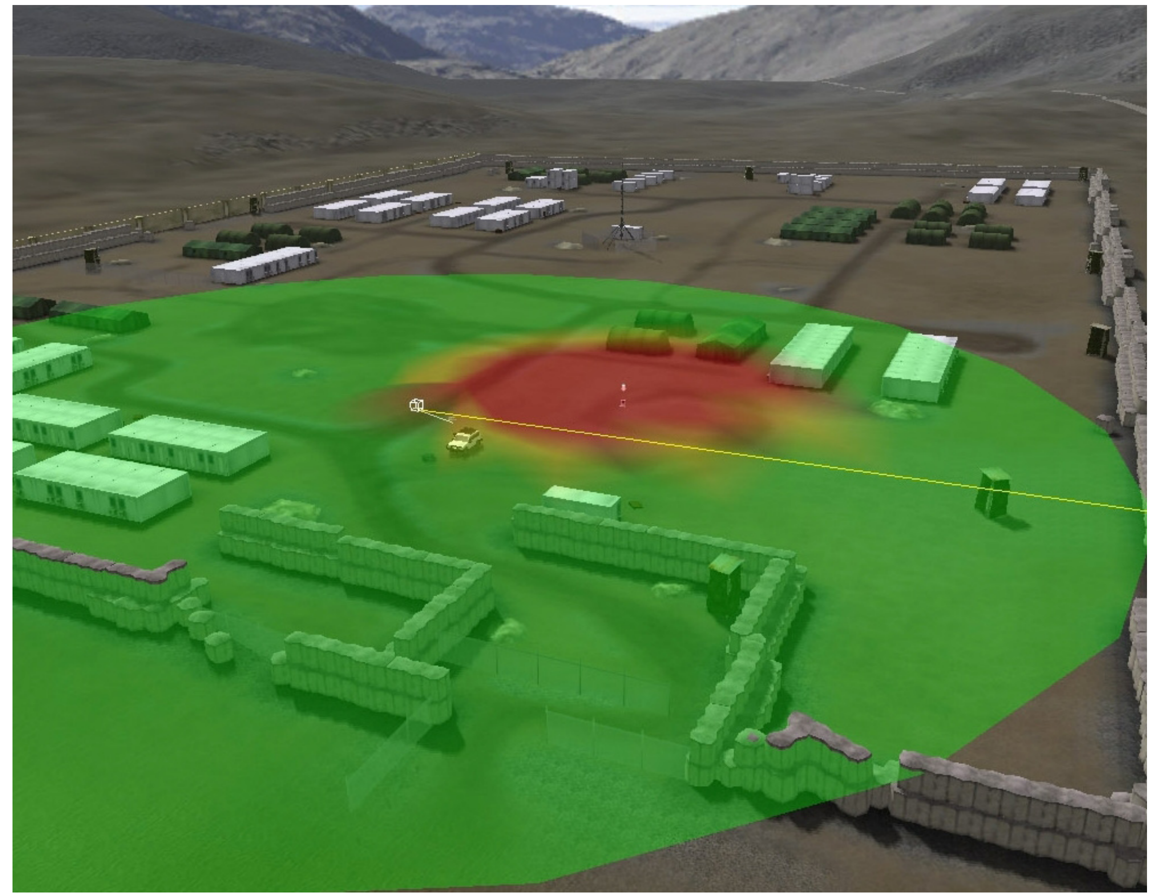
The impulsiveness correction factor for a mix of interference sources

KARINA FORS, KIA WIKLUNDH, SARA LINDER



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Sammanfattning

Förenklade approximativa formler för att bestämma prestanda för digitala radio kommunikationssystem är önskvärda. Dagens befintliga metoder är relativt komplicerade och tidkrävande då prestanda ska beräknas för störningsmiljöer med impulsaktig karaktär. Det finns behov av förenklade metoder exempelvis i telekonfliktanalysverktyg och för frekvensbandsmätningar för att undersöka beläggningen av störningar och andra användare vid dynamisk spektrumaccess (DSA)-tillämpningar.

En korrektionsfaktor (impulsiveness correction factor (ICF)) har tidigare föreslagits för att ge möjlighet att använda förenklade approximativa prestandaberäkningar. Med hjälp av korrektionsfaktorn kan den så kallade Gaussapproximationen av störningssignalen som ger enkla prestandaformler användas.

Korrektionsfaktorn har i detta arbete utvecklats för att täcka en större grupp av störningstyper och radiosystem vilket innebär att dess användbarhet i praktiska tillämpningar ökar avsevärt. Korrektionsfaktorn används i Försvarsmaktens nya datorbaserade verktyg (NTK) för telekonfliktanalys liksom i FOI:s demonstratorverktyg GENESIS. Korrektionsfaktorn har publicerats i två vetenskapliga tidsskriftsartiklar.

Detta projekt har finansierats av FMV.

Nyckelord: ICF, korrektionsfaktor, Gauss approximation, interferensmiljö, telekonflikt

Summary

Simplified algorithms used to determine the performance of digital radio communication systems is desirable. Today, existing methods are relatively complicated and time-consuming when performance is calculated for interference environments with impulse-rich character. There is a need for simplified methods for example in telecommunications conflict analysis tools and the frequency measurements to study the occupancy from disturbances and other users in the dynamic spectrum access (DSA) applications.

A correction factor (impulsiveness correction factor (ICF)) has previously been proposed to allow the use of simplified approximations performance calculations. Using the correction factor in the so-called Gaussian approximation of interference signal provides that the simple performance formulas can be used.

The correction factor in this work has been developed to cover a wider group of interference signals and radio systems which means that its usefulness in practical solutions has increased significantly. The correction factor are used in the Swedish armed forces new computer-based tool (NTK) for intersystem-interference analysis as well as in FOI's demonstrator tool GENESIS. Furthermore, the correction factor has been published in two different scientific articles.

This project was funded by the Swedish defence material administration.

Keywords: ICF, impulsiveness correction factor, Gaussian approximation, interference environment, intersystem interference

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1 Introduction

The herein correction factor has been developed to cover a wider group of interference signals and radio systems which means that its usefulness in practical solutions has increased significantly. The correction factor are used in the Swedish armed forces new computer-based tool (NTK) for intersystem-interference analysis as well as in FOI's demonstrator tool GENESIS. This work was funded by the Swedish defence material administration.

The concept of impulsive correction factor (ICF) has been shown useful as a correction factor for bit error probability (BEP) calculations in order to reduce the complexity in such calculations. It allows use of simple performance estimation formulas for arbitrary interference signals that may affect a radio communication system. The simplifications can be necessary in order to avoid time consuming calculations or complicated modeling of the reality. Examples of applications for ICF are:

- Intersystem interference analysis tools
- Dynamic spectrum access

To prevent crucial degradation of the communication system, it is necessary to analyze co-location situations of electrical equipment and radio systems. This can be performed in a so-called intersystem-interference analysis tool. The analysis may contain exhaustive modelling of transmitters and numerical electromagnetic modelling techniques to model the electromagnetic field radiated from the interference sources. An alternative way is to measure the interference signals at the input of the receiver antenna and from this information estimate its impact on the communication system performance. Another alternative way is to use a relevant interference model of the interference source to estimate the performance degradation of a digital radio receiver. Common for the different approaches is that they involve a lot of complex calculations. For this reason, it is essential to have appropriate simplified methods to get computationally tractable expressions.

The purpose of dynamic spectrum usage is to use frequency bands dynamically. Hence, methods to sense the actual occupancy and interference level in a certain frequency band are crucial, both on higher system level and in some cases in single receivers. A key issue in future dynamic wireless applications is therefore the ability to sense and consider the total electromagnetic interference within the receiver band of the wireless communication system. Such methods must be fast and of low complexity to be useful in on-line applications and in distributed solutions. Therefore a simple but useful method is tractable to find.

Common for both applications, interference sources are often modelled as additive white Gaussian noise (AWGN), for which there exist simple mathematical expressions. The Gaussian approximation 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, there are many situations where Gaussian-like interference is not the most common type. For pulse modulated signals, the approximation has been shown not to be valid [3].

For the application of dynamic frequency usage and spectrum sensing the measure is commonly named interference temperature. This measure is based on the same principle as the Gaussian approximation and considers the total interference average power within a certain frequency band. However, one difficulty with such approach is that the wave form, not only the power, of an interfering signal can significantly affect the performance of a digital wireless system. In practical applications, pulsed interference signals cause the largest errors in BEP when the GA is used. These errors can be in the order of several magnitudes.

An ICF has been proposed in [1]. The ICF can be used as a rough adjustment for the interference-waveform properties so that the measured total interference average power can be used for performance estimation of radio communication systems and as a decision metric in future dynamic applications.

In this work we will summarize the work on ICF for:

- One pulse modulated signal [1]
- A mix of several interference signals where one is dominant for a general class of signals, the Middleton Class A model [3].

Furthermore, new results are presented for the ICF when there is

- One non-periodic interference signal (Middleton Class A model). The ICF is presented for different modulation schemes
- A mix of several interference signals (Middleton Class A signals) when the power is divided equally between the signals

The interference model chosen, Middleton Class A model, has the advantage that it can represent a number of different types of interference signals with arbitrary impulsiveness.

The modulation methods studied are modulation methods used in current and coming new radio communication system used by the Swedish military.

The report is organized as follows. Chapter 2 describes the adopted simulation model and the interference model studied. Also the definition of the ICF is presented. Chapter 3 describes the ICF for a periodic or non-periodic interference source. In chapter 4, the ICF for multiple interference sources are investigated. Chapter 5 shows how the correction factor can be implemented in an intersystem-interference tool when the scenario can be complex with many interference sources. In chapter 6 and 7, the work is concluded and future work is described, respectively. Finally, two appendices are given where the interference model is presented more in detail and a paper accepted for the IET Communications is inserted.

2 Preliminaries

In this chapter the used simulation model of the radio communication system for investigating the measure ICF is described. Also, the different kinds of interference signals and the definition of the ICF are described.

