A* and *Γ*=0.01.

Table 3-1 The *desired ICF* for Class A interference with *A*=0.01 and varying *Γ*.

A	*Γ*	***Desired ICF*** **[dB]**
0.01	10	5.1
0.01	1	10.8
0.01	0.1	13.3
0.01	0.01	14
0.01	0.001	14.1
0.01	0.0001	14

3.2.2 *Desired ICF* and *A, Γ*

Since the *desired ICF* seemed to be correlated to booth *A* and *Γ* we used another approach where the parameters were considered. The relation between *IR* and the *desired ICF* was studied with one parameter fixed and the other varies. Here, *A* is fixed and *IR* is calculated for different *Γ*. In figure 3-3, the calculated *IR* is plotted against the *desired ICF*. We can see that the *IR* and the *desired ICF* is strongly correlated for a fixed *A*. In [8], the *IR* for an AWGN signal has been calculated to 1.049 dB. As we can see in figure 3-3, for all *A* and *Γ*=10 the *IR*≈1 dB. This result shows that the interference signal has strong AWGN properties. If the signal has strong AWGN properties the expected *desired ICF* should approach 0 dB. However, the *desired ICF* from simulations showed that different Class A signals with identical *IR* gives different *desired ICF*. The calculated *IR* is therefore not enough information about the interference signal to estimate the *desired ICF*. Another conclusion is that the *desired ICF* seems to approach the maximum when *IR* increases; e.g. for *A*=0.01 and *Γ*=0.01 the *desired ICF*≈13.5 dB and when *A*=0.01 and *Γ*=0.0001 the *desired ICF*≈14 dB. The maximum level differs for different *A*. However, when *A* for the interference is known we could use the maximum *desired ICF* for an upper limit on BEP.

Table 3-2 The *desired ICF* for Class A interference with varying *A* and *Γ*=0.01.

A	*Γ*	***Desired ICF*** **[dB]**
10	0.01	0.2
1	0.01	2.9
0.1	0.01	7.6
0.01	0.01	13.8
0.001	0.01	17.9
0.0001	0.01	14.2

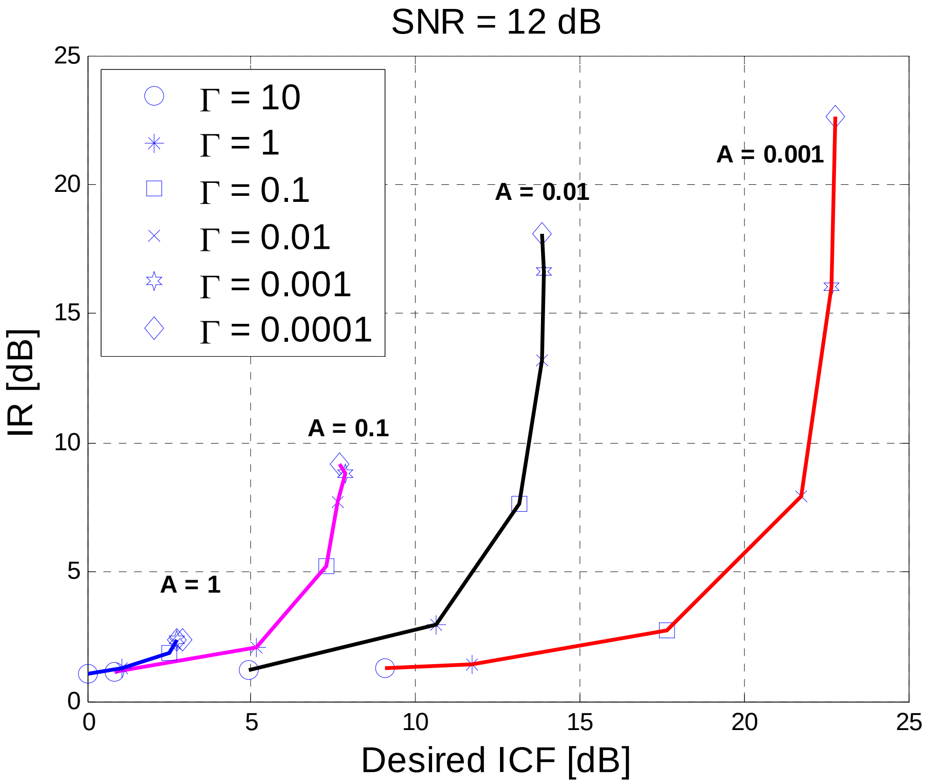

Figure 3-3 Calculated *IR* on the simulated class A interference as a function of the *desired ICF*.

The used Class A interference model is a flexible model with a possibility to vary the interference parameters from arbitrary impulsive to near Gaussian. As a consequence from this flexibility it is difficult to derive a direct relation between the *IR* and the *desired ICF* without considering the parameter *A* and *Γ*. It is probably easier to derive a relation between the *ICF* and the *IR* for a fixed *A*. In that case, only the ratio between the mean power of the Gaussian noise component to the non-Gaussian noise component is changed.

In figure 3-4 the *Γ* is plotted against the *desired ICF* for different *A*. For a fixed *A* and when *Γ* increase the *desired ICF* approaches a maximum value. This is the same behavior as for the case when we analyzed the *desired ICF* against the *IR*, see figure 3-3. As the *IR* increased the *desired ICF* approached a maximum value. Also, the *desired ICF* increases when *A* decrease.

In figure 3-5 the *A* is plotted against the *desired ICF* for varying *Γ*. When *A* and *Γ* decrease the *desired ICF* increases but for *Γ* lower than 0.1 the *desired ICF* seems independent of *Γ*.

The figures 3-3 – 3-5 can serve as look-up tables for *ICF* calculations in a computer-based tool for intersystem interference analyzes.

