Mitigation of Pulsed Interference in OFDM Based Systems

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***Abstract*— In order to enhance spectral efficiency an orthogonal frequency-division multiplexing (OFDM) based system is operated in a frequency band already in use by a licensed system. When transmitting an OFDM signal in the spectral gaps left by the licensed system, the OFDM system is exposed to severe interference, in the considered example characterised by short but strong Gaussian shaped pulses. Well-known approaches for mitigating the impact of pulsed interference are pulse blanking or clipping. As these techniques have not been applied to OFDM systems with this type of interference so far, the optimal thresholds for both techniques are determined. Simulations in a realistic interference scenario in the L-band show, that with clipping or pulse blanking based on the optimal threshold the impact of interference can be reduced considerably. The remaining gap to the interference-free case can be partly explained by the fact that not only the interference signal but also the desired OFDM signal is affected by pulse blanking or clipping.**

I. INTRODUCTION

OFDM based overlay systems are a promising approach for increasing spectral efficiency and for overcoming the problem of spectral scarcity since they enable the operation of an OFDM system in a frequency band that is already in use by licensed systems. In this paper, an OFDM system operated in the aeronautical L-band (960-1215 MHz) is regarded [1]. Large parts of the L-band are subdivided into 1 MHz channels and used by the distance measuring equipment (DME) or the tactical air navigation (TACAN) system, aeronautical navigation systems based on radar technology. As depicted in Fig. 1, the OFDM system is intended to be operated in the gap between two adjacent DME channels that has a bandwidth of approximately 500 kHz. For realising a successful coexistence, mutual interference between the two systems has to be kept at an acceptable level. For reducing out-of-band radiation of the OFDM signal causing interference towards the licensed system, powerful techniques have been proposed e.g. in [2]. As can be seen from Fig. 1, interference from DME systems operating in the directly adjacent channels affects most OFDM subcarriers hence degrading performance significantly. In the time domain, DME interference consists of short pulses that only affect a few subsequent samples of the OFDM signal. A well-known and straightforward approach for mitigating the impact of such pulsed interference is pulse blanking and/or clipping, i.e. interference pulses are detected and the affected samples are erased or set to a fixed value, respectively.

So far, pulse blanking has been employed for mitigating the impact of DME interference in satellite navigation systems [3], that are not based on OFDM. Furthermore, pulse blanking has been investigated for mitigating impulse noise in OFDM systems [4], [5]. However, in the context of impulsive noise that impairs only single samples of the OFDM signal, pulse blanking has a different impact on the OFDM system as when longer pulses originating from the DME system are considered. The application of pulse blanking and clipping techniques in OFDM based systems is topic of this paper.

The remainder of this paper is organised as follows. In Section II, DME signals are characterised and an appropriate interference model is proposed. The pulse blanking and clipping technique are described in Section III. Since the thresholds for the decision wether an affected sample is blanked or clipped are essential for the performance of interference mitigation and with that for the performance of the OFDM system, a separate chapter is dedicated to this issue. In Section V, simulation results with a realistic interference scenario are presented. Finally, conclusions are drawn in Section VI.

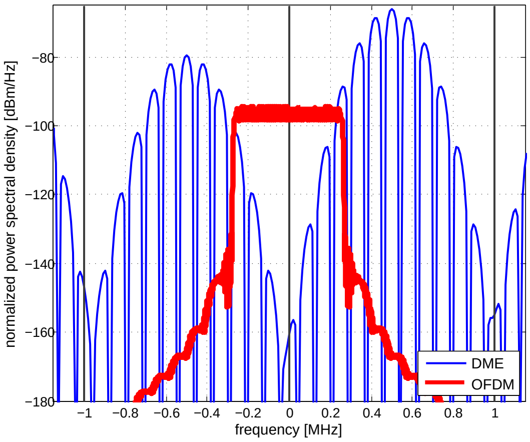

Fig. 1. Spectra of interference and OFDM signal.