2.1 Simulation model

In this work, the performance of a digital communication system is analyzed under the influence of interference and thermal receiver noise. In figure 1 the simulation model for the radio system is shown. The thermal receiver noise signal n is modeled as AWGN with the single-sided power spectral density N_0. Together with the signal bit energy E_b, the signal to noise ratio (SNR) can be determined. An interference signal u is added to the received signal. No error correction coding is assumed in the simulation model. The system performance is studied from the bit error probability (BEP) curves for different levels of signal to interference ratios (SIR), defined as E_b/N_I, where N_I is the corresponding power spectral density (psd) for the interference within the receiver bandwidth.. To estimate the BEP the received bit sequence is compared with the transmitted one.

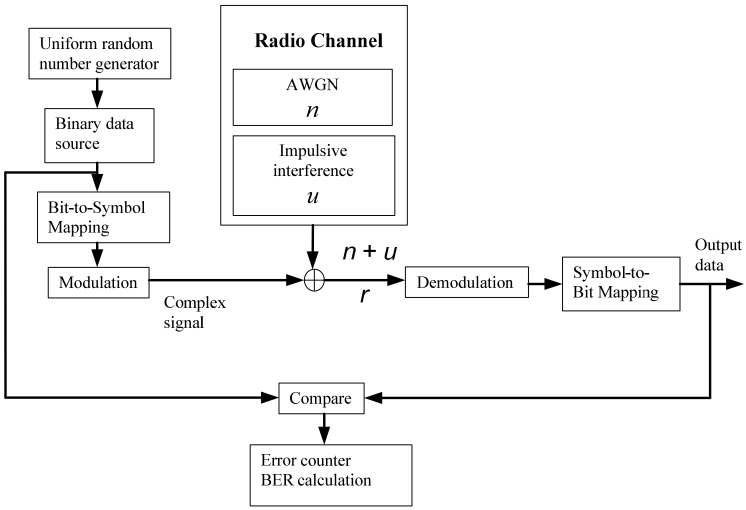


Figure 1 The simulation system model for illustrative. The received signal *r* contains the signal of interest, the thermal noise *n* and the interference signal *u*.

The BEP is also studied for the case when the interference consists of AWGN. From the simulated BEP-curves, the ICF is determined as the largest SIR difference achieved between the BEP determined for AWGN and Class A interference respectively. The performance is dependent on the adopted modulation scheme. For our purpose some different modulation schemes are of interest, namely:

- Binary phase shift keying (BPSK)
- Minimum shift keying (MSK)
- Differentially quadrature shift keying (DQPSK)
- Gaussian minimum shift keying (GMSK)
- Continuous phase modulation (CPM)

These modulation schemes are chosen as they are relevant for the radio communication systems used by the Swedish armed forces. The simulations are performed in Matlab or Simulink.

2.2 Interference signals

The considered interference signal *u* in the simulations is either a:

- Periodic pulsed interference.
- Non-periodic pulsed signal with random phase and arrival time. The arrival time is modeled as a Poisson process and the pulses in the signal can overlap each other.
- BPSK-modulated signal assumed to be in phase with the communication system and a pulse modulated signal.
- Middleton's Class A signals
    - One interference signal
    - A mix of several interference signal of which one is dominant
    - A mix of several interference signal of which the power is equally divided

For the case when the interference *u* consists of a mix of several signals, the signals are added together independently. However, the power for each signal is set to a predefined value. Two different cases are possible, either the total power is equally divided on all signals or one has higher power level than the rest of the signals. The latter is the case with a dominant interference signal.

2.3 The definition of the impulsiveness correction factor

The measure ICF is defined as the maximum SIR difference, between the two BEP curves estimated for AWGN and for a certain interference signal with the same average power. In figure 2, one example of the ICF, is showed.

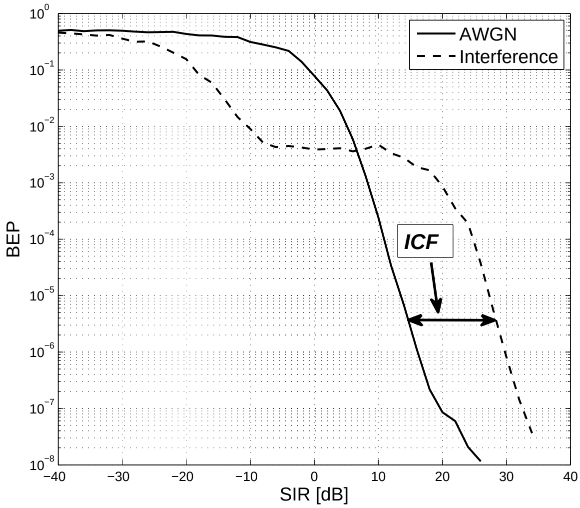


Figure 2 The ICF is the largest SIR difference between the BEP-curve for AWGN and the current interference signal with the same equal average power.

3 ICF for one signal

In this chapter, the ICF is analyzed for the case when the digital communication system are subjected to one interference signal. The interference is either a periodic or non-periodic signal. Also, different un-coded modulation schemes are considered. The results for periodic pulsed interference and non-periodic pulsed interference below are summarized from previous published work.

3.1 Periodic pulsed interference

In [1] it has been shown that the ICF for a a periodic pulsed interference on an un-coded binary phase shift keying (BPSK) is investigated can be approximated as

$$ICF \approx ICF_{\text{offset}} + \frac{3}{4} IR \text{ , [dB]} \qquad (1)$$

were the $\text{ICF}_{\text{offset}}$ is a offset factor and depend on the used modulation scheme. The impulsiveness ratio (IR) is defined as

$$IR = 20 \log \frac{V_{\text{RMS}}}{V_{average}} \text{ , [dB]} \qquad (2)$$

where V_{RMS} and V_{average} are the root-mean square and time average values of the interference. For pulse modulated interference with pulse repetition frequency f_{p} passed through an IF filter with bandwidth W_{IF} , the IR is [2]

$$IR = 20 \log \frac{\sqrt{W_{\text{IF}}}}{\sqrt{f_{\text{p}}}} \text{ . [dB]} \qquad (3)$$

It should be noted that both the ICF and IR measurements should be performed with the same bandwidth as the digital communication system of interest use.

For this kind of interference the power level in the interference signal is only present during the pulse part (during the duty cycle) in one period.

3.2 Non-periodic pulsed interference

In [2], the ICF has been analyzed for a non-periodic pulsed signal. The signal differs from the previous described signal simply by the fact that the signals arrive randomly with random phase. However, the repetition time and duration time are not changed. The interference can still be characterized by two different states; one state with no interference and one state with interference. The analysis showed that the expression in (1) can be used for this type of signal when the pulses occurs every tenth bit or more rarely, for BPSK modulation.

3.3 Non-periodic Class A interference

So far, the ICF measure for a digital communication system subjected to some kind of pulsed interference has been analyzed. Typical for this kind of interference is that the signal power is present only in the signal pulse. Now, we consider another type of interference. For this purpose, Middleton Class A interference model is used. For more details, see Appendix A. This model is very flexible and by varying the models parameters, it can be used to generate an arbitrary impulsive or close to a Gaussian signal. In contrast to the pulse modulated interference (both periodic and non-periodic), the interference for this model is continuously transmitting interference power

The relation in (1) has been analyzed for an uncoded coherent BPSK modulated communication system exposed to Class A interference, [3]. For this kind of interference, the relation in (1) is not applicable. Conclusions from the investigation showed that the information of IR is not sufficient information of the Class A signal. The model parameter A and Γ must also be considered. For various Class A signals, with different A and Γ, the calculated IR is identical but the ICF differ.

In this work we have further investigated the relation between A and Γ and the ICF for different modulation schemes. In figure 3-7, the ICF is shown in combination with different Class A model parameters. For every figure a certain modulation scheme is analyzed. The IR is plotted against the ICF for different A and Γ. The used Γ is shown in the figure legend. For each A, the curve approaches a maximum ICF value, ICF_{max}, the dotted red lines. From the figures, it is obvious that signals with the same IR, for example with IR≈1 dB, can result in different ICF. The measure IR, is apparently not enough information about the Class A signal and the relation in (1) is hence not valid for this kind of signal. However, if the parameter A is known, we can use the ICF_{max} to give the worst case. In table 1 the ICF_{max} are given for A between 0.001 and 1.

Table 1 The ICF_{max} for Class A signals with different *A* and modulation schemes.

	ICF_{max} [dB]			
Modulation scheme	Middleton's Class A parameter *A*			
	1	0.1	0.01	0.001
BPSK	3	8	14	23
MSK	3	8	13.5	22
DQPSK	-	3	7.5	14
GMSK	1.5	5	9	
4-CPM	1.5	5	8	

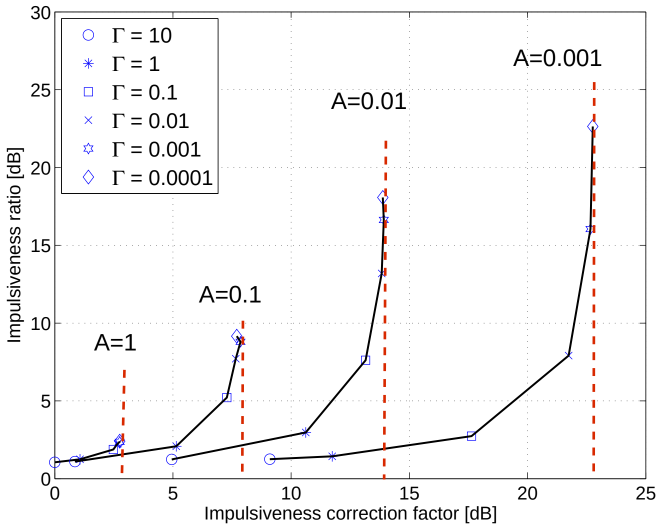


Figure 3 Simulated ICF for Middleton´s Class A model with different *A* and *Γ* for uncoded coherent BPSK-modulated system.