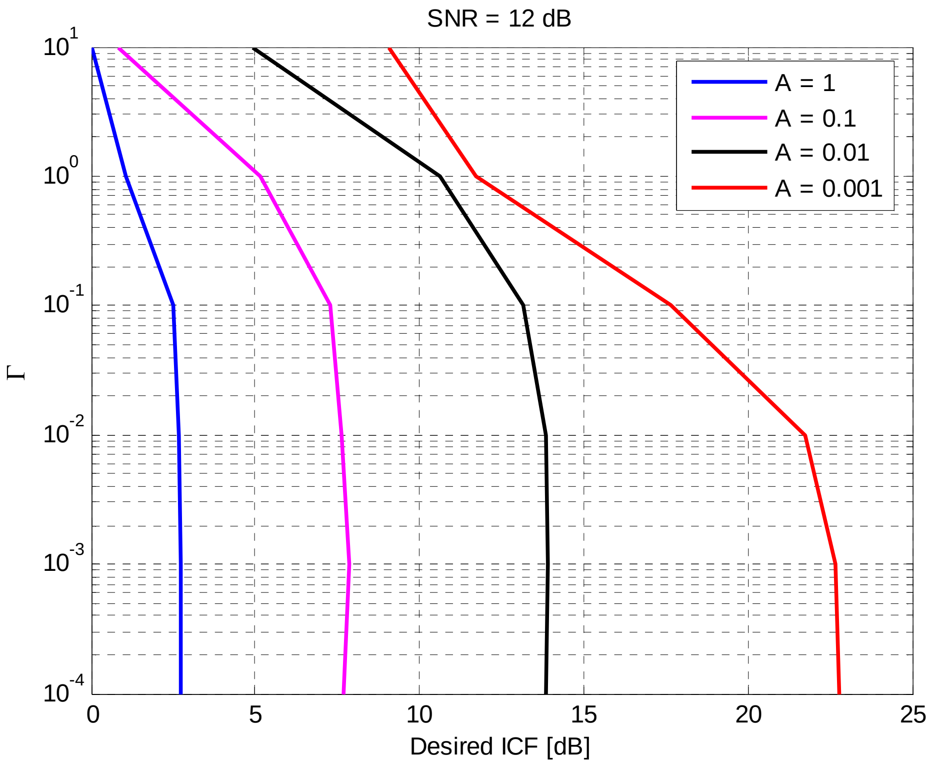

Figure 3-4 The *desired ICF* for Class A interference with different *A* and *Γ*.

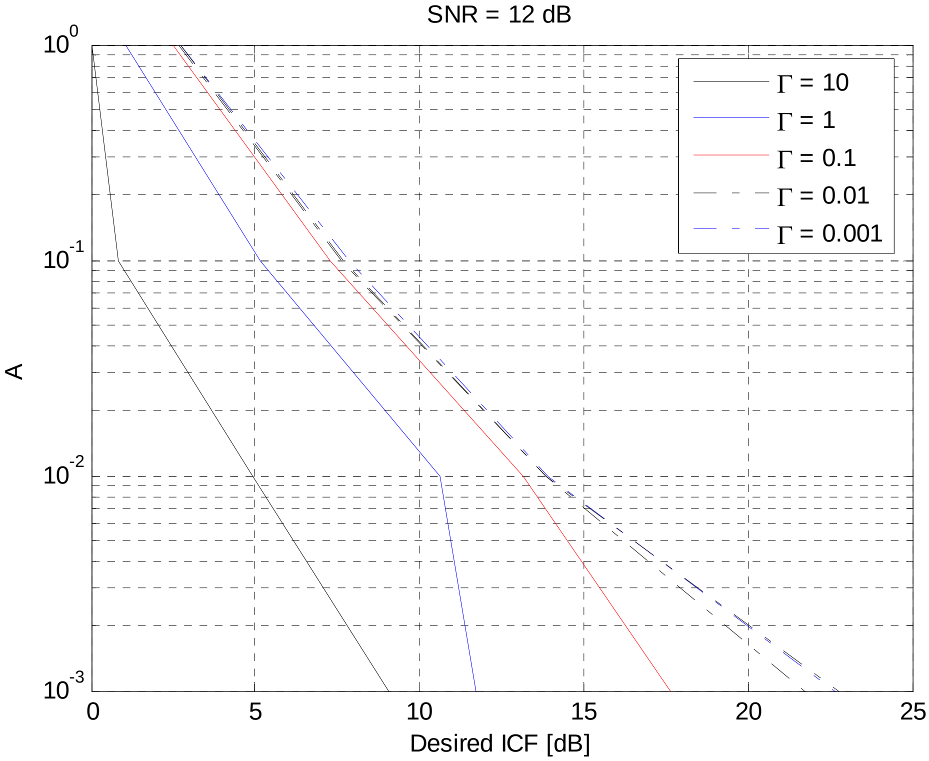

Figure 3-5 The *desired ICF* for Class A interference with varying *A* and *Γ*.

3.2.3 Demonstration of using the *desired ICF*

The method of using the estimated *desired ICF* according to (7) can be seen in figure 3-6. The black line is the theoretical BEP for AWGN interference. The solid pink line is the simulation result for Class A with A=0.01 and Γ=0.01 and the dotted line is the corrected theoretical BEP according to the method. The BEP is corrected by using the *desired ICF* to simply move the BEP of the AWGN interference according to the *ICF* to right. For high SIR the theoretical BEP will fit the simulation result. Thereby, the *desired ICF* gives the possibility to use the AWGN approximating for estimate the BEP, and avoid severe underestimation of the BEP.