II. CHARACTERISATION AND MODELLING OF INTERFERENCE

The DME signal consists of pairs of Gaussian shaped pulses with a separation of $\Delta t = 12\mu s$ or $36\mu s$. One pulse pair in the base band writes

$$p(t) = e^{-\alpha/2t^2} + e^{-\alpha/2(t-\Delta t)^2}. \quad (1)$$

The parameter $\alpha = 4.5 \cdot 10^{-11} 1/s^2$ is set such that the time interval between the 50% amplitude point on leading and trailing edges of the pulse envelope is $3.5\mu s$. For generating the interference signal relevant for the OFDM system, these pulse pairs are modulated to relative carrier frequencies of the channels to the left and to the right of the OFDM bandwidth, i.e. $\Delta f_i = \pm 500$ kHz with $i = 0, \ldots, I-1$ denoting the index of the interferer. Interferers operating in channels at larger frequency offsets are neglected as their impact is assumed to be reduced significantly by the Rx filter of the OFDM receiver. In the channels at ±500 kHz offset, the interference signals of multiple DME stations superimpose. Each of the I contributing DME stations is received with different power level P_i and different pulse rate. According to the pulse rate of the ith station, L_i pulse pairs are generated in the considered time interval. The starting times $t_{i,l}$ are modelled as a Poisson process. The phases $\varphi_{i,l}$ are equally distributed in the interval $[0, 2\pi]$. The resulting interference signal composed of contributions from I DME stations is given by

$$i(t) = \sum_{i=0}^{I-1} \sum_{l=0}^{L_i-1} \sqrt{P_i}\, p(t - t_{i,l}) e^{j2\pi\Delta f_i + \varphi_{i,l}}. \quad (2)$$

At the OFDM receiver, the received signal is composed of the desired OFDM signal and the interference signal. In order to model the impact of interference onto the OFDM signal as realistically as possible, the interference signal has to be processed in the same way as the OFDM signal would be processed at the receiver. Therefore, it is first filtered by a bandpass filter. Its filter characteristic is derived from filter characteristics of commonly used DME equipment and scaled to the bandwidth of the OFDM system. When sampling the received signal with sampling frequency f_s, the Nyquist sampling theorem is violated for the interference signal, since the bandwidth of the OFDM system is smaller than the bandwidth of the interference signal. This results in periodic repetitions of the interference spectrum with periodicity f_s that partly coincide with the OFDM bandwidth hence causing additional interference. To overcome this problem over-sampling in introduced. In the considered OFDM system with $f_s = 666.6$ kHz, four-times over-sampling is used to increase the sampling frequency to 2.66 MHz. In addition, an anti-aliasing filter is applied to diminish influences of DME interference signals in channels at larger offsets. For that purpose, a standard raised-cosine filter with roll-off factor 0.22 as applied in the Universal Mobile Telecommunications System (UMTS) is used. Its bandwidth is adjusted to the bandwidth of the OFDM system.

When modelling the desired OFDM signal, the filters can be neglected as in the ideal case, they do not affect the OFDM signal lying in the pass-band of the filters. However, over-sampling has to be taken into account by over-sampling the OFDM signal as well and adding the interference contribution to the over-sampled OFDM signal. To transform the resulting signal to the frequency domain, the FFT length has to be increased accordingly. Afterwards, the resulting signal composed of interference and desired signal is down-sampled to the target OFDM sampling rate. The resulting block diagram of an OFDM receiver including interference simulator for DME interference is shown in Fig. 2. Note, in the interference simulator, the I interference signals are generated quasi-continuously with 16-times over-sampling and are down-sampled to sampling rate $4 \cdot f_s$ after filtering.