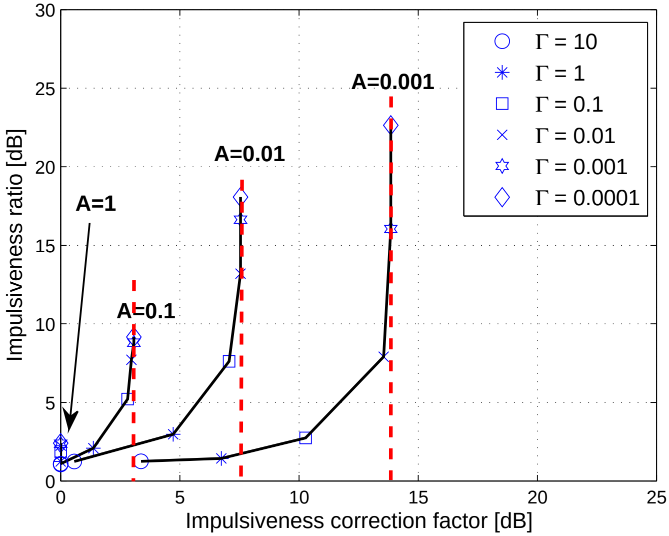


Figure 4 Simulated ICF for Middleton´s Class A model with different *A* and *Γ* for an uncoded DQPSK-modulated system.

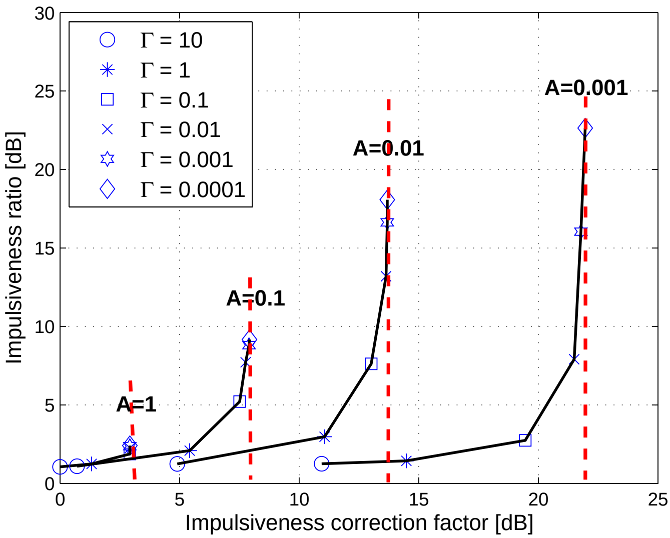


Figure 5 Simulated ICF for Middleton´s Class A model with different *A* and *Γ* for an uncoded MSK-modulated system.

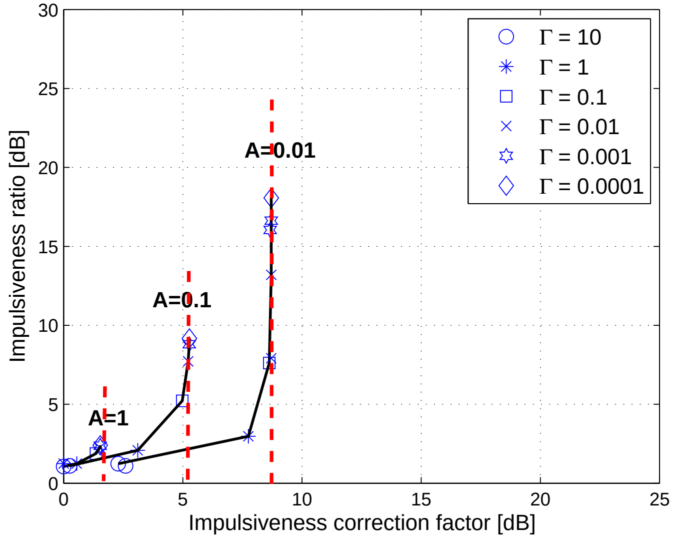


Figure 6 Simulated ICF for Middleton´s Class A model with different *A* and *Γ* for an uncoded GMSK-modulated system.

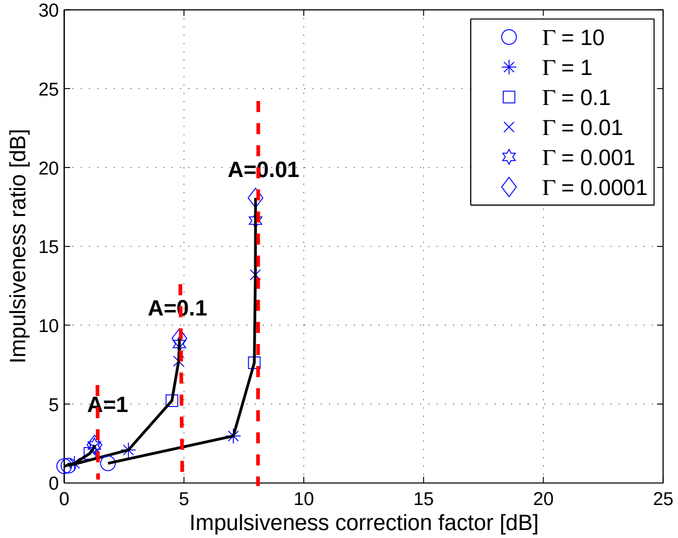


Figure 7 Simulated ICF for Middleton´s Class A model with different *A* and *Γ* for an uncoded 4-CPM-modulated system.

3.4 IR dependent on Class A parameters A and Γ

In section 3.3, we stated that the information of the IR for a Class A signal is clearly not enough information of this kind of signals. Different A and Γ give the same IR but different ICF. Therefore, we have calculated the IR for different parameters and in figure 8 the IR is plotted against A and Γ in dB. In the figure, it can be seen that there is a maxima of the IR for the current parameter around A=-40 dB and Γ=-30 dB. For the analyzed A values the IR increases as A reduces. However for Γ, there is not such a simple relation. For Γ, there is a local maxima around Γ=-30 dB.

3.5 Relation between the Class A parameters and the ICF

In [1], a theoretic relation between IR and ICF was derived. This relation has shown not to be valid for Class A signals. However, the results shown in section 3.3 indicate that the model parameter A and Γ has great influence on the ICF. By analyzing the properties of the Class A probability density function (pdf) [9], a theoretic relation can be used to obtain an approximate value of the ICF. In [9],

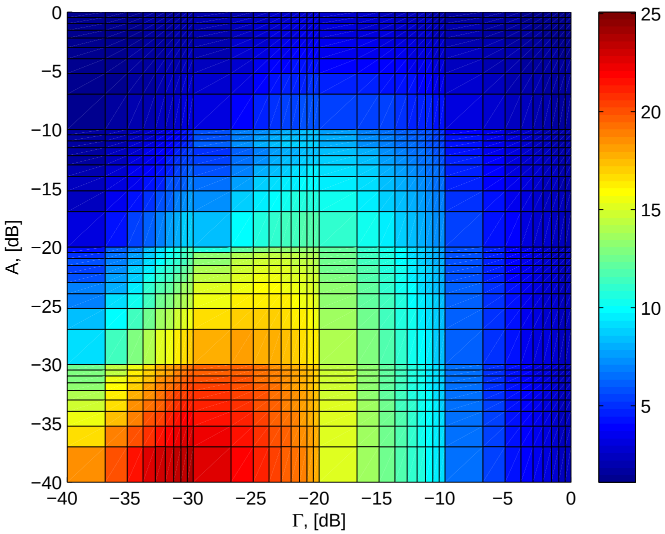
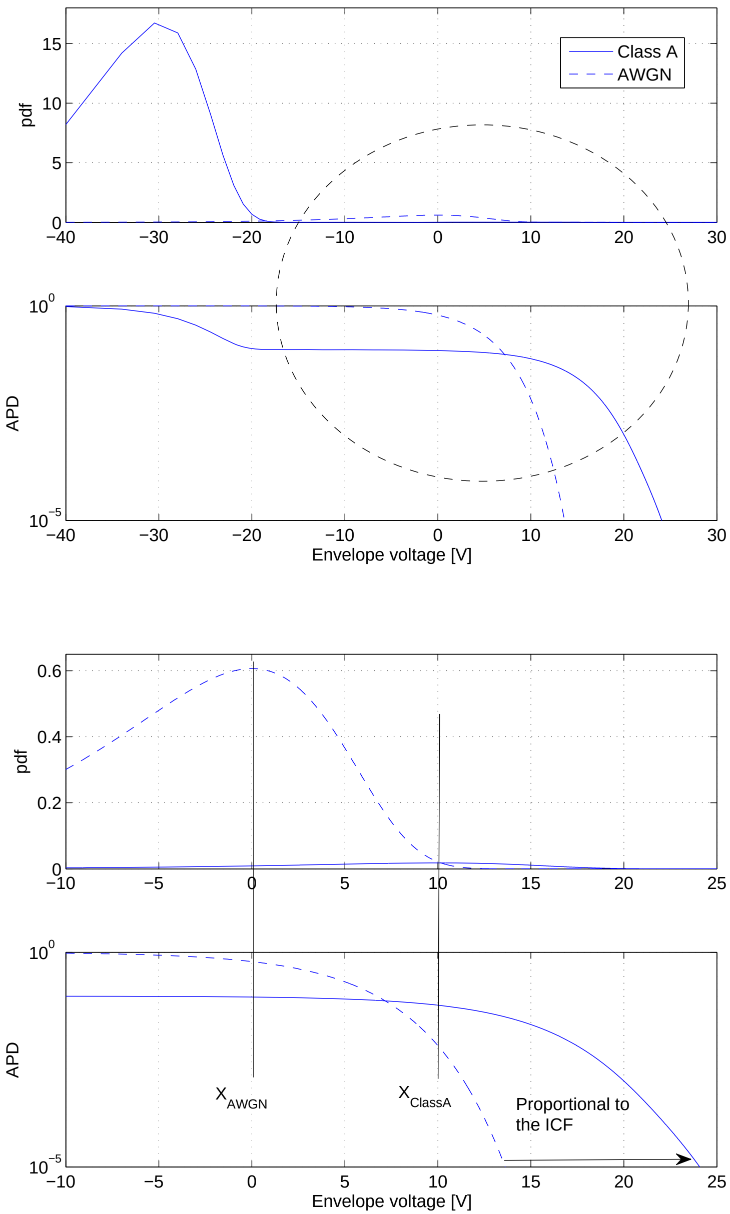


Figure 8 The IR plotted against the Class A parameters A and Γ in dB.

the pdf and the amplitude probability distribution (APD) of a Class A interference is examined. In particular, expressions for the location of the peaks in the pdf are shown. Based on the fact that the APD of an interference signal is proportional to the BEP of several modulation schemes [10], we can identify the maximum difference between the two APDs as a factor times the ICF. Unfortunately, this distance is difficult to determine. Instead, an approximate value of the distance can be derived by taking the difference between X'_{ClassA} and X'_{AWGN}, which are the amplitude vales where the peak of a Gaussian pdf X'_{AWGN} and the right-most peak of the Class A pdf X'_{ClassA} appear. In figure 9, we can see an example of the pdf and the APD plotted for a Class A interference with the parameter values A=0.1, Γ=0.001.