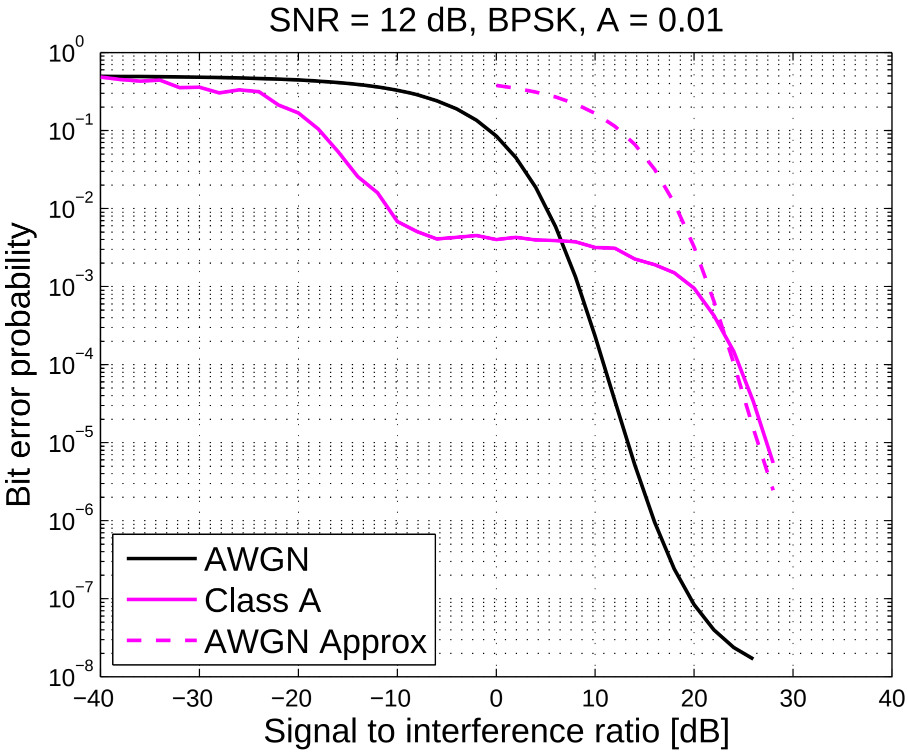

Figure 3-6 The results from correcting the AWGN approximation with the *desired ICF*.

3.3 *Desired ICF* dependence of the SNR

Before further investigations are made of the *desired ICF* it is important to determine if the measure is dependent of the used signal-to-noise ratio (SNR). If the measure is dependent of the SNR we must consider the impact when the *desired ICF* is used for correcting BEP. Therefore, several simulations have been done with used model in section 2.3. In all simulations the interference signal is a Middleton Class A interference with A=0.01 and with different values on Γ.

The estimated *desired ICF* from the simulated BEP are shown in figure 3-7 for different SNR. The values on the *desired ICF* can also be seen in table 3-3. When the figure is inspected we can se that the *desired ICF* is clearly dependent on used SNR. The *desired ICF* increases with SNR for all Γ. Also, for Γ<1 the *desired ICF* seems to reach a plateau at SNR=12 dB. However, for higher Γ the *desired ICF* still increase. The estimated *desired ICF* for SNR=18 dB is lower than for SNR=15 dB. The level difference depends on errors which originate from the simulations. For high SIR levels the simulations are very time consuming and if the *desired ICF* is estimated in incorrect SIR-interval (to low SIR) it causes error.

In table 3-3 two regions are marked. The large section shows that the *desired ICF* seems independent of Γ for Γ<0.1. Furthermore, the grey colored area shows a region for which either Γ or SNR influence the *desired ICF*. Moreover, the influence on the *desired ICF* from changing SNR must be further analyzed in future work.

Table 3-3 The estimated *desired ICF* for Class A interference with A=0.01 and different Γ and SNR.

	***Desired ICF* [dB]**					
SNR [dB]	**Γ=10**	**Γ=1**	**Γ=0.1**	**Γ=0.01**	**Γ=0.001**	**Γ=0.0001**
7	0.6	3.4	5.5	5.8	5.9	6
9	1.7	7.1	9.6	10	10.1	10.2
12	5.1	10.8	13.3	14	14.1	14
15	7.6	12.2	14	14.5	14.5	14.6
18	-	-	13.6	13.9	13.9	13.9

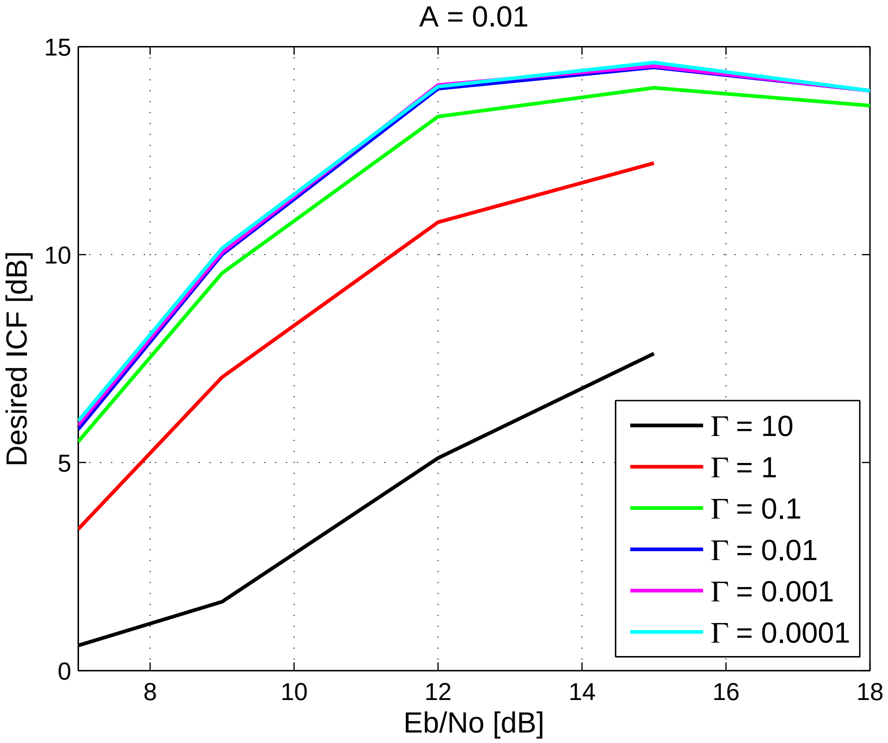

Figure 3-4 The estimated *desired ICF* from BEP curves from simulations with different SNR.

