Mitigation of Impulsive Frequency-Selective Interference in OFDM Based Systems

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***Abstract*—In this paper, an algorithm for mitigating impulsive interference in OFDM based systems is presented. It improves the conventional blanking nonlinearity approach for interference mitigation, which typically distorts the entire received signal, by combining the blanked and the original signal. The algorithm uses a Neyman-Pearson like testing procedure to detect interference at individual sub-carriers. Provided interference is detected, the blanked and the original received signals are then optimally combined such as to maximize the signal-to-interference-and-noise ratio. The algorithm does not require any prior knowledge about the impulsive interference and only marginally increases computational complexity as compared to the conventional blanking nonlinearity approach. Numerical results demonstrate the superior performance of the proposed scheme.**

***Index Terms*—OFDM, impulsive interference, interference mitigation, blanking nonlinearity.**

I. Introduction

ORTHOGONAL frequency-division multiplexing (OFDM) is a multi-carrier modulation technique, which has established itself in the recent years and is currently deployed in numerous communications systems such as digital audio broadcasting (DAB), digital video broadcasting (DVB), or 3GPP long term evolution (LTE), to mention just a few. These systems are often exposed to impulsive interference that originates from switching processes on the power distribution network, ignitions of passing vehicles, or other systems operating in the same frequency range [1].

For moderate impulsive interference power and infrequent occurrence, OFDM systems can cope relatively well with the interference, as it is spread among several sub-carriers of an OFDM symbol. However, for frequent occurrence or high interference power, such interference significantly affects the performance of the system [2] and interference mitigation techniques are required. A common approach to mitigate the impact of impulsive interference is to apply a memoryless blanking nonlinearity (BN) at the receiver input prior to the conventional OFDM demodulator [3], [4]. Such nonlinearity blanks all samples of the received signal with an amplitude exceeding a predefined threshold. Although BN does cancel the impulsive interference, it also affects the useful OFDM signal, which is a significant drawback of this scheme [5]; also the whole received signal is typically discarded during the blanking interval, despite only a fraction of the transmission bandwidth might be affected by the interference. Another critical issue when applying the BN to an OFDM-based system is the detection of interference impulses. It is well known that OFDM signals have a relatively high peak-to-average power ratio. This makes a differentiation of interference impulses from OFDM signal peaks challenging.

In recent years, several sophisticated algorithms for the mitigation of impulsive interference have been proposed [6]–[9]. They rely on decision directed and/or iteratively obtained estimates, which improve decoding at the cost of an increased computational complexity. Furthermore, iterative schemes tend to slow convergence and have difficulties converging at all if poorly initialized.

Here, we propose an alternative, non-iterative scheme that leads to a remarkable performance improvement also for poor transmission conditions, yet only marginally increases the computational complexity as compared to the BN approach. Specifically, we propose a new algorithm that profits from combining the original received signal with the blanked signal. The approach is realized by first detecting the interference at each sub-carrier using a new Neyman-Pearson-like testing procedure, and then optimally combining both the blanked and the original received signal such as to maximize the signal-to-interference-and-noise ratio (SINR) provided the interference has been detected. In this way the proposed algorithm compensates losses due to falsely blanked OFDM signal samples that are not corrupted by interference.

II. System Model

Let us consider a digital baseband model of the transmission system. A stream of information bits enters an OFDM transmitter. The latter incorporates channel coding of the source bits, mapping of the coded bits onto modulated symbols, and insertion of pilot symbols. N modulated symbols $X_k,\ k = 0, 1, ..., N-1$, are arranged in a vector $\mathbf{X} = [X_0, X_1, ..., X_{N-1}]^T$ to form an OFDM symbol[1]. The latter is then transformed into the time domain using an N-point inverse fast Fourier transform (IFFT). Finally, the resulting IFFT samples are preceded by N_{cp} cyclic prefix samples, forming the transmit vector $\mathbf{s} = [s_0, s_1, ..., s_{N+N_{\mathrm{cp}}-1}]^T$. The transmitted vector $\mathbf{s}$ is then used as input to a multi-path channel with an impulse response $\mathbf{h} = [h_0, h_1, ..., h_{N+N_{\mathrm{cp}}-1}]^T$. It is assumed that $h_l = 0$ for $l \geq N_{\mathrm{cp}}$, where l denotes the sample index in the time domain. We will assume that the received signal is corrupted by additive white Gaussian

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[1] Since the presented algorithm depends on information from the current received OFDM symbol only, the OFDM symbol index is omitted.