Figur 9: The pdf and the APD for a Class A interference with *A*=0.1, *Γ*=0.001, with the locations X'_{ClassA} and X'_{AWGN} inserted. The lower two plots are an enlargement of the upper two.

The location of the peak of the *m*th term X'_m in the Class A pdf can be obtained as [9] $X'_m = 10\log\left(\frac{1}{L_m}\right)$, where $L_m = \frac{1}{m\frac{\sigma_I^2}{A} + \sigma_G^2}$ and $\Gamma = \frac{\sigma_G^2}{\sigma_I^2}$ for a Class A interference. In [8], it is shown that *m*=0 and 1 have the largest influence on the pdf and the APD, why the approach is to use the X'_1 as an approximate value of the place where the Class A APD begins to fall (*m*=0 corresponds to the first slope and *m*=1 to the second, which we are interested of). That is

$X'_{ClassA} \approx X'_1 = \frac{\sigma_I^2}{A} + \sigma_G^2 = \frac{\sigma_G^2}{A\Gamma} + \sigma_G^2 = \sigma_G^2\left(\frac{1}{A\Gamma}+1\right) = \left(\bar{I} - \sigma_I^2\right)\left(\frac{1}{A\Gamma}+1\right)$, where $\bar{I}$ denotes the average power

For the AWGN interference, the value X'_0 is the location of the peak of the AWGN pdf. Hence, X'_{AWGN} can be obtained as

$X'_{AWGN} = X'_{0,AWGN} = \sigma_{AWGN,G}^2 = \bar{I}$.

Therefore, the difference between X'_{ClassA} and X'_{AWGN} is

$$10\log X'_{ClassA} - 10\log X'_{AWGN}$$

$$= 10\log\left(\frac{\left(\bar{I}-\sigma_I^2\right)\left(\frac{1}{A\Gamma}+1\right)}{\bar{I}}\right) = 10\log\left(\left(1-\frac{\sigma_I^2}{\sigma_I^2+\sigma_G^2}\right)\left(\frac{1}{A\Gamma}+1\right)\right)$$

$$= 10\log\left(\left(\frac{1}{1+\frac{1}{\Gamma}}\right)\left(\frac{1}{A\Gamma}+1\right)\right)$$

Since the ICF is proportional to this distance, we can derive an approximation of the ICF as

$$ICF \approx \alpha 10\log_{10}\left(\frac{1+\frac{1}{A\Gamma}}{1+\frac{1}{\Gamma}}\right), \text{ [dB]}, \qquad (4)$$

where α is a factor to obtain the ICF. In figure 10, some results calculated with (4) and $\alpha = 1$ are shown. The estimated ICF (4) is shown on the x axis for different *A* and *Γ* values. Also, the calculated IR is shown on the y axis. The relation between the estimated ICF and the different *A* and *Γ* values is very similar to the figures 3-7 shown in chapter 3.3. In figure 11, the estimation of the ICF (eq (4) with $\alpha = 1$) is shown in combination with the simulated ICF for

DQPSK and BPSK shown in figure 3 and 4. We can see that the relation in (4) catches the general behavior as the simulation suggests but the scaling factor needs to be adjusted for the special modulation schemes. To make the relation in (4) to conform better to the simulation results for different modulation methods, (4) needs further investigations.

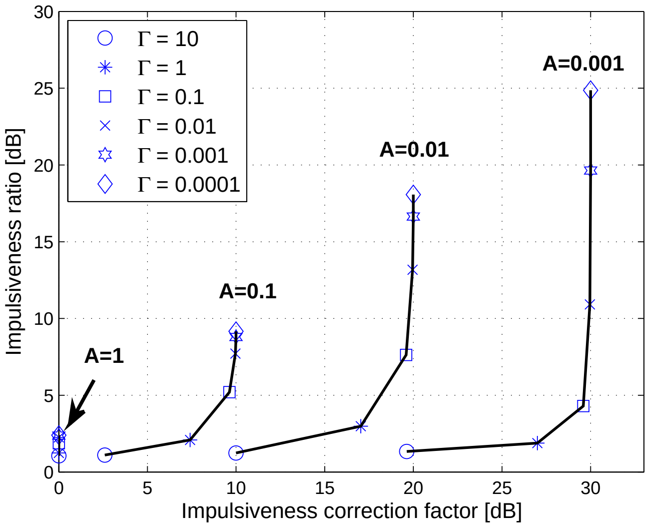
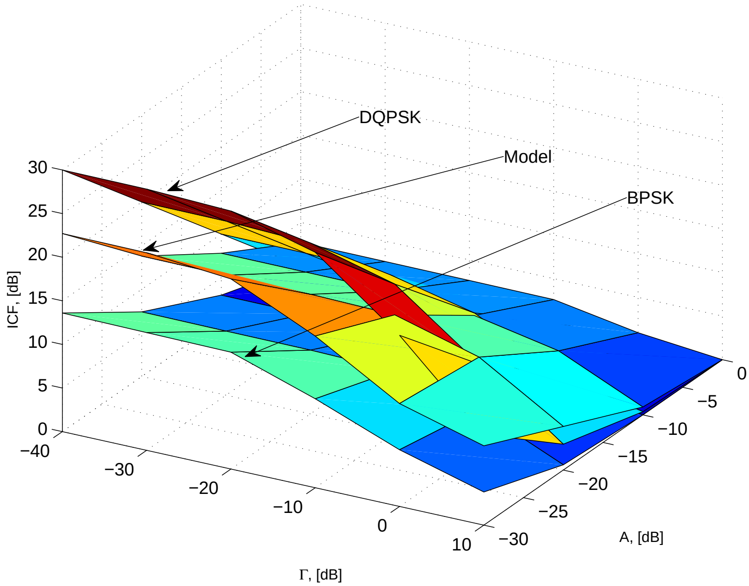


Figure 10 IR plotted against, with (4) calculated, ICF. The IR is calculated for each Class A signal with A and Γ.



Figur 11: Estimated ICF according to (4) and the simulated ICF for BPSK and DQPSK for different *A* and *Γ* values.

4 ICF for multiple signals

A digital communication system can typically be co-located with several electronic equipment, such as microwave ovens and personal computers where the sum of interference signals create the interfering environment. Hence, it is necessary to be able to obtain the ICF also for mixed signal sources. For this purpose, the BEP has been studied for such interference. The mixed signal sources studied are created in two different ways with Middleton's Class A noise model:

- One dominant signal part which contribute with most power and one part with several signals with equal power.
- Several signals with equal power.

All signals in the mixed signal source above is created with the Class A model with the same A and Γ.

However, earlier simulations with two additional interference sources [2] are also analyzed:

- One dominant interference signal made of one BPSK-signal part and the rest of a pulsed signal with random phase and arrival time.
- Several signals consisting of pulsed signals with random phase and arrival time, with equal power

The results are valid for an uncoded coherent BPSK modulation scheme.

4.1 A mix of several interference signals where one is dominant in signal power

For the simulations of the digital communication system, the total interference source is created by adding several signal sources. In the simulations each interference source is assigned a certain power with corresponding spectral density level, N_{i} [W/Hz]. The total power spectral density N_{I}, of the interference signal within the receiver band is the sum of the power spectral density of the k interference signals. The N_{I} can be denoted as

$$N_{\mathrm{I}} = \sum_{i=1}^{k} N_{\mathrm{i}} \ . \tag{5}$$

N_i is the power spectral density of interference signal number i. For the case when one of the interference signals N_i is dominant (contribute with highest power spectral density level) (5) can be rewritten as

$$N_{\mathrm{I}} = N_{\mathrm{d}} + N_{k-1}\,. \tag{6}$$

N_{d} is the dominant signal and N_{k-1} is the sum of the other k-1 interference signals. From analyzes and simulation results some conclusions can be made of how the *ICF* for N_{I} and $N_{\mathrm{d}} + N_{k-1}$ respectively are related to each other. If N_{k-1} has Gaussian properties it does not need to be corrected and therefore the following relation can be derived,

$$ICF_{\mathrm{I}} N_{\mathrm{I}} = ICF_{\mathrm{d}} N_{\mathrm{d}} + N_{k-1}\,. \tag{7}$$

The total interference consists of one part N_{d} that needs to be corrected with its corresponding ICF_{d} and one part that does not have to be corrected. (7) can therefore be rewritten as

$$ICF_{\mathrm{I}} = ICF_{\mathrm{d}}\,\rho + 1 - \rho\,, \tag{8}$$

where $\rho = N_{\mathrm{d}}/N_{\mathrm{I}}$ ($0 \le 1 - \rho \le 1$) and used for correcting the ICF_{d} valid for the case when the interference only consist of one signal. The final $ICF_{\mathrm{I}}^{\mathrm{dB}}$ can thus be written in [dB] as

$$ICF_I^{dB} \approx ICF_d^{dB} + 10\log_{10}(\rho)\,. \tag{9}$$

Thus, by identifying the dominant interference signal, a correction can be made to adjust for the largest error if the AWGN approximation is used to determine the interference impact.

4.1.1 Non-periodic Class A interference

The relation in (9) is evaluated for a Class A interference with different A and Γ parameters. The evaluation will be published in [11] and is also available in appendix B. It is shown that for this kind of interference model we will have a very good agreement with the relation in (9).

4.1.2 Non-periodic pulsed interference and BPSK interference

In [2] some results of the analysed ICF for a mixed signal consisted of a BPSK-modulated signal and a pulsed signal was published. The pulses in the pulsed signal arrived randomly and had random phase. By its rich impulsiveness, the pulsed signal is the dominant interference in this case. For this case the composite interference signal consists of two different signals, one with large impulsiveness and one (The BPSK signal) with nearly none impulsiveness. For such a case, the impulsive interference can be considered as the dominant signal. The total power spectral density of the signal was divided between the two signals in different proportions, see figure 12.