3.4 Conclusions

In chapter 3 we have performed simulations for a uncoded BPSK modulated radio system. From simulated BEP curves the *desired ICF* have been estimated. The used Class A interference model is a flexible model with a possibility to vary the interference parameters from arbitrary impulsive to near Gaussian. As a consequence from this flexibility it is difficult to derive a direct relation between the *IR* and the *desired ICF* without considering the parameter A and Γ. This can also be seen in the simulation result done to compute the *desired ICF*. It is probably easier to derive a relation between the *ICF* and the *IR* for a fixed A. In that case, only the ratio between the mean power of the Gaussian noise component to the non-Gaussian noise component is changed.

In order to achieve the *desired ICF*, the *IR* was suggested in (2) for pulse modulated signals. Here, we have investigated the relation between the *IR* and the *desired ICF* for all the simulations with all combinations of A and Γ. Those simulation results indicated that there exist no obvious relation between the calculated *IR* and the *desired ICF* regardless of A and Γ. Consequently, the relation in (2) was also shown to fail for this kind of interference.

Since the *desired ICF* seemed to be correlated to booth A and Γ we used another approach. The relation between *IR* and the *desired ICF* was studied with one parameter fixed and the other varies. When the calculated *IR* was plotted against the *desired ICF* a strong correlation between those was obvious, especially to *A*. Also, the *desired ICF* seems to approach the maximum level when *IR* increases. The maximum level differs for different *A*. If *A* is known for the interference we could use the maximum *desired ICF* which would give an upper limit on BEP. Also, the result showed that different Class A signals with identical *IR* gives different *desired ICF*. The calculated *IR* is therefore not enough information about the interference signal to estimate the *desired ICF*.

The method of using the estimated *desired ICF* according to (7) has also been shown. The BEP is corrected by using the *desired ICF* factor to simply move the BEP of the AWGN interference according to the *ICF* to right. In the SIR area of interest the theoretical BEP will fit the simulation result. Thereby, it gives us the possibility to use the AWGN approximation for estimate the BEP, and avoid severe underestimating of the BEP.

Furthermore, the measure *ICF* dependencies of used SNR have been analyzed. The evaluation is based on several simulations. The result shows that the *desired ICF* depend on used SNR but the effect from this on the corrected BEP must be further analyzed in future work. For low SNR the BEP is already high but there is a need to evaluate how much BEP is underestimated by not correcting SIR with the *desired ICF*. With increasing SNR the *desired ICF* reaches a maximum which depends on used *A* and *Γ* of the interference signal.

Another interesting conclusion can also been made from the simulations. In the BEP curves a saddle point can be observed which is dependent on the parameter *A* and used modulation method. The saddle point can be approximated to *A*/2 for BPSK systems. This level can be useful for deciding when it is necessary to correct the AWGN approximation or not. Different services used in a digital radio system require a certain BEP level and if *A*/2 is lower than the requirement correcting is not needed. For example, if the required BEP is 10^{-3} and for A=0.001 then $A/2=5\cdot 10^{-4}$ and correction is not necessary.

To conclude:

The *desired ICF* for a class A interference signal is dependent on the parameter *A* and *Γ* and the SNR, of which all can be estimated. This opens up for driving a method to deliver the *desired ICF* by using a look-up table. It is left in future work to derive a theoretical expression or approximation of the *desired ICF* which would simplify the usage in real applications.

4 ICF for multiple Middleton Class A sources

A digital communication system can typically be co-located with different electronic equipment such as microwave ovens and personal computers. Hence, the ambient environment of the radio system often contains different kinds of interference sources from AWGN to interference with impulsiveness nature. Such environments generally have a severe influence on the digital communication system performance such as the bit error probability (BEP). Therefore, it is desirably to investigate the impact on the measure impulsiveness correction factor (*ICF*) from such environment with mixed signal sources. Earlier work done with Middleton's Class A noise model has shown that there exists no easy theoretical relation between the impulsiveness ratio (*IR*) and the ICF. Therefore, extended simulations have been performed for analyzing how the *desired ICF* is influenced of an environment with mixed signal sources. One mixed signal source can also be described as an aggregated interference source produced by a number of transmitting signal sources.

4.1 Received interference signal

The total received interference signal in the radio receiver which includes the internal noise in the receiver may be expressed as

$$i(t) = n(t) + u(t) = n(t) + c(t) + c_{\mathrm{mixed}}(t) \tag{10}$$

were each interference source (signal) is described as

$n(t)$	the internal AWGN noise in the receiver,
$c(t)$	a pure Class A interference signal with specific A and Γ,
$c_{mixed}(t)$	interference contribution from the mixed interference source.

For the rest of the chapter we assume that the internal noise $n(t)$ is always present in the receiver. The pure Class A interference signal $c(t)$ is also used when the simulated BEP is evaluated to estimate the *desired ICF* for the case when the radio system is subjected to one Class A interference signal with A and Γ. The signal $c(t)$ can be described as

$$c(t) = \sqrt{P} c^{\mathrm{A},\Gamma}(t) \tag{11}$$

where P is the power of $c(t)$ and $c^{\mathrm{A},\Gamma}(t)$ is a Class A interference signal with A and Γ with unit power. The mixed interference source $c_{\mathrm{mixed}}(t)$ is created through adding together several Class A sources with a certain A and Γ. The mixed interference source $c_{\mathrm{mixed}}(t)$ can now be described as

$$c_{mixed}(t) = \sum_{k=1}^{N} \sqrt{P_k^{mixed}} c_k^{\mathrm{A},\Gamma}(t) \tag{12}$$

where N is the number of Class A interference signals used for creating the mixed signal source, $P_{\mathrm{k}}^{\mathrm{mixed}}$ is the interference power for each signal and $c_k^{\mathrm{A,T}}(t)$ is a Class A interference signal with A and Γ with unit power. Here, it is assumed that A and Γ have the same value for all $c_k^{\mathrm{A,T}}(t)$ and $c^{\mathrm{A},\Gamma}(t)$. Furthermore, in this analysis it is also assumed that $P_{\mathrm{k}}^{\mathrm{mixed}}$ are equal for all k. The total received interference signal $i(t)$ can now be written as

$$i(t) = n(t) + \sqrt{P}c^{\mathrm{A},\Gamma}(t) + \sum_{k=1}^{N}\sqrt{P_k^{mixed}}c_k^{\mathrm{A},\Gamma}(t). \tag{13}$$