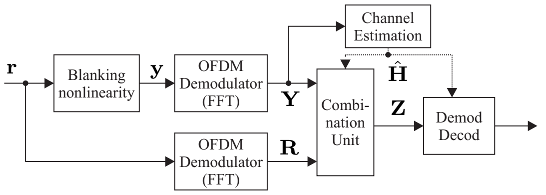

Fig. 1. Receiver model for OFDM transmission with blanking nonlinearity.

noise (AWGN) $\mathbf{n} = [n_0, n_1, ..., n_{N+N_{\text{cp}}-1}]^T$ and impulsive interference $\mathbf{i} = [i_0, i_1, ..., i_{N+N_{\text{cp}}-1}]^T$. Finally, the baseband model of the received signal can be represented as $\mathbf{r} = \mathbf{h} \circledast \mathbf{s} + \mathbf{n} + \mathbf{i}$, where "$\circledast$" denotes a circular convolution and $\mathbf{r} = [r_0, r_1, ..., r_{N+N_{\text{cp}}-1}]^T$ is a vector of received samples. In this model a perfect time and frequency synchronization at the receiver is assumed. The signals $\mathbf{s}$, $\mathbf{n}$, and $\mathbf{i}$ can be assumed as statistically independent; further, without loss of generality, we will also assume that the power of the transmitted signal is normalized to one, i.e. $E\left\{|s_l|^2\right\} = 2\sigma_s^2 = 1$. For the average power of the AWGN samples it holds that $N_0 = 2\sigma_n^2$, with σ_s^2 and σ_n^2 being the component-wise variances of the transmit signal and the noise signal, respectively. The impulsive interference model will be described later on in the text.

The vector $\mathbf{r}$ is an input to the receiver, as shown in Fig. 1. In order to remove high peaks of the impulsive interference a BN is applied. The BN is described by a memoryless nonlinear mapping $f : \mathbb{C} \to \mathbb{C}$ specified as

$$y_l \;=\; f(r_l) \;=\; \begin{cases} r_l, & \text{if } |r_l| < T_{\text{BN}}, \\ 0, & \text{else}, \end{cases} \tag{1}$$

for $l = 0, 1, ..., N + N_{\text{cp}} - 1$ and T_{BN} denoting the blanking threshold. In Section IV we will address the selection of T_{BN} in more detail. Following the nonlinearity, the blanked signal $\mathbf{y} = [y_0, y_1, ..., y_{N+N_{\text{cp}}-1}]^T$ enters an OFDM demodulator. The demodulator incorporates the removal of the cyclic prefix and a fast Fourier transform (FFT), which results in the frequency domain signal $\mathbf{Y} = [Y_0, Y_1, ..., Y_{N-1}]^T$. The pilot symbols extracted from $\mathbf{Y}$ are used to calculate estimates $\hat{\mathbf{H}}$ of the channel transfer function $\mathbf{H} = [H_0, H_1, ..., H_{N-1}]^T$, which is defined as the Fourier transform of the channel impulse response.

Unfortunately, this simple approach also inevitably distorts the received signal. In particular the BN leads to an attenuation of the OFDM signal and introduces inter-carrier interference (ICI), as investigated in [5]. In order to reduce the effects of this distortion, we propose to linearly combine the blanked signal $\mathbf{Y}$ and the original received signal $\mathbf{R}$ to form a new signal $\mathbf{Z}$ that is used for demodulation and subsequent decoding for obtaining estimates of the transmitted information bits. $\mathbf{R}$ is the output of the OFDM demodulator fed with the received signal $\mathbf{r}$. The combined signal $\mathbf{Z}$ is computed so as to maximize the SINR for each sub-carrier.

III. Proposed Algorithm

In this section, we describe the algorithm for calculating the optimally combined signal $\mathbf{Z}$. It should be noted that the algorithm does not rely on a known shape or model of the interference signal, neither in time, nor in frequency domain; also it does not exploit any previous decisions about transmitted data. The algorithm incorporates three steps. In the first step, interference is detected for each sub-carrier; in the second step, the SINR is estimated; finally, in the third step, both signals are combined optimally so as to maximize the SINR.