In this work, we have by inspecting the BEP-curve in figure 12 (the figure is also published in [2]) determined the ICF for the different signal cases. The ICF is then compared to with ICF calculated with (9). First, the ICF for the pulsed signal was estimated to be around 12 dB. The ICF from the simulations shown in figure 12 and the calculated ICF from (9) are summarized in table 2. From the results, we can se that (9) works very well for this kind of interference signal mix. The BPSK-modulated signal is not impulsive and the calculated IR for that kind of signal is 0 dB. Earlier results has shown that when you mix a dominant signal with a signal, or mix of signals, that have a IR close or less than 1 dB then (9) works very well.

Table 2 The ICF from the simulations shown in figure 12 and the ICF calculated with (9) for a interference signal consisted of a BPSK and a pulsed signal part. For all the cases, the pulsed signal is considered as the dominant interference.

Interference signals	**Estimated *ICF* from BEP-curve**	**With (7) calculated *ICF***
25 % BPSK and 75 % pulsed	10.7	10.8
50 % BPSK and 50 % pulsed	8.6	9
75 % BPSK and 25 % pulsed	6	6

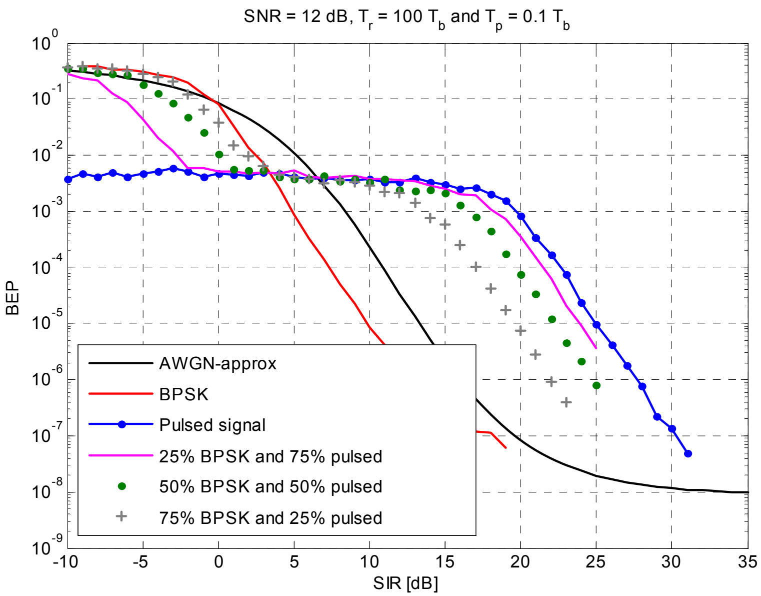


Figure 12 BEP for signals mixed of a pulsed signal and a BPSK modulated signal, [2].

4.1.3 Periodic pulsed interference

For a mix of periodic pulsed interference signals no deeper analyze has been made. However, based on current knowledge, we can still draw some conclusions. If the mixed signal consists of a periodic pulsed signal with no other signal content between the pulses then adding a dominant or several equal signals together should have no effect on the ICF. For this case, the ICF should be the same for one or multiple signals.

For this type of periodic pulsed interference further investigation are needed.

4.2 A mix of several interference signals where the power is equally divided

For a mix of several interference signals with the power equally divided, the total interference source is also created by adding several signal sources together and each source is assigned a certain power with corresponding power spectral density level, N_i [W/Hz]. The total power spectral density N_I is defined as (5). However, for this case all signals have equal power spectra density and therefore no dominant part is present.

4.2.1 Non-periodic Class A interference

To investigate the resulting ICF for a mix of Class A interference, multiple signals with A and Γ is added together all signals with equal power. For this purpose, simulations have been performed with Class A signals with A=0.01 and Γ=0.001. Three different modulation schemes have been considered, BPSK, DQPSK and MSK. By simulations, an empirical relation of the ICF has been derived, as

$$ICF_{\mathrm{I}}^{\mathrm{dB}} = \frac{ICF_{\mathrm{I,one}}^{\mathrm{dB}}}{N^{1/p}} . \qquad (10)$$

The $ICF_{\mathrm{I,one}}^{\mathrm{dB}}$ denotes the ICF of one of the signals, N is the number of interference signals and p is related to the used digital communication scheme and probably also dependent on the SNR. All simulations have been performed in matlab with SNR=12 dB. From simulation results, we can see that:

$$\begin{aligned} &B = \frac{1}{A}, \text{for the modulation schemes studied} \\ &\mathrm{C} = \begin{cases} 1, & \text{BPSK, MSK} \\ 0, & \text{DQPSK} \end{cases} \end{aligned} \qquad (11)$$

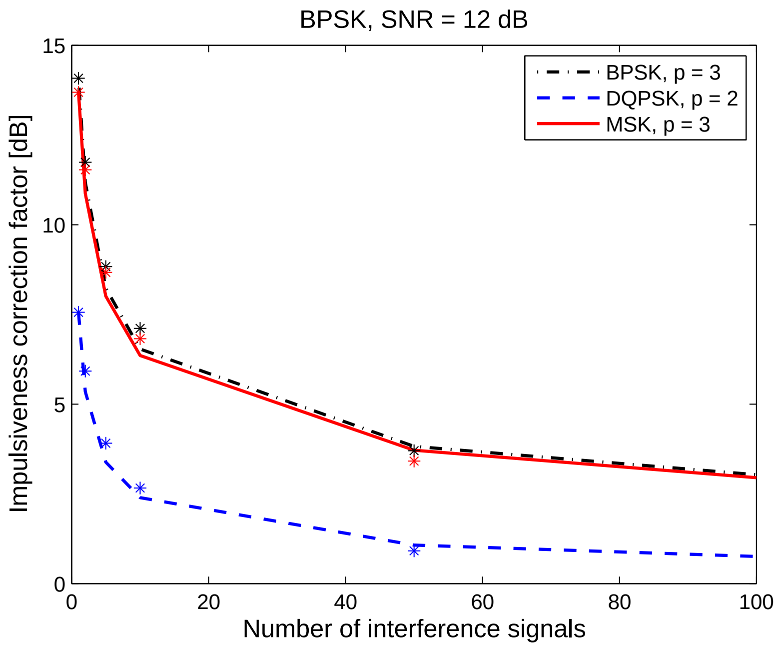


Figure 13 ICF as function of number of Class A signals with *A*=0.01 and *Γ*=0.001 and equal power spectral density. The stars in the figure are the ICF from BEP-curves and the lines are calculated with (10).

In figure 13, the ICF obtained by simulations are shown by lines, while the estimated ICF from (11) are shown with dots. This is shown for BPSK, DQPSK and MSK modulation. By changing *B* and *C* in (11) properly, the relation (10) is very usable to extend the ICF measure for one signal to the case with several signals. This is valid under the condition that the mix of signal sources consists of signals which have the same statistical properties and power spectral density.

4.2.2 Periodic pulsed interference

No simulations are performed for a periodic pulsed interference why no results are carried out. For this type of periodic pulsed interference further investigation are needed.

4.2.3 Non-periodic pulsed interference

In [2], BEP simulations are performed for an uncoded coherent BPSK-modulated digital communication system exposed to several different summated pulsed signals with random phase and arrival time. In all simulations the SNR=12 dB has been used. The simulated ICF for one signal is compared to the ICF when the interference consists of multiple summated signals with equal power spectral densities. From the results, it can be concluded that the relation in (10) is applicable also for this kind of interference and that the parameter p in (10) can be expressed as

$$p = \log_{10}(B) + C \qquad (11)$$

For a non-periodic pulsed signal (in [2]) B is the repetition time factor T_r expressed in the used bit time T_b. For example, in [2] if T_r=100T_b then B=100. C is dependent of the used modulation scheme and SNR. For an uncoded coherent BPSK-modulated system C=1. In figure 14, the results calculated with (10) and the estimated ICFs from BEP-figures in [2] are shown and they conform very well.

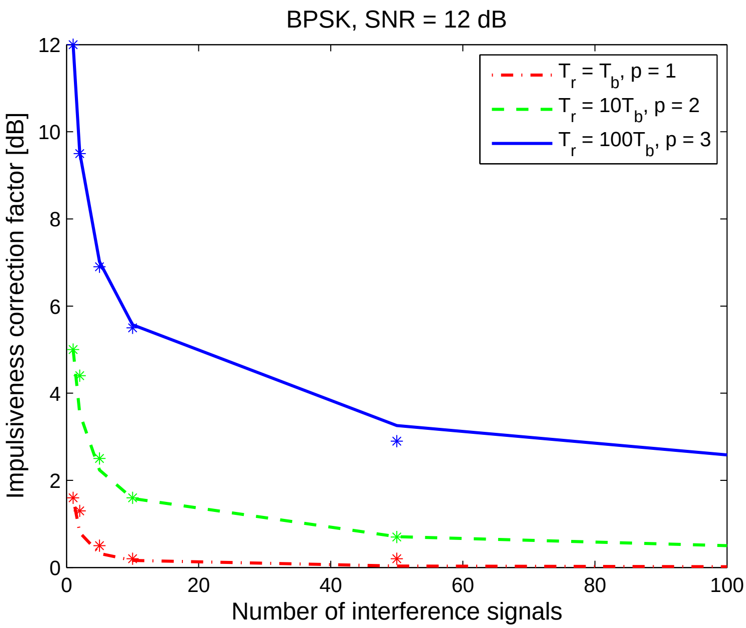


Figure 14 ICF as function of number of pulsed signals with random phase and arrival time. The stars is the, from figures in [2], estimated ICF and the lines calculated with (10).

5 The ICF measure used in a intersystem-interference analysis tool

It is tractable to have simplified methods to estimate the BEP for a digital communication system. For this purpose, the AWGN-approximation is often used. This approximation is simple. However, the approximation needs correction with ICF to be more suitable for impulsive rich interference signals. In this chapter, we will summarize how the ICF concept can be implemented in an intersystem interference tool.