The total power P_{total} for the interference signals $c(t)$ + $c_{\mathrm{mixed}}(t)$ can be obtained as

$$P_{\mathrm{total}} = P + \sum_{k=1}^{N} P_k^{mixed}. \tag{14}$$

The power of $n(t)$ are used together with the received signal bit energy to give the correct level on the signal-to-noise ratio (SNR). P_{total} in (14) together with SNR gives the correct level on the signal-to-interference ratio (SIR). The power ratio ρ is $\rho=P/P_{\mathrm{total}}$. For the case when only $c(t)$ is present, the case with one Class A signal, the total received interference power P_{total} is equal to P. In that case is the power ratio $\rho=P/P_{\mathrm{total}}=1$.

One conclusion for the interference source $c_{\mathrm{mixed}}(t)$ can be made. By creating the mixed interference source through adding together N Class A sources with A and Γ, we create a interference signal that can be approximated as Gaussian. This is valid if N is sufficiently high. This is shown by the central limit theorem (CLT) which states that the sum of an infinite amount of equally distributed variables approaches a Gaussian distribution [9]. Therefore, the mixed interference signal $c_{\mathrm{mixed}}(t)$ can be assumed a Gaussian signal if we add sufficient number of signal sources together.

If the mixed interference source $c_{\mathrm{mixed}}(t)$ can be assumed Gaussian, the factor ρ can be used for correcting the estimated *desired ICF* for the case when only $c(t)$ in (10) is present. The new *desired ICF* can now be defined as

$$ICF = \begin{cases} ICF_{\mathrm{D}} + 10\log_{10}(\rho) & 10\log_{10}(\rho) > -ICF_{\mathrm{D}} \\ 0 & 10\log_{10}(\rho) \le -ICF_{\mathrm{D}} \end{cases} \tag{15}$$

where ICF_{D} is the *desired ICF* for the case with only $c(t)$ present ($\rho=1$). The equation (15) is valid for $\rho \in (0,1]$. Furthermore, instead of using N as criteria to decide whether the source $c_{\mathrm{mixed}}(t)$ is Gaussian enough the *IR* can be used. The *IR* for a Gaussian signal is near 1.049 dB [10]. Then, if $IR \le 1.049$ dB for $c_{\mathrm{mixed}}(t)$ we can use (15). Another approach is to use the knowledge of the parameter A for the interference signal $c_{\mathrm{mixed}}(t)$. In figure 3-3 the estimated *desired ICF* from simulated BEP was plotted against the calculated *IR* for the Class A interference signal with different A and Γ. From the figure we can conclude that for A below or near 0.1 we can approximate the

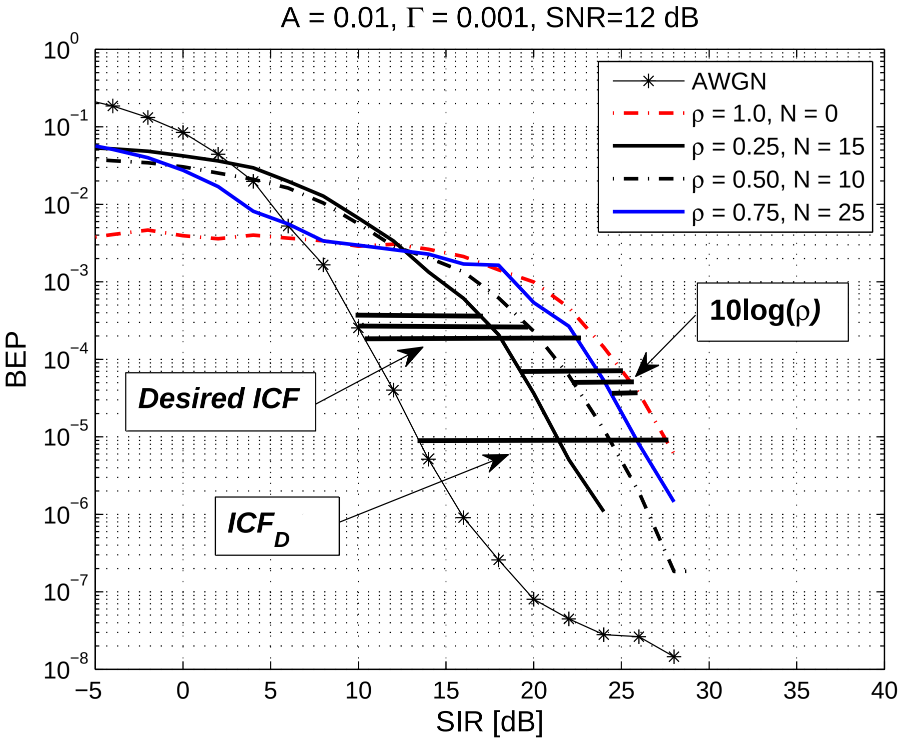

Figure 4-1 The *desired ICF* (*ICF*$_D$) estimated from BEP for one Class A source with A=0.01 and Γ=0.001. The *ICF*$_D$ are corrected with ρ to get the new *desired ICF* for the case when the Class A signal is mixed with a aggregated interference source.

maximum *desired ICF* to 7.5 dB. In that case, (15) is valid if ρ>0.18 and for lower ρ we can use the AWGN approximation instead. Otherwise, *ICF*$_D$ is too small and the new *desired ICF* gets negative.