A. Step I: Detection of the interference

The kth sub-carrier of a received OFDM symbol after the OFDM demodulation can be described by

$$R_k = H_k X_k + N_k + I_k, \tag{2}$$

with N_k and $I_k, k = 0, ..., N-1$, being the Fourier transform of the AWGN and the impulsive interference, respectively. In the following we assume that I_k is Gaussian distributed for an individual sub-carrier k. In [10] it is shown that this approximation is valid, independently of the structure of the noise, due to the spreading effect of the FFT. After the BN the signal in the frequency domain is represented as [5]

$$Y_k = K H_k X_k + D_k, \tag{3}$$

where K is an attenuation factor given by $K = (1 - {}^{N_{\mathcal{B}}}\!/_{N})$. Here, $N_{\mathcal{B}}$ denotes the number of blanked samples in the respective OFDM symbol. The distortion term D_k in (3) can be represented as the sum of attenuated AWGN N_k', and the ICI $I_{\text{ICI},k}$ introduced by the BN

$$D_k = N_k' + I_{\text{ICI},k}. \tag{4}$$

Since the impulsive interference occurs only occasionally and with a power well above the OFDM signal power, we assume that the impulsive interference is almost completely removed by the BN and remaining impulsive interference below the blanking threshold T_{BN} is neglected in the following. Now we define

$$\Delta Y_k = K R_k - Y_k = K I_k + D_k', \tag{5}$$

with $D_k' = \Delta N_k - I_{\text{ICI},k}$ and $\Delta N_k = K N_k - N_k'$. The signal ΔY_k is a useful indicator whether the kth sub-carrier is affected by interference. Indeed, if $I_k = 0$, ΔY_k equals D_k' only; alternatively, ΔY_k will include the combination of both D_k' and impulsive interference I_k. Unfortunately, the signal D_k' is not available at the receiver. However, we can approximate its statistics. The variance of ΔN_k can be easily calculated when keeping in mind that N_k differs from N_k' only by the noise contributions from the blanked samples; we obtain $\text{Var}(\Delta N_k) = (1-K) K N_0$. The ICI term $I_{\text{ICI},k}$ can be approximated by a Gaussian distribution for a sufficiently high number of sub-carriers [5]. It has zero mean and variance $\text{Var}(I_{\text{ICI},k}) = (1-K) K \hat{H}_{\text{av}}^2 E\left\{|X_k|^2\right\}$, where $\hat{H}_{\text{av}} = \frac{1}{N} \sum_{k=0}^{N-1} |\hat{H}_k|$. In [5], (6) was derived for AWGN only. For arbitrary channel models, it is required to scale $E\left\{|X_k|^2\right\}$ by $\hat{H}_{\text{av}}^2$ since on average the other sub-carriers contribute equally to the ICI at the kth sub-carrier.[2] Since

[2]This assumption is valid for uncorrelated blanking positions. Otherwise, the contribution of the other sub-carriers might not be equal in the long run.

ΔN_k and $I_{\text{ICI},k}$ are statistically independent, the variance of D'_k can be approximated by

$$\text{Var}(D'_k) = (1-K)K\left(\hat{H}^2_{\text{av}} E\left\{|X_k|^2\right\} + N_0\right). \quad (6)$$

Result (6) allows us to formally pose the impulsive interference detection problem as a composite statistical hypothesis test as follows.

Define the hypotheses $\mathcal{H}_0 : I_k = 0$, and $\mathcal{H}_1 : I_k \neq 0$, and consider the distribution of $|\Delta Y_k|$ under these hypotheses. Under $\mathcal{H}_0$ the value of $|\Delta Y_k|$ follows a Rayleigh distribution with the scale parameter $\text{Var}(D'_k)$. Under $\mathcal{H}_1$ the situation is different since ΔY_k now follows a distribution of the mixture of D'_k and I_k. Assuming that for a specific k the interference I_k is Gaussian, we have the following. If I_k is zero mean, then $|\Delta Y_k|$ can be approximated with a Rayleigh distribution, yet with a larger scale parameter that accounts for the variance of I_k. When I_k is not zero mean, then $|\Delta Y_k|$ can be approximated with a Rician distribution. Thus, we need to decide between $\mathcal{H}_0$, when $|\Delta Y_k|$ follows a Rayleigh distribution, and a composite alternative $\mathcal{H}_1$, when $|\Delta Y_k|$ follows a Rician distribution. Note that this is a one-sided test. Moreover, the critical region of such test is independent of the statistics of I_k but depends merely on the statistics of D'_k, which are known; in other words, it depends on the distribution of $|\Delta Y_k|$ under the hypothesis $\mathcal{H}_0$. Thus, in order to decide between $\mathcal{H}_0$ and $\mathcal{H}_1$ in a Neyman-Pearson-like sense, we fix the probability of the type-I error at some level p_I. A type-I error is defined as the probability of selecting $\mathcal{H}_1$ when $\mathcal{H}_0$ is true. Then, the optimal hypothesis $\hat{\mathcal{H}}$ is selected as

$$\hat{\mathcal{H}} = \begin{cases} \mathcal{H}_0 : & |\Delta Y_k| < T_{\text{ICI},k}, \\ \mathcal{H}_1 : & |\Delta Y_k| \geq T_{\text{ICI},k}, \end{cases} \quad (7)$$

where the decision threshold $T_{\text{ICI},k}$ is found as $T_{\text{ICI},k} = \sqrt{\text{Var}(D'_k)\log(1/p_I)}$. The latter expression follows directly from the properties of the Rayleigh distribution.