First of all the modulation scheme of the communication system needs to be determined. In the table 3 below some examples of radio systems and their modulation scheme are given.

Table 3 Radio systems and modulation schemes

Radio System	**Modulation scheme**
Ra180	MSK
Tetra	DQPSK
IGR, gen. II	GMSK
TDRS-A	4-CPM

Secondly, the kind of interference signal the radio system can be subjected to is of great importance. For the interference signal, we need to determine:

- whether it is composed of one of several interfering signals
- if the signals are periodic or non-periodic
- for non-periodic: pulse modulated or if the signal can be modeled as Class A interference
- for several interfering signal: one dominant or equally divided in power

5.1 One signal

Case 1: One interfering signal, (periodic or non-periodic) pulse modulated interference:

$$ICF \approx ICF_{\mathrm{offset}} + \frac{3}{4} IR \, .$$

For this kind of interference, the IR is [2]

$$IR = 20 \log \frac{\sqrt{W_{\mathrm{IF}}}}{\sqrt{f_{\mathrm{p}}}} \; . \text{ [dB]},$$

where f_{p} is the pulse repetition frequency passed through an IF filter with bandwidth W_{IF} .

Case 2: One interfering signal, non-periodic Class A interference:

The parameters *A* and *Γ* may be estimated from a measured time sequence of the interference or the APD of the interference APD [10].The parameter *A* is easiest estimated by estimating how often in time the pulses arrives. Then we can use the worst case scenario. The ICF_{max} for each modulation scheme in the table below is estimated from the vertical dotted lines in figure 3 – figure 7 in section 3.3.

Table 4 ICF_{max} for different modulation schemes and different *A* values

	ICF_{max} [dB]			
Modulation scheme	Middleton's Class A parameter *A* 1	0.1	0.01	0.001
BPSK	3	8	14	23
MSK	3	8	13.5	22
DQPSK	-	3	7.5	14
GMSK	1.5	5	9	
4-CPM	1.5	5	8	

5.2 A mix of several interference signals

Case 1: Equally divided in power

Table 5 Radio systems and modulation schemes

Resulting ICF for several signals with equal power			
Non-periodic signal	$ICF_{\mathrm{I}}^{\mathrm{dB}} = \frac{ICF_{\mathrm{I,one}}^{\mathrm{dB}}}{N^{1/p}}$, $p = \log_{10}(B) + C$	**Class A signals**	$B = \frac{1}{A}$, for the modulation scheme $\mathrm{C} = \begin{cases} 1, & \mathrm{BPSK, MSK} \\ 0, & \mathrm{DQPSK} \end{cases}$
		Pulse modulated signal	B: pulse repetition factor, C modulation dependent, C=1, BPSK
Periodic signal	No results	**Pulse modulated signals**	-

Case 2: One dominant signal

Table 6 Resulting ICF for a mix of several interference signals with one dominant signal

Resulting ICF for several signals with one dominant interference	
$ICF_I^{dB} \approx ICF_d^{dB} + 10\log_{10}(\rho)$	**Class A signals**
	Pulse modulated signal
Worst case when parameter *A* or repetition time is available of the dominant interference	
$ICF_I^{dB} \approx ICF_{\max}^{dB} + 10\log_{10}(\rho)$	**Class A signals**

5.3 Further important parameters

The SNR is of importance for the ICF. If the SNR is very low (approximate SNR < 5 dB), the ICF is not necessary and the ICF can be set to zero dB. For such a case, the BEP level will approach a high value as SIR grows large and there will only be a minor difference between the BEP for the Gaussian approximation and for the impulsive interference.

SNR > 5 dB, use the ICF

SNR < 5 dB, ICF = 0 dB

For a Class A interference with very low *A* then no correction is needed (ICF = 0 dB) because the pulses in the signal arrive very seldom.

6 Conclusions

In this work, a correction factor (ICF) has been further developed for correcting the Gaussian approximation for BEP calculations on other than AWGN-interference signals. The concept has been further developed for an extended group of interfering signal, namely Middleton's Class A interference. This interference model has been investigated both as one signal as in a multiple of several such signals. For the latter case, the ICF has been derived for the situation when one of the signals is dominant and for the case when the power is equally divided on the signals.

New expressions are derived on the resulting ICF. It is shown that these expressions also are applicable for other composite interference signals like non-periodic pulsed signals.

A proposal for how these results and together with earlier findings can be structured is also included. The proposal summarizes the expressions for different scenario cases to be incorporated in an intersystem-interference analysis tool.

7 Future work

For development of a general intersystem analysis tool that should have the ability to cope with a large variety of interference sources, this work needs to be complemented. In particular, a mix of several pulsed signals where one is dominant needs to be further analyzed.

From this work it seems possible to develop an ICF expression directly related to the A and Γ parameter of the Class A interference. This need to be further investigated. The aim is to derive a closed form expression of the ICF in terms of the Class A parameters maybe in combination of the IR of the interference.

Further guidelines regarding the influence of the SNR are desired. At this state the results are based on the assumption that SNR is relatively high, about 12 dB.

A final subject to analyze is to develop a less complicated method to derive the ICF of an individual interference signal based on measurements. Such a method is attractive, since the current method is quite complicated and time consuming as it requires performance simulations of a communication system with the current interference signal.

8 Appendix A

8.1 Interference model

For the investigation, Middleton's Class A model is used as interference model. 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 [4]. In general, a narrow-band noise x(t) is represented by its envelope r(t) and phase $\phi(t)$ as

$$x(t) = r(t)\cos\left(2\pi f_c t + \phi(t)\right) \qquad \text{(A.1)}$$

where f_c is the center frequency of the noise. The Class A probability density function (pdf) of the amplitude X normalized to the root mean square (rms) value, is defined as [4].

$$p_X(x) = e^{-A} \sum_{m=0}^{\infty} \frac{A^m}{\sqrt{2\pi\sigma_m^2}} e^{-\frac{x^2}{2\sigma_m^2}} \qquad \text{(A.2)}$$

where $\sigma_m^2 = (m / A + \Gamma)/(1+\Gamma)$, with Γ as the mean power ratio of the Gaussian noise component σ_G^2 to the non-Gaussian noise component σ_I^2 [5]. 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 [4]. 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 microwave oven has been demonstrated to be modeled well with $A \approx 5 \cdot 10^{-3}$ and $\Gamma \approx 9$ [7].

9 Appendix B

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9.1 Improved Impulsiveness Correction Factor for Controlling Electromagnetic Interference in Dynamic Spectrum Access Applications

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***Abstract* – Initiatives to open certain frequency bands for dynamic spectrum access (DSA) are ongoing. Examples are the Wireless Access Policy for Electronic Communications Services (WAPECS) and White Spaces Coalition. A key issue in DSA is how to measure occupancy and interference in an open frequency band to decide whether or not it can be used for a certain service. Such measurement must be easy to perform and provide a result that can be used as decision metric. An earlier proposal, based on a so-called Impulsiveness Correction Factor (*ICF*), with this purpose has been shown to work properly if the interference is dominated by a single pulsed signal. In this paper, the former approach is extended to the case in which the interference signal consists of a multiple of interference signals. This extension is shown as a closed expression involving only parameters that can be determined from an interference measurement.**

I INTRODUCTION

In recent years, interest in opening certain frequency bands for dynamic spectrum access (DSA) has increased because measurements have shown [1][2][3] that frequency bands allocated in the traditional way show an average occupancy in the order of a few percent. Even in the most dense population centers and during busy hours, typically less than 1/3 of the frequency spectrum seems to be used. This insight has spawned intense activity in this research arena during the past 5 – 7 years, exploring new ways to efficiently manage the spectrum. The main thrust has been in the methods for “real time” or DSA. In particular, distributed schemes, in which individual transmitters or groups of transmitters attempt to identify “pieces” of instantaneously unused spectrum, so-called “spectrum holes” or “white space”, that could be used temporarily by secondary users, are usually referred to as *overlay spectrum sharing* [6]. Developments within software-defined radio (SDR) and cognitive radio (CR) as enablers for DSA concepts have further increased the interest in taking initiatives within the area. Examples of such initiatives are Wireless Access Policy for Electronic Communications Services (WAPECS) [4] and the White Spaces Coalition [5].

To use frequency bands dynamically, methods for sensing the actual occupancy and interference level in a certain frequency band must be available, both on higher system level and in some cases in individual receivers. A key issue in future dynamic wireless applications is therefore the ability to sense and consider the total electromagnetic interference within the receiver band of the wireless communication system. Such methods must be fast and of low complexity to be useful in on-line applications and in distributed solutions. Therefore, it is desirable to find a simple but useful method. A simple method proposed in [7] is to consider the total interference average power (called *interference temperature*) within a certain frequency band. This is a common approach as the well-known Gaussian approximation (GA) to determine the bit error probability (BEP) is based on this underlying assumption of average power [16]. With this approach, new devices would be permitted to operate in a band if their operation does not cause overall emissions in the band to exceed a pre-set limit. One difficulty with such an approach is that the wave form, not only the power, of an interfering signal can significantly affect the performance of a digital wireless system. In practical applications, pulsed interference signals cause the largest errors in BEP when the GA is used. These errors can be in the order of several magnitudes. An impulsiveness correction factor (*ICF*) to adjust for these errors has been proposed in [8]. The *ICF* can be used as a rough adjustment for the interference-waveform properties so that the measured total interference average power can be used as a decision metric in future dynamic applications. The *ICF* proposed in [8] is optimized to capture the errors from one impulsive interference signal and therefore has to be extended to cover a mix of several interference signals. In this paper, we present a natural extension of the *ICF* in [8] to cover the case in which the total interference is a mix of one dominant waveform and an arbitrary number of other signals. This is done for a general class of signals, the Middleton Class A model [13]. This advantage of the model is that it can represent a number of interference signals with arbitrary impulsiveness, see Appendix A. The extended *ICF* is expressed in a closed expression containing only parameters that are easy to extract from an interference measurement. The paper is organized as follows. In Chapter II, the *ICF* for pulsed interference is briefly reviewed. In Chapter III, the extended *ICF* for multiple interference signals is derived and a closed expression is found. In Chapter IV, the extended *ICF* is evaluated for two characterizing interference cases. In Chapter V the usefulness in a practical application is demonstrated. Chapter VI contains the conclusion.