4.2 *Desired ICF* for multiple Class A sources

The validity of the relation (15) has been investigated through extensive simulations. Also here, the estimated *desired ICF* is determined from the simulated BEP figures and is measured as the largest SIR exceeding difference achieved from the BEP determined for AWGN. In all simulations the simulation model in section 2.3 is used. The background interference $c_{\text{mixed}}(t)$ is created by adding several Class A sources with A and Γ. Each interference source is assigned a certain power level which depends on used distribution scheme presented in table 4-1. In the simulations we use the signal-to-noise ratio (SNR) together with the signal-to-interference ratio (SIR) to give the interference signal correct power level. In the case when ρ=1 and N=0, the interference signal (10) only consists of *c(t)* which contains the total amount of power. Another example of how the power is shared between signals is for ρ=0.5 and N=10. Then, the original interference source *c(t)* contains half of the power and 10 other signals (used to create the source $c_{\text{mixed}}(t)$) share the other half equally.

In figure 4-1 the BEP for the signal combinations in table 4-1 are shown. The proportions of the original interference signal are ρ=(1, 0.25, 0.50, 0.75) and the rest of the interference power are equally shared between N=(0, 15, 10, 25) number of Class A signals with A=0.01 and Γ=0.001. By inspecting the figure we can observe that correcting the *desired ICF* for the case with one signal with ρ is possible. In table 4-1 the estimated *desired ICF* from BEP curves and the new calculated *desired ICF* with (15) for the mixed interference source are shown. As we can see, the estimated and the calculated *desired ICF* agrees excellent. From the simulation results (not shown in figure 4-1) we could also conclude that for ρ=0.50 and N=2 the relation (15) is not valid. The reason for this is that the interference signal with (A, Γ)=(0.01, 0.001) have IR≈17 dB and with N=2 the interference signal $c_{\text{mixed}}(t)$ is not Gaussian enough. Therefore, for this case N must be much higher than 2 to approach a Gaussian distributed source. To conclude, for the case when $c_{\text{mixed}}(t)$ was created with Class A signals with (A, Γ)=(0.01, 0.001) N=5 seemed high enough. But for cases when $c_{\text{mixed}}(t)$ is created with Class A with other A and Γ N should differ.

The dependence between the signal measure IR and N for the source $c_{\text{mixed}}(t)$ seemed to be a natural next step to examine. With IR for $c_{\text{mixed}}(t)$ it is possible to conclude if N is high enough. If IR≈1 dB for $c_{\text{mixed}}(t)$, then N are sufficient high and the signal can be assumed Gaussian. To prove this conclusion several interference signals with different IR have been used for evaluation of (15).

Simulations have also been done with Class A signals with other A and Γ. From those simulations we can see that we can use a role of thumb that the *desired ICF* doesn't need correcting for interference signals when $A \geq 1$. The method of correcting the *desired ICF* has also been analyzed for different SNR. The results from those simulations proved that as long as the signal source $c_{\text{mixed}}(t)$ is Gaussian the method in (15) is valid and independent of the used SNR.

In [2] the *desired ICF* have been estimated for an uncoded BPSK modulated system subjected to interference signals mixed with different proportions of a pulsed and a BPSK modulated signal. In that work simulations have been done when *c(t)* consists of a pulsed signal and the mixed signal source $c_{\text{mixed}}(t)$ of a BPSK modulated interference signal with N=1.

Table 4-1 The *desired ICF* for Class A interference with $A=0.01$ and Γ=0.001. The total interference energy is shared by different combination of dominant sources ρ and number N of signal for the mixed source.

ρ, N	***Desired ICF* [dB]**	**Calculated *desired ICF* [dB] according to (15)**
ρ=1, N=0	14.1	-
ρ=0.25, N=15	8	8
ρ=0.50, N=10	10.9	11
ρ=0.75, N=25	12.4	12.7

The simulations was done with SNR=12 dB. The pulsed signal part for *c(t)* are ρ=(0.25, 0.50, 0.75). When (15) are used to calculate the *desired ICF* the results agrees with the results presented in BEP figure in [2]. It could be concluded that the relation in (15) is also valid for this kind of mixed interference signals. However, the BPSK modulated interference signal is neither impulsive nor Gaussian and the measure *IR* becomes inappropriate. Still, the effect from mixing the pulsed interference with the BPSK modulated part has the same effect on the *desired ICF*. In [2] the *desired ICF* also have been estimated for the case when the received interference signal consists of several pulsed signals with equal power and N=(1, 2, 5, 10, 50). In that case the signal *c(t)* is not present in *i(t)* and for such signal combinations the relation in (15) is not suitable.

4.3 Conclusions

The influence on the digital communication system performance in terms of the bit error probability (BEP) from a mixed interference environment has been evaluated. A new method has been derived to calculate a new *desired ICF* for a mixed interference signal by using the *desired ICF* estimated for one interference signal. The new *ICF* for multiple interference sources is defined as (15)

$$ICF = \begin{cases} ICF_{\mathrm{D}} + 10\log_{10}(\rho) & 10\log_{10}(\rho) > -ICF_{\mathrm{D}} \\ 0 & 10\log_{10}(\rho) \le -ICF_{\mathrm{D}} \end{cases}$$

where ICF_{D} is the *desired ICF* for the case with one interference source and the power ratio $\rho = P/P_{\mathrm{total}}$ were P and P_{total} comes from (14).

For the case with one interference signal, we can also use a role of thumb that the *desired ICF* does not need to be corrected when $A \geq 1$ for *c(t)*. In this case the *desired ICF* is below 3 dB and the result with (15) gets negative. The method has also been analyzed for different SNR, which verified that as long as the mixed signal source $c_{\mathrm{mixed}}(t)$ achieve Gaussian properties, the method is valid and independent of used SNR.