As can be seen from Fig. 1, when DME interference occurs, a significant fraction of the OFDM subcarriers is affected. One DME station may transmit up to 3600 pulse pairs per second (ppps). In a typical interference scenario three DME stations occur in both adjacent channels producing a total pulse rate as high as 10800 ppps. Modelling the starting times of the pulse pairs as a Poisson process, the probability that an OFDM symbol is hit by DME interference is given by the complementary probability of the event that no interference occurs within an OFDM symbol, i.e.

$$P_{\text{hit}} = 1 - e^{-\lambda(T_O + 3.5\mu s)} \quad (3)$$

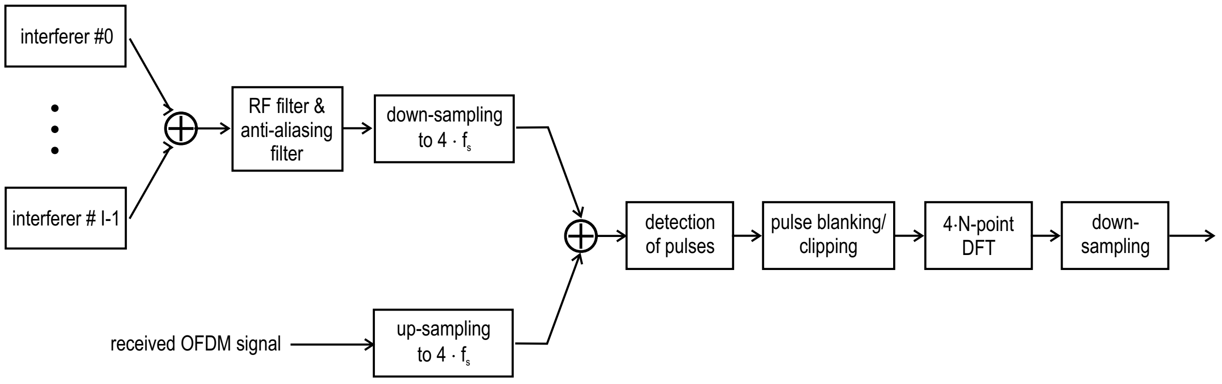

Fig. 2. Block diagram of OFDM receiver with DME interference simulator and pulse blanking/clipping.

with T_O denoting the duration of an OFDM symbol which is 96 μs for the considered OFDM system. Note, the observed interval has to be extended by the duration of one pulse. The intensity λ of the Poisson process is determined by the number of pulses which is $2 \cdot 10800$ pulses per second in the regarded example. With the given parameters, the probability that an OFDM symbol is hit is 88%. The probability that one OFDM symbol is hit by two pulses is as high as 25%.

Taking into account the sampling rate of the OFDM system that is $1.5 \mu s$ or $0.375 \mu s$ without or with four times over-sampling, about three or 12 samples of the desired signal are affected when a DME pulse occurs, respectively. Due to the high duty cycle and high power, DME interference has a severe impact on the performance of the OFDM system and hence has to be mitigated.

III. Interference Mitigation

DME pulses can easily be detected in the time domain received signal due to their high signal level exceeding the signal level of the desired OFDM signal. Hence, a straightforward and simple approach for mitigating the impact of DME interference is cutting out the affected samples as illustrated in Fig. 3. This approach referred to as pulse blanking is applied in satellite navigation systems operating in the E5 or L5 band at 1176.45 MHz or 1207.14 MHz that are also affected by DME interference [3]. Although very simple this method suffers from the drawback that the desired OFDM signal is erased when a DME pulse occurs. This effect can be diminished by choosing the threshold for blanking pulses properly. Alternatively or even additionally, clipping [5] can be applied which is also illustrated in Fig. 3. In that case, samples affected by interference are set to the threshold rather than erasing them as for pulse blanking.

When applying pulse blanking or clipping to OFDM signals, the high peak-to-average power ratio of OFDM signals has to be taken into account. When the threshold is chosen below the maximum possible peak amplitude of the OFDM signal, it may happen that samples of the OFDM signal are falsely detected as pulses. Blanking or clipping theses samples affects the desired OFDM signal and degrades performance. Hence, actual interference pulses have to be detected prior to the pulse blanking or clipping operation. This can be realised by first detecting the samples exhibiting an amplitude exceeding the threshold for pulse blanking or clipping. In a second step, a plausibility check is performed based on a priori knowledge about the shape of the pulses. When the amplitude of more than two subsequent samples is above the threshold, it is likely that a DME pulse occurs and the corresponding samples can be blanked or clipped. The exact number of affected subsequent samples depends on the chosen threshold and the power of the interference signal. When only one or two single samples exceed the threshold, peaks in the OFDM signal itself occur and hence pulse blanking or clipping must not be applied.