Obviously, if $\mathcal{H}_0$ is selected, then $Z_k = R_k$ as there is no impulsive interference. If, however, $\mathcal{H}_1$ is selected, then R_k and Y_k have to be optimally combined based on their sub-carrier SINR for obtaining Z_k.

B. Step II: Calculation of the SINR

Under the assumption that I_k and $I_{\text{ICI},k}$ are mutually uncorrelated, the interference power at the kth sub-carrier can be computed from (5) as

$$|I_k|^2 = \begin{cases} \frac{|\Delta Y_k|^2 - \text{Var}(D'_k)}{K^2}, & \text{if } |\Delta Y_k| \geq T_{\text{ICI},k}, \\ 0, & \text{else}. \end{cases} \quad (8)$$

This allows us to calculate the sub-carrier SINR for the received signal R_k from (2) and (8), and the sub-carrier SINR for the blanked signal Y_k from (3), (4), and the variance of the ICI

$$\text{SINR}_{R_k} = \frac{|\hat{H}_k|^2}{N_0 + |I_k|^2}, \quad (9)$$

$$\text{SINR}_{Y_k} = \frac{K^2|\hat{H}_k|^2}{K^2 N_0 + (1-K)K(\hat{H}^2_{\text{av}} + N_0)}. \quad (10)$$

C. Step III: Combination of both signals

Having computed (9) and (10) we consider an optimal combination of R_k and Y_k that maximizes the SINR. For that we construct a combined signal Z_k as

$$Z_k = w_k R_k + (1-w_k)Y_k, \quad (11)$$

where $w_k \in [0,1]$ is a weighting factor. It is now straightforward to obtain the SINR of the combined signal Z_k as a function of the weighting factor w_k

$$\text{SINR}_{Z_k} = \frac{|\hat{H}_k|^2\left(w_k + (1-w_k)K\right)^2}{w_k^2|I_k|^2 + \left(w_k + (1-w_k)K\right)^2 N_0 \cdots} \frac{1}{+(1-w_k)^2(1-K)K\left(\hat{H}^2_{\text{av}} + N_0\right)}. \quad (12)$$

After some tedious but rather straightforward algebra the extremum of (12) with respect to w_k is found at

$$w_k = \begin{cases} \frac{(1-K)(\hat{H}^2_{\text{av}} + N_0)}{(1-K)(\hat{H}^2_{\text{av}} + N_0) + |I_k|^2}, & \mathcal{H}_1 \text{ is selected}, \\ 1, & \mathcal{H}_0 \text{ is selected}. \end{cases} \quad (13)$$

Obviously, when no blanking is applied $(K = 1)$ or no interference is detected $(I_k = 0)$ for a specific k, the signal Y_k is discarded as it contains no additional information. In all other cases, both the original signal R_k and the blanked signal Y_k are linearly combined with the combination weights chosen such as to maximize the SINR; it is this feature of the proposed algorithm that leads to the improved performance.

The computational complexity overhead for our proposed scheme is only minimal. In the combination unit, the number of operations scales linearly with the number of sub-carriers, i.e., $\mathcal{O}(N)$. The introduced second FFT has a complexity of $\mathcal{O}(N\log(N))$; moreover, it can be computed in parallel to the FFT of Y_k.

IV. Simulation Results

In order to evaluate the performance of the proposed algorithm, the transmission scenario is adopted from [6]. In this context LDACS1 [11] as exemplarily chosen OFDM system is exposed to impulsive interference from the DME system[3]. LDACS1 operates at $994.5\,\text{MHz}$. The LDACS1 channel occupies $625\,\text{kHz}$ bandwidth, resulting in a sub-carrier spacing of $\approx 9.8\,\text{kHz}$, with 64 sub-carriers. For channel coding, a concatenated scheme of a Reed-Solomon code with rate 0.9 and a convolutional code with rate $1/2$ is used. The coded bits are QPSK modulated. This OFDM signal is interfered by Gaussian shaped pulse pairs with short duration but high power, generated by DME stations. These stations are transmitting at a $\Delta f_c = \pm 0.5\,\text{MHz}$ frequency offset compared to the LDACS1 carrier frequency, however with a spectrum partially overlapping with the LDACS1 bandwidth. This leads to a frequency-selective impulsive interference, which mainly affects the edges of the LDACS1 bandwidth. The interference scenario from [6] comprises four DME stations, which are characterized in Table I. The signal-to-interference ratio (SIR)

[3]More detailed information about the two considered system can be found in [6], [11].