The method has also been evaluated on simulated results shown in [2]. It could be concluded that the method is also valid for mixed interference signals consisted of a pulsed signal and a BPSK modulated part. The method is not useful when the interference consists of N pulsed signals with equal power and when *c(t)* is not present in the received signal.

5 From measurements to application

In this chapter we discuss some issues regarding measurements of different interference sources and the possibility to use the result from these in different applications. However, the focus is not on the measurements setup or on the realization. Until now we have done the evaluation from an intersystem-interference perspective. Now, we discuss how the measurements of electromagnetic background noise or from emitting electronic equipment can be useful in different applications as e.g. simulations. The discussion have Middleton's Class A interference model in focus. This chapter will give a short survey of a conceivable routine as follows.

- The routine from measurement results made for different environment or from emitting electric equipment. Generate amplitude probability distributions (APD) from results. From the APD, estimate the parameter A and Γ for use in the interference model.
- Generate a time-domain signal from measurements and estimate A and Γ based on a Middleton's Class A model assumption. The generated signal is used in simulation to estimate a specific system influence.
- Examples of system-performance influence from Class A interference could be BEP of a digital communications system or position and time error for a Global Positioning System (GPS) receiver.

5.1 From measurements to parameter A and Γ

Measurement can be done for different kinds of electromagnetic background noise as e.g. a sub-urban electromagnetic signal environment. This kind of interference is always present and will influence the radio receiver performance. Also, different co-located electric equipment (e.g. personal computers) radiates emission levels and the emission will influence the receiver. This type of interference is often called intersystem-interference. The radiated emissions from the electric equipment are usually measured as electric field strength according to some standardized method. This is done with a certain bandwidth in a specific frequency band. Another way is to make measurements that will result in a time-domain signal instead of electric field strength. Figure 5-1 shows schematic figure of the procedure from measurements to get the estimated parameters valid for a specific noise model. Here, we use the Middleton's noise model with A and Γ. Another, interesting approach is if we have a complex environment containing several types of electric equipments positioned in e.g. urban environment. Then, it is possible to measure the complete interference signal contributed from all sources. From the measurements, we can estimate A and Γ and generate a signal with similar statistical characteristics.

It is not possible to transform the electric field strength to a time-domain signal, since the time information is lost in the electric field strength measurements. However, there still might be possible to do adequate assumptions and use the electric field strength measurements for estimation of an APD or other statistical functions describing the interference signal. From these functions a time-domain signal can be generated (directly or via the A and Γ). The APD is

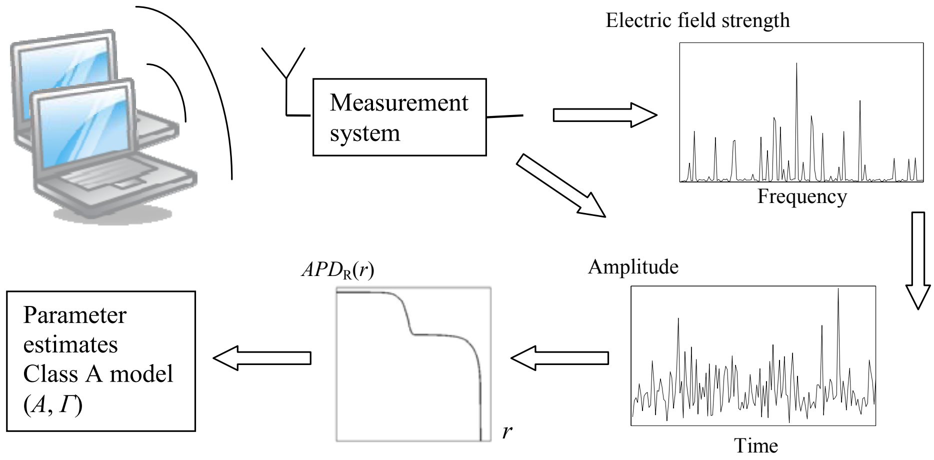

Figure 5-1 Schematic figure shows the steps from measurement to estimated parameter A and Γ from APD. The measurements can also be done for man-made noise in different background environments.

defined as the part of time the measured envelope of a disturbance exceeds a certain level [11]. From the APD we can estimate A and Γ according to method described in [12]. Further research needs to be done on how the translation can be performed.

5.2 From *A* and *Γ* to simulations

According to section 5.1, there are methods to generate an interference signal. The generated time-domain signal has some statistical characteristics typical for the measured background environment or the electric equipment. The simulations are made to analyze the interference influence of a specific system. It is important to note that the interference model used here, Middleton's Class A noise model, assumes that the noise signal has smaller or equal bandwidth as the receiver or other used simulations system. Furthermore, it models the amplitude statistics and does not describe the order in time the amplitude samples come. Hence, the generation of the time-domain signal, from a certain A and Γ, results in a randomly order of the amplitude samples. If the radio receiver uses deinterleaving or do not utilizes any memory in the detection (some of these assumptions are usually fulfilled) this is not a problem.

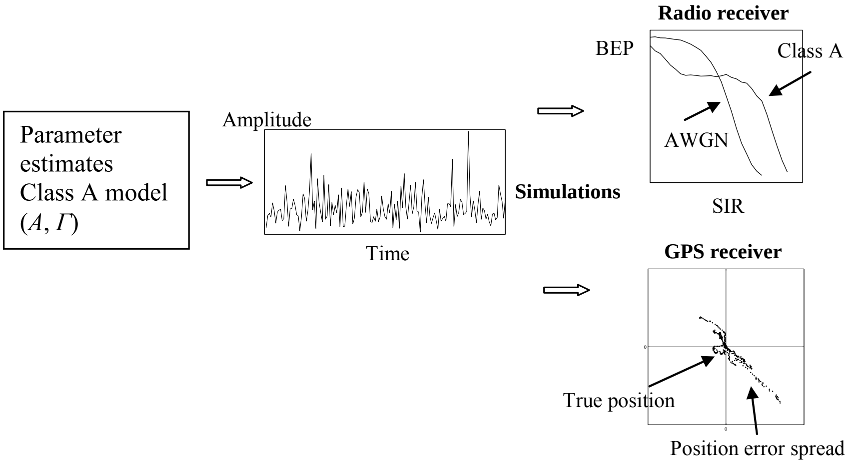

Figure 5-2 The figure shows examples of simulations when estimated *A* and *Γ* from an APD can be used.

