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A dual protection scheme for impulsive noise suppression in OFDM systems

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) can be susceptible to impulsive noise arising from numerous sources in a noisy communications environment. Conventional Reed–Solomon (RS) codes are particularly useful for burst-error corrections and have been employed in OFDM systems to manage impulsive noise. The performance gains, however, have been somewhat limited given the sensitivity to other noise types typically present in a noisy channel. In this regard, a novel scheme utilizing a time-domain pre-processing mean filter in combination with RS coding is proposed for impulsive noise suppression in OFDM systems. This scheme is split into two stages. In the first stage, a proposed mean filter effectively detects and removes the impulsive noise using the measured statistics of the impulsive noise. In contrast to a conventional blanking type filter, the traditional mean replacement value is replaced by a composite comparison value (CCV). This principle creates a more accurate estimate of the original OFDM signal after impulsive noise removal. The residual impulsive noise is then managed by a RS decoder in the second stage. Our results show that this dual faceted approach improves OFDM performance when compared to filtering and coding techniques alone.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a modulation technology that is widely used in various communications systems, such as wireless local area network (WLAN), digital audio broadcasting (DAB), and power-line communications (PLC). The concept of OFDM is based on multi-carrier technology where data is transmitted over N orthogonal subcarriers. OFDM has several advantages when compared to single carrier communications systems such as resistance to multipath distortion, improved spectral efficiency, and robustness to narrowband noise [1]. However, excessive impulse noise in terms of event probability, duration, and amplitude can cause difficulties in OFDM transmission [2]. Typical impulsive noise is due to power lines, heavy current switches, vehicle ignition systems, high voltage discharge and other sources that cannot be assumed to be additive Gaussian in nature [3–5]. Impulsive noise is formalized as an additive channel noise component with typical characteristics such as: spike-like with short time durations, random occurrence, and a high power spectral density. With respect to the latter, impulsive noise amplitude can be several dB over the received signal and other background noise [6]. As a result, impulsive noise can result in the performance degradation of the OFDM system, since its energy spreads to the all OFDM carriers through the discrete Fourier transform (DFT) demodulation process.

To decrease the impact of impulsive noise, a basic suppression procedure was proposed, and is formulated using two basic steps: impulsive noise detection and error correction [7,8]. Based on these concepts, filtering and coding methods to manage impulsive noise have been previously proposed. For example, a blanking nonlinearity process [9] is employed to locate and filter an impulsive noise event if its amplitude exceeds an assigned threshold in the time domain. In [10], a novel algorithm was proposed to estimate impulsive noise in the frequency domain based on similar concepts as blanking nonlinearity process. Although these techniques have been found to improve the overall system bit error rate (BER), but the performance gains are somewhat limited due to ill-defined impulse noise thresholds and the blanking of the data content.

Recent research demonstrates several advantages of coding methods for error detection and correction in an impulsive noise environment, especially in regard to the Reed–Solomon coding scheme. A creative approach called burst error recovery technique (BERT) is presented for impulsive noise mitigation [11]. In addition to RS coding, an over-sampling procedure is employed to improve robustness to impulsive noise. However, theoretical analysis and simulation results show that this approach is sensitive to increased levels of additive white Gaussian noise (AWGN). This is due to small variations in the infinite impulse response filter coefficients due

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to AWGN result in large variations at the output when the filter poles are close to each other. Kumaresan proposed some decoding strategies based on least-squares errors and a singular value decomposition process to correct for impulse errors [12]. Dlhan described an alternative approach to protect OFDM signals against impulsive noise and AWGN [13]. The proposed syndrome-based decoding algorithm using soft decision making showed promise but is still unable to fully resist the detrimental effects of higher levels of AWGN.

Our research is focused on improving the performance of the impulsive noise cancelation process as well as to provide the ability to resist the influence of AWGN in OFDM systems. Hence, in this paper, we present a practical scheme for such a purpose. The reminder of the paper is organized as follows. In Section 2, the theoretical background and impact of impulsive noise on OFDM are introduced. Some existing impulsive noise suppression approaches which are based on filtering techniques are also described in this section. In Section 3, the details of our dual protection scheme are proposed. Several simulations and numerical results are represented in Section 4. Finally, conclusions of our work are provided in Section 5.