TABLE I
PARAMETERS OF INTERFERENCE SCENARIO.

Station	Δf_c [MHz]	SIR [dB]	Pulse pair rate [1/s]
DME_1	-0.5	-18.7 + SNR [dB]	3600
DME_2	-0.5	-17.2 + SNR [dB]	3600
DME_3	-0.5	-2.9 + SNR [dB]	3600
DME_4	+0.5	-23.3 + SNR [dB]	3600

is defined as the ratio of the average OFDM signal power and the peak power of DME pulses. The signal-to-noise ratio (SNR) is defined as $1/N_0$. Unlike the simulations, in real systems an increasing SNR corresponds to an increasing OFDM signal power but does not reduce the AWGN power. This is taken into account when calculating the SIR by adding the SNR.

For statistical impulsive noise models, the optimal blanking threshold is derived in [12]. However, this approach cannot be easily extended to more evolved interference scenarios, like multiple DME interference. Hence we derive the threshold based on simulations, as shown in [13]. When applying the BN, $T_{\mathrm{BN}} = 3.5$ leads to the best results. Yet the proposed algorithm leads to a lower optimal threshold at $T_{\mathrm{BN}} = 2.5$. This results from the fact that falsely blanked OFDM signal peaks have a less profound effect as now the testing procedure is employed to determine the presence of interference. If the test shows that no interference occurred only the non-blanked signal is used for further processing. The type-I error probability was set to $p_I = 0.001$, which led to the best performance.[4]

We use a realistic aeronautical en-route channel model adopted from [6]. It takes into account a two-path channel model with a strong line-of-sight path and Doppler frequencies of up to $1.25\,\mathrm{kHz}$. The estimation of the channel transfer function is realized using Wiener filtering based on the pilot information.

Simulations were carried out for the BN case only, the proposed scheme, and the blanking compensation (BC) algorithm proposed in [6]. The latter algorithm removes blanking-induced ICI in an iterative way. The resulting bit error rate (BER) is plotted in Fig. 2 as a function of the SNR. As expected, the simple BN leads only to moderate improvement due to interference detection failures and the induced ICI. Iterative removal of ICI by the BC does improve the BER. However, the proposed scheme outperforms the BC by $\approx 1\,\mathrm{dB}$ while preserving a low complexity. Compared to the simple BN the proposed scheme achieves gains higher than $3\,\mathrm{dB}$. The remaining gap between the performance of the proposed scheme and the interference-free case is due to the reduction of the OFDM signal power by the BN and inaccuracies in estimating the SINR of R_k and Y_k signals.

V. CONCLUSION

In this paper, we have addressed the mitigation of pulsed interference in OFDM based systems. The proposed scheme is an extension of the conventional blanking nonlinearity, which uses a Neyman-Pearson-like testing procedure to (i) detect the presence of the interference pulses, and then, provided the interference has been detected, to (ii) optimally combine the blanked signal with the original received signal such as to maximize the sub-carrier signal-to-interference-and-noise ratio. The algorithm can be potentially used with any type of impulsive interference, yet we expect that it copes particularly well with frequency-selective interference. The presented numerical simulations support this claim. Specifically, the proposed algorithm has demonstrated a superior performance in terms of the achieved bit error rate as compared to other state-of-the-art interference mitigation techniques while preserving a low complexity.

[4] Note that the optimal selection of p_I depends on the interference scenario. However, values from $p_I = [0.01, 0.0001]$ led to similar results for several tested scenarios.

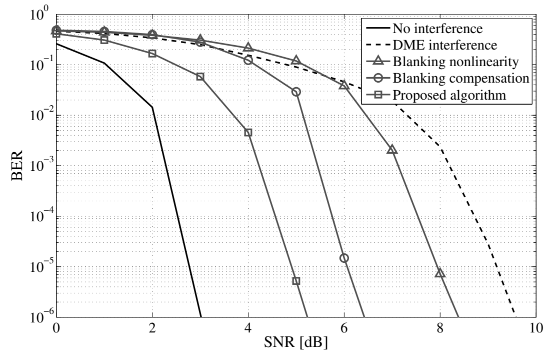

Fig. 2. Simulated BER performance for en-route transmission channel.

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