II ICF FOR PULSED INTERFERENCE.

The performance of a digital communication system subjected to periodic pulsed interference is analyzed in [9]. In Fig. 1 the BEP as a function of the signal-to-interference ratio (*SIR*) is shown for pulse-modulated signals with different pulse-repetition frequencies (R_S is the symbol rate of the digital communication system). The modulation scheme in Fig. 1 is Binary Phase Shift Keying (BPSK). The *SIR* is the ratio of the bit energy and the interference power spectral density. The signal-to-noise ratio (*SNR*), defined as the ratio between the bit energy and the power spectral density of the thermal receiver noise, is 12 dB for the calculations shown in the figure. The BEP for the pulsed interference is compared with the BEP for Gaussian noise (Additive White Gaussian Noise, AWGN). As seen, the BEP for pulsed interference differs significantly from the BEP caused by the AWGN. However, the largest difference in SIR for a constant BEP is 7.5 dB for a shift in pulse-repetition frequency f_p of one decade. The analytical proof for this is shown in [10].

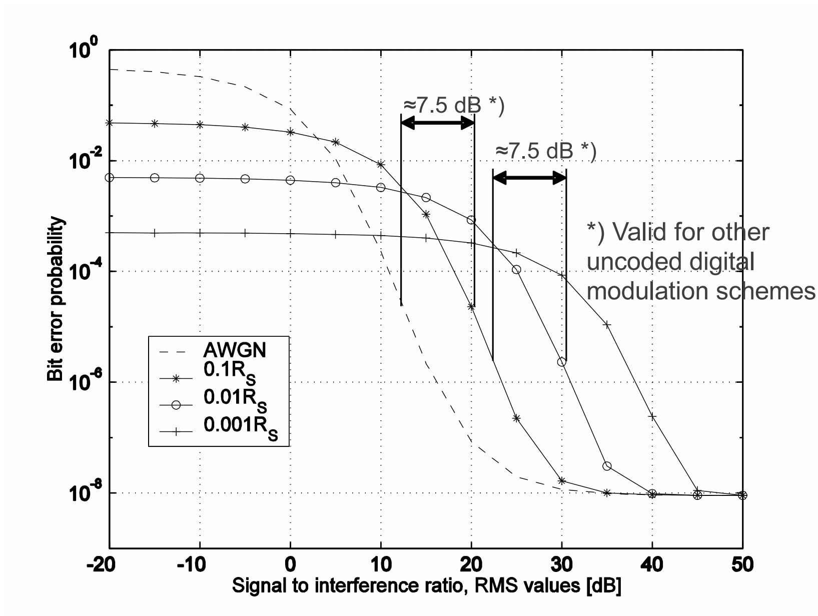


Fig. 1. The BEP for pulsed sine wave versus Gaussian (AWGN) interference of a digital communication system.

In [10] it is also shown that this behavior is true even for other digital modulation schemes. From Fig. 1 it is obvious that only using the interference power to predict the impact on a digital communication system can give large errors as the impact is strongly dependent on the waveform properties of the interference signal. These errors can be in the order of several magnitudes or up to a factor 10,000 with respect to estimated BEP.

A well-known measure of the impulsive properties of noise is the Impulsiveness Ratio (IR) [11] defined as

$$IR = 20\log\frac{V_{\mathrm{RMS}}}{V_{average}}, \qquad \text{(B.1)}$$

where V_{RMS} and V_{average} are the root-mean square and time average values of the envelope of the output of the IF (Intermediate Frequency) filter of a measurement receiver. For periodic pulses with pulse-repetition frequency f_p passed through an IF filter with bandwidth W_{IF}, the IR is [12]

$$IR = \frac{\sqrt{W_{\mathrm{IF}}}}{\sqrt{f_{\mathrm{p}}}}. \qquad \text{(B.2)}$$

By inspecting Fig. 1, the ICF in dB, ICFdB, for BPSK can be expressed approximately as

$$ICF^{\mathrm{dB}} \approx \begin{cases} ICF_{\mathrm{offset}}^{\mathrm{dB}} - 7.5\log\frac{f_{\mathrm{p}}}{R_{\mathrm{S}}} & f_{\mathrm{p}} < R_{\mathrm{S}} \\ ICF_{\mathrm{offset}}^{\mathrm{dB}} & f_{\mathrm{p}} \geq R_{\mathrm{S}} \end{cases}, \text{ [dB]} \qquad \text{(B.3)}$$

where $ICF_{\mathrm{offset}}^{\mathrm{dB}}$ is a modulation-dependent constant which is -4 dB for BPSK. By using the common approximation $W_{\mathrm{IF}} \cong R_{\mathrm{S}}$ we can combine equation (B.2) and (B.3) so that

$$ICF \approx -4 + \frac{3}{4} IR, \text{ [dB]} \qquad \text{(B.4)}$$

By knowing the actual modulation scheme, the corresponding offset is used when the ICFdB is determined. From [10] the $ICF_{\mathrm{dB}}^{\mathrm{offset}}$ for MSK and 64-QAM can be determined to approximately -3 dB and -5 dB, respectively. Thus, by knowing the IR and the actual modulation scheme of interest, we can determine how much, in terms of SIR, the measured interference signal differs from a Gaussian distributed signal causing the same BEP at the victim. Another way of expressing the application of the ICF is that the AWGN approximation for BEP can be used even if the interference signal is not Gaussian. In general, the BEP, Pb, for AWGN can be derived as

$$P_{\mathrm{b}} = f\left(\frac{E_b}{N_0 + N_{\mathrm{I}}}\right) \qquad \text{(B.5)}$$

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 wireless receiver of interest. For pulsed interference, the BEP according to (B.5) can result in errors in the order of magnitudes. By using the *ICF*, this error can be significantly reduced and restore the usefulness of the AWGN approximation. The corrected BEP, $P_{\mathrm{b,corr}}$, can now be denoted as

$$P_{b,corr} = f\left(\frac{E_b}{N_0 + ICF \cdot N_I}\right). \tag{B.6}$$

III EXTENDED ICF FOR MULTIPLE INTERFERENCE SIGNALS

Let $i_{\mathrm{I}}(t)$ be the total interference signal amplitude that is a sum of k interference signals so that

$$i_{\mathrm{I}}(t) = \sum_{j=1}^{k} i_j(t)\,, \tag{B.7}$$

where $i_j(t)$ is interference signal j and t is the time. Let the total equivalent power spectral density N_{I} of the interference signal $i_{\mathrm{I}}(t)$ within the receiver band be a sum of the power spectral density of these k interference signals. Then N_{I} can be denoted as

$$N_{\mathrm{I}} = \sum_{i=1}^{k} N_i\,, \tag{B.8}$$

where N_i is the power spectral density of interference signal number i.

The *ICF* can also be applied to a multiple of interfering signals on the same form as in (B.6), i.e.

$$P_{b,corr} = f\left(\frac{E_b}{N_0 + ICF_I \cdot N_I}\right) \tag{B.9}$$

where ICF_{I} is the *ICF* for $i_{\mathrm{I}}(t)$. Now, let $i_{\mathrm{d}}(t)$ be the dominant interference signal in terms of interference power. Furthermore, the equivalent power spectral density of $i_{\mathrm{d}}(t)$ is N_{d}. If the remaining (k-1) interference signals can be considered independent and identically distributed (*iid*) random variables each with finite mean and variance, the sum of the signals will approach a normal distribution (according to the central limit theorem) when k increases so that

$$i_{\mathrm{I}}(t) = i_{\mathrm{d}}(t) + \sum_{j=1}^{k-1} i_j(t) \rightarrow i_{\mathrm{d}}(t) + n_{k\text{-}1}(t),\ k \rightarrow \infty\,, \tag{B.10}$$

where $n_{k\text{-}1}(t)$ is a zero-mean normal distributed signal with constant power spectral density

$$N_{k-1} = N_\mathrm{I} - N_\mathrm{d} \,. \qquad \text{(B.11)}$$

The consequence of (B.10) is that the interference consists of one part $n_{k\text{-}1}(t)$ that does not have to be corrected and one part $i_\mathrm{d}(t)$ that must be corrected with its corresponding ICF_d. Thus, (B.9) can now be rewritten to

$$P_{b,corr} = f\left(\frac{E_b}{N_0 + ICF_\mathrm{d} N_\mathrm{d} + N_{k-1}}\right). \qquad \text{(B.12)}$$

From (B.9) and (B.12) we have the following relation between ICF_I and ICF_d,

$$ICF_\mathrm{I} N_\mathrm{I} = ICF_\mathrm{d} N_\mathrm{d} + N_{k-1} \qquad \text{(B.13)}$$

which can be rewritten as

$$ICF_\mathrm{I} = ICF_\mathrm{d} \rho + 1 - \rho \qquad \text{(B.14)}$$

where

$$\rho = \frac{N_\mathrm{d}}{N_\mathrm{I}} \,. \qquad \text{(B.15)}$$

As $i_\mathrm{d}(t)$ is the dominant interference signal, the product $ICF_\mathrm{d}\rho$ will in this case be significantly larger than $(1-\rho)$, $(0 \le 1-\rho \le 1)$. The final $ICF_\mathrm{I}^{\mathrm{dB}}$ can thus be written in [dB] as

$$ICF_\mathrm{I}^{\mathrm{dB}} \approx ICF_\mathrm{d}^{\mathrm{dB}} + 10\log_{10}(\rho)\,, \qquad \text{(B.16)}$$

which can now be used in (B.9). Thus, by identifying the dominant interference signal, a correction can be made to adjust for the largest error if the AWGN approximation is used to determine the interference impact. To show the application of this result, two characteristic examples are given in the next chapter.

IV EVALUATION OF THE EXTENDED ICF

To evaluate the extended $ICF_\mathrm{I}^{\mathrm{dB}}$ in (B.16) for mixed interference signals, an uncoded coherent BPSK system is studied. This system is analyzed under the influence of thermal receiver noise together with interference. The thermal receiver noise is modeled as AWGN and the interference by Middleton's Class A model. The interference model is described in Appendix A. For evaluation purposes the simulated BEP is studied as a function of *SIR*. From the BEP curves the $ICF_\mathrm{I}^{\mathrm{dB}}$ is determined as the largest *SIR* difference between AWGN and Class A interference. In all simulations, which are performed in Matlab, the thermal receiver noise is generated with an *SNR* of 12 dB.