5.3 Examples of simulations with Class A noise

This section will give some reasons for why Middleton's noise model is usable for a variety of different simulations. Firstly, the model is very flexible. When the model parameters vary the interference is changed from arbitrary impulsive to near Gaussian. As long as the generated signal has smaller or equal bandwidth as the simulated system the Class A model are usable. The system of interest can be e.g. a digital communications system or a Global Positioning System (GPS) receiver. The simulations of a radio system can be made in e.g. Matlab and for GPS systems it can be performed in a GPS simulator. Studying a GPS system, the the GPS simulator can be loaded with a specific Class A signal with *A* and *Γ* to evaluate the influence on the time or position error for a specific tested GPS receiver. In figure 5-2 examples of simulations when the generated Class A interference with *A* and *Γ* is used.

Another interesting approach is to save all required information in a database. The database makes it possibly to translate the characteristics of the interference signal direct into system performance influence. The database information can be divided in two parts. One part is about the interference signal as *A*, *Γ*, and the calculated *IR*. The other part is about the simulated system. For the case when a digital communication system is simulated we collect information about e.g. the modulation method and the *desired ICF*. The database makes it possible to load the *desired ICF* for a specific parameter setup and then simply correct the AWGN approximation. Furthermore, with *IR* for the interference signal we can also estimate if the derived method for mixed interference sources is valid.

6 Summarized conclusions

The correction factor *desired ICF* has been investigated for an uncoded BPSK modulated radio system subjected to different combination of Middleton's Class A signals. The *desired ICF* is used for correcting the Gaussian approximation as the approximation has been shown to not be valid especially for pulse modulated signals [1]. For large SIR, the degradation can be severe. The measure *desired ICF* has been investigated for two different cases.

- When the interference signal consists of a single source.
- When the interference signal consists of several aggregated transmitting sources creating a mixed interference environment.

6.1 Single interference source

In order to achieve the *desired ICF*, the *IR* was suggested in (2) and in [1] for pulse modulated signals. With that aim, one part of this work was to investigate the relation between the *IR* and the *desired ICF.* The results indicate that there exist no obvious relation between the calculated *IR* and the *desired ICF* regardless of A and Γ. Also, the result show that different Class A signals with identical *IR* gives different *desired ICF*. The calculated *IR* is evidently not enough information about the interference signal to estimate the *desired ICF*.

Instead it is stated that the *desired ICF* has a strong correlation to the parameter A. With a fixed A the *desired ICF* approach a maximum level with increasing *IR*. The maximum level differs for different A. If we know A for the interference signal we could use the maximum level on the *desired ICF* to get an upper limit on the BEP.

In the BEP curves, a saddle point can be observed, which is dependent on the parameter A. The saddle point can be approximated to $A/2$ for a BPSK receiver. This level can be used for deciding when it is necessary to correct the AWGN approximation or not. When a communication service in a digital radio system require a BEP level below $A/2$ then a correction is not needed.

Furthermore, the *desired ICF* seems dependent of used SNR and the effect on the corrected BEP must be further analyzed. With increasing SNR, the *desired ICF* reaches a maximum which depends on used A and Γ of the interference signal.

The *desired ICF*, for the case with one interference signal, doesn't need correcting when $A \geq 1$, as the signal has approximately a Gaussian distribution.

6.2 Multiple interference sources

A new method has been derived to calculate a new *desired ICF* for a mixed interference signal by using the *desired ICF* estimated for one interference signal. The new *ICF* for multiple interference sources is defined as

$$ICF = \begin{cases} ICF_{\mathrm{D}} + 10\log_{10}(\rho) & 10\log_{10}(\rho) > -ICF_{\mathrm{D}} \\ 0 & 10\log_{10}(\rho) \le -ICF_{\mathrm{D}} \end{cases}$$

where ICF_{D} is the *desired ICF* for the case with one interference source and the power ratio $\rho = P/P_{\mathrm{total}}$ were P and P_{total} comes from (14).

For the case with one interference signal, we can also use a role of thumb that the *desired ICF* does not need to be corrected when $A \geq 1$ for *c(t)*. In this case the *desired ICF* is below 3 dB and the result with (15) gets negative. The method has also been analyzed for different SNR, which verified that as long as the mixed signal source $c_{\mathrm{mixed}}(t)$ achieve Gaussian properties, the method is valid and independent of used SNR.

The method has also been evaluated on simulated results shown in [2]. It could be concluded that the method is also valid for mixed interference signals consisted of a pulsed signal and a BPSK modulated part. The method is not useful when the interference consists of N pulsed signals with equal power and when *c(t)* is not present in the received signal.

7 Further work

The results in this work show strong correlation between the *desired ICF* and different interference parameters. Most promising seems to be the relation between *desired ICF* and of A and Γ of the Midddleton class A interference model. Also the SNR is shown to influence the *desired ICF*. The conclusion is that the concept *desired ICF* is promising and that it can be used in a variety of applications as described in chapter 5. However, to simplify the usage and the applicability it would be advantages to:

- Derive a theoretical expression between the *desired ICF* and of A and Γ while considering the SNR.
- Derive a theoretical expression or modify the one for the *desired ICF* for other modulation schemes.
- Develop a method to transform the measured electrical field strength to a time-domain sequence of the interference valid under certain assumptions. Such an interference model could then be used in different kinds of simulations.

Derive of A and Γ of measured background environments to be used in different kinds of simulations.

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