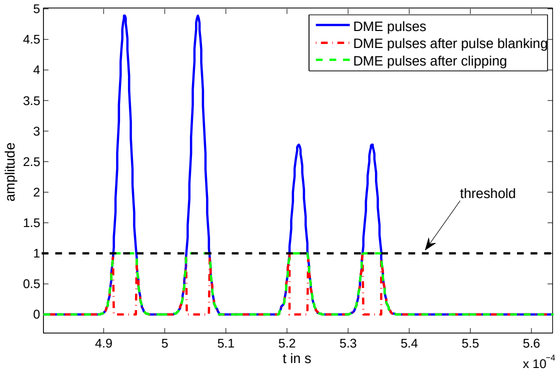

Fig. 3. Illustration of pulse blanking and clipping principle.

The two blocks for detecting pulses and for blanking or clipping are also depicted in the block diagram of the OFDM receiver in Fig. 2.

IV. Thresholds for Pulse Blanking and Clipping

The choice of the threshold for pulse blanking or clipping is crucial for the performance of interference mitigation and the overall performance of the OFDM system. Since not only interference is affected by pulse blanking or clipping, but the OFDM signal as well, the threshold has to be chosen as a trade-off between the achievable interference reduction and the number of sacrificed samples of the OFDM signal. In [4], [5], this threshold has been derived analytically for impulsive noise. However, due to the far more complex structure of the DME interference signal, this approach cannot be easily extended to DME interference. Therefore, the optimal threshold is determined by means of simulations in a simple interference scenario.

An OFDM system with $N = 64$ subcarriers is considered. 48 subcarriers in the center of the available bandwidth are used for transmitting QPSK modulated data, encoded with a rate 1/2 convolutional code. The variance of the additive white Gaussian noise (AWGN) channel is set such that a signal-to-noise ratio (SNR) of 10 dB is obtained. Assuming the thermal noise level at -174 dBm/Hz, the power of the received OFDM signal in the considered bandwidth equals -105.76 dBm for the given SNR. The OFDM signal is superimposed by interference from one DME station with variable duty cycle and a constant peak power of -70 dBm resulting in average signal-to-interference-and-noise ratios (SINR) of 0.86 dB, -1.96 dB and -3.47 dB for pulse rates of 3600, 7200 and 10800 ppps, respectively. In addition, one interferer with peak power -75 dBm and pulse rate 7200 ppps is simulated resulting in 2.48 dB SINR. The average power of the OFDM signal is normalised to 1 and the power of the interference signal is scaled accordingly. For reasons of simplicity, the thresholds for pulse blanking and clipping are determined for the such normalised received signal. The obtained bit error rate (BER) for different thresholds is given in Fig. 4 and Fig. 5 for pulse blanking and clipping, respectively.

As expected performance is rather poor, when the threshold is set too low. In that case interference is reduced considerably, but at the same time too many samples of the desired OFDM signal are blanked or clipped. The resulting BER is close to or even exceeds the BER obtained without any interference mitigation which is given as reference in Fig. 4 and Fig. 5 as well. When the threshold is too high, i.e. larger than 4 in the considered example, the impact of interference is hardly reduced such that the BER of the case without any interference mitigation is reached.

In nearly all simulated cases, the minimal BER is obtained when the threshold for pulse blanking as well as for clipping is set to 2.5 with the average power of the OFDM signal being normalised to 1. Consequently, the optimal threshold is independent of the interference power and duty cycle.

Note, this threshold is far below the maximum peak power of the OFDM signal that corresponds to the number of subcarriers used in the OFDM system. The OFDM signal exceeds the threshold of 2.5 from time to time resulting in difficulties to distinguish interference pulses from OFDM samples with high peak power. Hence, actual interference pulses have to be detected before applying pulse blanking or clipping as described in the previous section.