The total used interference power is divided in two parts with corresponding power spectral densities, N_d and $N_{k\text{-}1}$. The ratio ρ is determined according to (B.15). The mixed interference signal is created by summarizing N Class A signals with the same *A* and *Γ*. Here, the dominant signal also consists of a Class A signal with the same parameter values, *A* and *Γ*.

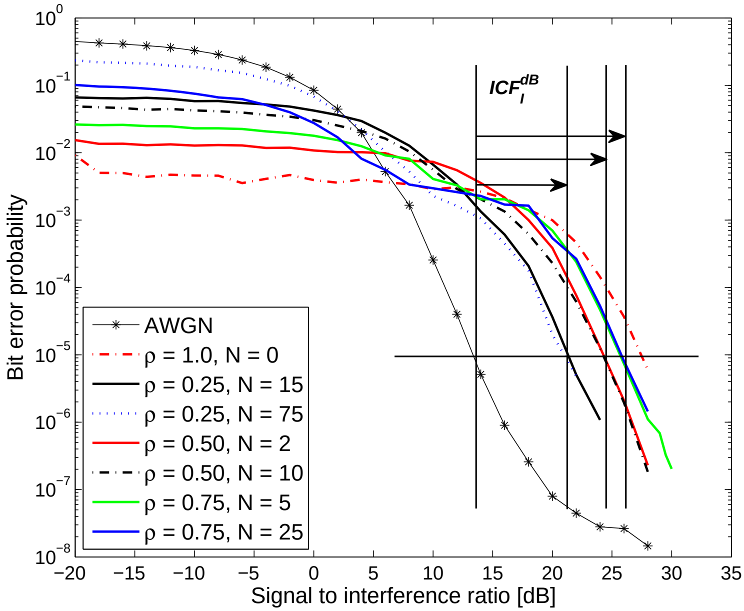


Fig. 2. The simulated BEP for a mixed interference signal created with several Middleton's Class A sources with *A*=0.01 and *Γ*=0.001 with varying *SIR*.

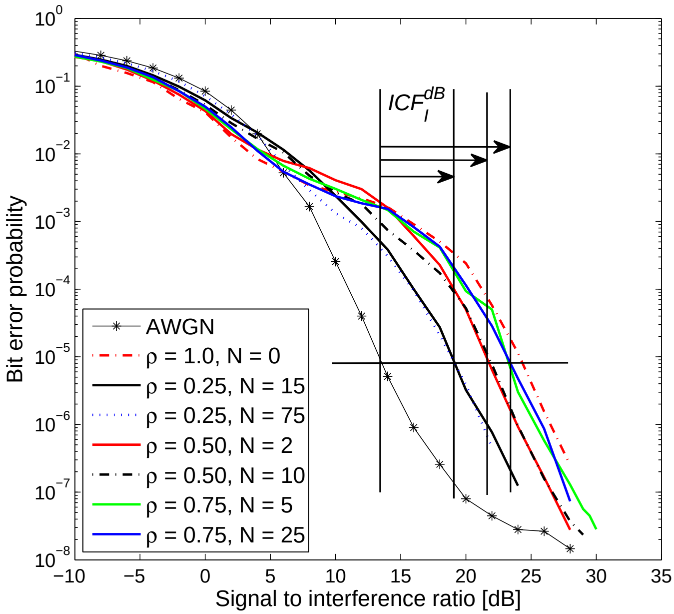


Fig. 3. The simulated BEP for a mixed interference signal created with several Middleton's Class A sources with A=0.01 and Γ=1 with varying *SIR*.

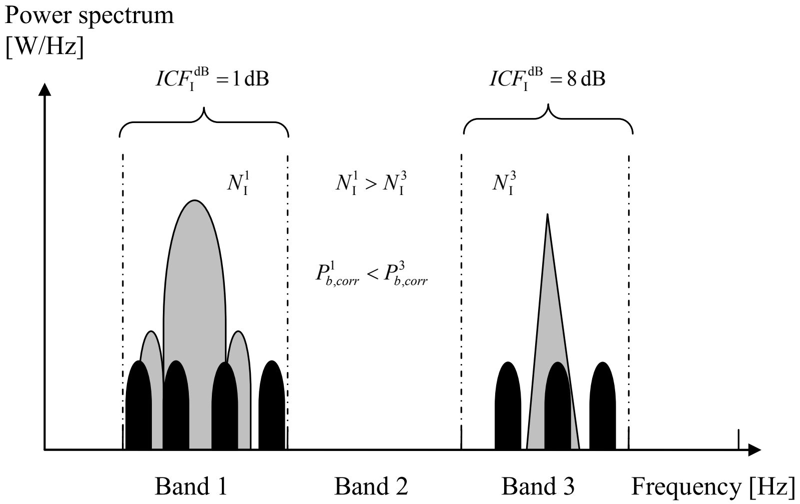
Results from two different simulation setups are shown in Figures 2 and 3. In Table 1 the estimated $ICF_{\mathrm{I}}^{\mathrm{dB}}$ from the figures and the calculated $ICF_{\mathrm{I}}^{\mathrm{dB}}$ from (B.16) are summarized. The first column shows used power ratios ρ and the signal number N used to create the mixed interference, i.e. N=k-1. For example, for (ρ, N) = (1.0, 0) the total interference power only consists of the dominant part with power spectral density N_{d}. Another example is (ρ, N) = (0.5, 10) which implies that the two signal parts, $i_{\mathrm{d}}(t)$ and $\sum_{j=1}^{k-1} i_j(t)$, respectively, share the power equally and the mixed part consists of 10 Class A signals each with equal power. The second and third column show the results for Class A interference with (A, Γ) = (0.01, 0.001); the fourth and fifth column, the results for Class A interference with (A, Γ) = (0.01, 1). The estimated $ICF_{\mathrm{I}}^{\mathrm{dB}}$ from the figure is determined as the maximum *SIR* value and is determined here for a BEP value of 10^{-5}. In the first simulation ((A, Γ) = (0.01, 0.001)), the calculated $ICF_{\mathrm{I}}^{\mathrm{dB}}$ from (B.16) gives slightly higher values than the estimated $ICF_{\mathrm{I}}^{\mathrm{dB}}$ from the figure. The opposite behavior is shown in the second simulation ((A, Γ) = (0.01, 1)). But both cases prove that the extended method seems well suited for correcting the $ICF_{\mathrm{I}}^{\mathrm{dB}}$ for a multiple of Middleton's Class A signals.

	A=0.01, Γ=0.001		**A=0.01, Γ=1**	
ρ, N	Estimated ICF_I^{dB}	ICF_I^{dB} with (B.16)	Estimated ICF_I^{dB}	ICF_I^{dB} with (B.16)
ρ=1.0, N=0	14.1	-	8.1	-
ρ=0.25, N=15	8	8.1	5.6	4.8
ρ=0.25, N=75	7.6	8.1	5.4	4.8
ρ=0.50, N=2	10.9	11.1	8.2	7.8
ρ=0.50, N=10	10.9	11.1	8.4	7.8
ρ=0.75, N=5	12.3	12.8	9.8	9.5
ρ=0.75, N=25	12.4	12.8	9.8	9.5

Table 1: The estimated ICF_I^{dB} from figure 2 and 3 and the ICF_I^{dB} calculated from (B.16) for two different setups of mixed interference signals.

V APPLICATION EXAMPLE OF THE EXTENDED ICF

As an example of the use of the extended *ICF*, we consider a scenario, see Figure 4. In the scenario, a system in a DSA application is supposed to decide whether frequency band 1 or 3 should be utilized. In both bands we have one dominant interference source. However, the waveform properties of these dominant sources differ between the two bands. A decision made on energy detection only would propose band 3, as the total interference in this band is lowest. However, considering the interference impact in terms of BEP, by using the extended *ICF* concept, the frequency band 1 with ICF_I = 1dB will result in a lower BEP than in band 3, with ICF_I = 8dB. Thus, although the interference power in band 1 is higher than in band 3, the corrected BEP in band 1 will be lower than in band 3, $P^1_{b,corr} < P^3_{b,corr}$.



Fi

Fig. 4. Improved *ICF* concept used in a simple DSA application.

VI CONCLUSION

With initiatives to use frequency bands more effectively, methods of determining the interference impact on other radio systems are essential in order to evaluate the co-existence of users in the same frequency band. In earlier work, a simple method was proposed to judge the impact of interference signals. The method is based on a correction of the Gaussian approximation of the interference. In this work, we have extended the former method for a pulsed interference signal to a mix of an arbitrary number of Middleton's Class A signals. The interference correction factor for a mix of a number of interference signals can be determined by a closed-form expression, based on parameters that can be obtained by measurements. The method is verified by simulations for different parameter settings of the interference signal. In conclusion, the extended method is well suited for multiple interference signals.

APPENDIX A

INTERFERENCE MODEL

For the investigation, Middleton's Class A model is used as the interference model. 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 [13]. In general, a narrow-band noise $x(t)$ is represented by its envelope $r(t)$ and phase $\phi(t)$ as

$$x(t) = r(t)\cos\left(2\pi f_c t + \phi(t)\right), \qquad \text{(B.17)}$$

where f_c is the center frequency of the noise. The Class A probability density function (pdf) of the amplitude X normalized to the root-mean-square (rms) value, is defined as [13]

$$p_X(x) = e^{-A} \sum_{m=0}^{\infty} \frac{A^m}{\sqrt{2\pi\sigma_m^2}} e^{-\frac{x^2}{2\sigma_m^2}} , \qquad \text{(B.18)}$$

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 [14]. It is known that for A approaching 10 or larger, the Class A pdf is very close to a Gaussian distribution [13]. 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 arbitrarily impulsive or close to a Gaussian distribution. For example, the interference from a switching-type microwave oven has been demonstrated to be modeled well with $A \approx 5 \cdot 10^{-3}$ and $\Gamma \approx 9$ [15].

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