For low interference power and low pulse rate at threshold 2.5 only a local minimum occurs. The absolute minimum is observed at 1.75 or at 2.0. This can be explained as follows. At threshold 2.5, interferers are mitigated considerably at the cost of an acceptable performance loss of the OFDM system. For interferers with low duty cycle or low power the tolerable fraction of erased samples is not yet exploited completely at this point. Hence, the threshold can be reduced and with that the number of blanked or clipped samples can be increased without sacrificing performance of the OFDM system. In contrast, BER decreases as interference is further reduced. However, actual interference conditions are supposed to be characterised more likely by multiple interferers with high overall duty cycle and power. Hence, the optimal threshold at 2.5 is considered feasible.

Comparing clipping and pulse blanking, qualitatively, the same observations have been made. However, pulse blanking slightly outperforms clipping. It is advantageous to erase samples affected by interference completely rather than providing the subsequent detector and decoder with information falsified by interference as in the case of clipping.

V. SIMULATION RESULTS

The performance of clipping and pulse blanking in combination with the optimal threshold determined in the previous section is evaluated in a realistic interference scenario. The interference scenario is retrieved from real DME channel assignments in the area around Paris, France, as this is the area with the highest density of DME stations in Europe.

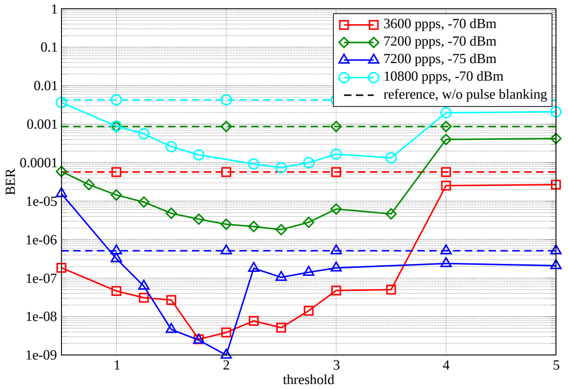

Fig. 4. Threshold for pulse blanking.

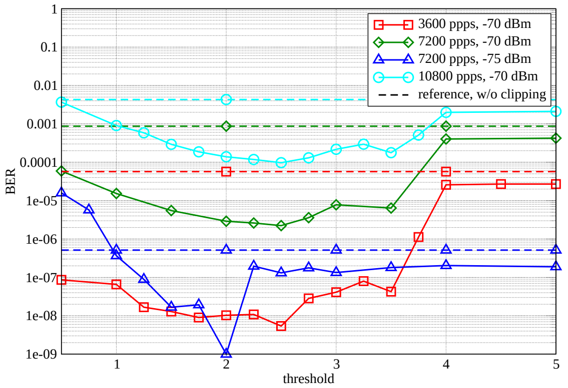

Fig. 5. Threshold for clipping.

The victim OFDM receiver is positioned at Paris, Charles-de-Gaulles airport at an altitude of 15 km to reproduce interference conditions at an en-route flight. The peak interference power originating from all surrounding DME/TACAN stations on the ground is determined via simple link budget calculations, taking into account free space loss and antenna patterns dependent on elevation angles. Typical interference conditions are observed when the OFDM system is operated at 995.5 MHz, for example. In the channels at ±500kHz offset, three TACAN stations with power and duty cycle as listed in Tab. I are observed.

TABLE I
INTERFERENCE SCENARIO.

Station	**Frequency**	**Interference power at victim Rx input**	**Pulse rate**
TACAN	995 MHz	-67.9 dBm	3600 ppps
OFDM	995.5 MHz		
TACAN	996 MHz	-74.0 dBm	3600 ppps
TACAN	996 MHz	-90.3 dBm	3600 ppps

The basic parameters of the OFDM system that is operated in the spectral gap between two adjacent DME channels are listed in Tab. II. For coding and modulation, a (133,171) convolutional code with rate 1/2 and QPSK modulation are applied, respectively. In order to make the OFDM signal more robust towards DME interference, in [1], the concatenation with a Reed-Solomon code is proposed. However, the investigation of the coding scheme is out of the scope of the paper. Propagation through the radio channel is modelled by an appropriate en-route channel model taking into account a strong line-of-sight path, Doppler frequencies of up to 1.05 MHz, and two delayed paths. Note, although the maximum path delay does not exceed 15 μs the length of the cyclic prefix is much longer. The additional samples are employed in the OFDM transmitter for transmit windowing in order to reduce out-of-band radiation.

TABLE II

OFDM SYSTEM PARAMETERS.

Parameter	**Value**
Used bandwidth	500 kHz = 48 · 10.416 kHz
Subcarrier spacing	10.416 kHz
FFT length	64
Sampling rate	666.666 kHz
OFDM symbol duration	96 μs
Cyclic prefix	24 μs
Total OFDM symbol duration	120 μs
OFDM symbols per frame	54
OFDM frame duration	6.48 ms

The performance of the OFDM system under typical interference conditions is shown in Fig. 6 in terms of BER versus SNR. The performance without interference is given as reference. With interference, but without applying any interference mitigation techniques, performance is degraded significantly. SNR to achieve BER $= 10^{-4}$ is reduced by 3.7 dB when clipping with threshold 2.5 is applied. Pulse blanking performs slightly better and SNR required to achieve BER $= 10^{-4}$ is reduced by another 0.15 dB. Although not shown in Fig. 6, for other thresholds the performance achieved with pulse blanking or clipping is worse, hence proofing the optimal choice of the threshold.

The existing gap between the performance in the interference-free case and the performance after clipping and pulse blanking can be explained by the facts that first the pulses are not mitigated completely and second the OFDM signal is affected by pulse blanking and clipping. The latter effect is analysed by applying pulse blanking and clipping to the same samples of the received signal as before, but neglecting the actual interference signal. Performance is improved by about 1.2 dB compared to the case with interference. The remaining gap of 2.8 dB to the interference-free case can be explained by the fact that the desired OFDM signal is impaired considerably by clipping or pulse blanking.

In addition, the BER performance for the case without pulse detection before clipping is given. Compared to the case with pulse detection, performance degrades by 2.3 dB. As expected, in this case, peaks in the OFDM signal are falsely identified as interference pulses leading to too many clipped or blanked samples that degrade the performance of the OFDM system. This justifies the demand for a simple algorithm for detecting pulses prior to applying pulse blanking or clipping.

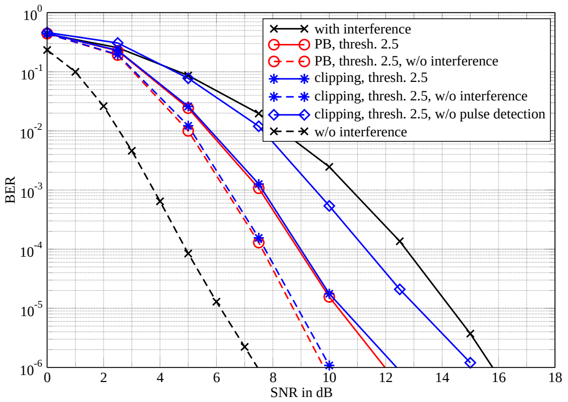

Fig. 6. BER performance with clipping or pulse blanking in typical interference scenario.

VI. CONCLUSIONS AND OUTLOOK

In this paper, pulse blanking and clipping are investigated as a means for mitigating the impact of pulsed interference in OFDM based systems. The thresholds for applying pulse blanking or clipping are determined in simple simulations with one interferer with different pulse rate and power. Since the threshold is well below the maximum peak power of the OFDM signal, interference pulses have to be detected before pulse blanking or clipping in order to prohibit samples of the desired OFDM signal to be blanked or clipped falsely. The BER performance of pulse blanking and clipping with the optimally chosen threshold is demonstrated for a realistic interference scenario. Although performance can be improved with pulse blanking or clipping in combination with pulse detection, a gap of about 4 dB to the interference-free case remains. This performance loss can be explained by the impact of pulse blanking and clipping onto the OFDM signal itself. The compensation and reduction of this impact is topic of future work.

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