2. Impact of impulsive noise on OFDM

With a RS coded OFDM transmitter, the signal sequence to be transmitted, given as $\bar{Y}_n$, is first RS coded and then serial-to-parallel (S/P) converted to form the N data streams Y_n, where $0 \le n \le N-1$. The S/P output is subcarrier modulated using QPSK, QAM, etc., prior to the application of the N-point inverse discrete Fourier transform (IDFT) process [14], that is,

$$\begin{aligned} x_k &= \mathrm{IDFT}(S_n) \\ &= \sum_{n=0}^{N-1} S_n \exp\left(j\frac{2\pi nk}{N}\right), \quad 0 \le k \le N-1, \end{aligned} \tag{1}$$

where IDFT indicates IDFT process, and S_n is the subcarrier modulated signal. The k output streams of x_k are then parallel-to-serial (P/S) converted and used to modulate a radio frequency (RF) carrier for transmission over the desired communications channel.

Generally, noise in the channel can be grouped into two classes: AWGN and impulsive noise [15]. The OFDM receiver simply reverses the transmission process and after the RF demodulation, the received OFDM signal r_k is modeled as follows:

$$r_k = x_k * h_k + n_k = x_k * h_k + w_k + i_k, \tag{2}$$

where h_k, w_k, and i_k are the channel impulse response, AWGN, and impulsive noise representations, respectively. * indicates a convolution operation and n_k is the aggregation of w_k and i_k. The resulting sequence r_k is then S/P transformed into a parallel format.

A N-point DFT process is applied:

$$\begin{aligned} R_n &= \mathrm{DFT}(r_k) \\ &= \sum_{k=0}^{N-1} r_k \exp\left(-j\frac{2\pi nk}{N}\right), \quad 0 \le n \le N-1, \end{aligned} \tag{3}$$

where DFT indicates DFT process. The N-point DFT is then P/S converted with a subcarrier demodulation process corresponding to the subcarrier modulation used during transmission. In our research, the fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) are utilized for the implementation of DFT and IDFT, respectively. When a channel equalizer is not considered, we can represent R_n as

$$R_n = S_n H_n + W_n + I_n, \tag{4}$$

where H_n is the channel frequency response, W_n and I_n are AWGN and impulsive noise in frequency domain, respectively.

The concept of AWGN is known in the area of communications and signal processing, and its model has been well documented. Less popular but still invasive is the impulsive noise component. Referring to previous research work, impulsive noise i_k is normally accepted as the following expression [16]:

$$i_k = b_k g_k, \tag{5}$$

where b_k is a Bernoulli process indicating the arrival of the impulsive noise event and g_k is the random Gaussian process with zero mean and σ_i^2 variance. b_k contains independently distributed zeros and ones where the ones indicate the arrival of impulsive noise events. The arrival rate of the impulsive noise events is represented as $p = P(b_k = 1)$. The arrival and variance parameters can be altered to facilitate varying noise conditions. In this research, the probabilistic arrival rate of the impulsive noise events p was set to 1% and 10% and the variance was held constant.

In the time domain, the characteristics of impulsive noise can have significant differences when compared to transmitted signal and can be summarized as follows: (1) impulsive noise peak amplitudes can be much higher than that of the transmitted signal; (2) impulsive noise energy is concentrated into short periods. Given this, a method based on a blanking nonlinearity filter was proposed in [9]. The impulsive noise is suppressed by the process:

$$r_k^{\mathrm{comp}} = \begin{cases} r_k, & \text{if } |r_k| < A_0, \quad k = 0, 1, \ldots, N-1 \\ 0, & \text{otherwise} \end{cases}, \tag{6}$$

where r_k is the time domain signal at the receiver and A_0 is the experimental threshold value.

Also, Zhidkov proposed a promising peak detection method (VBF) based on the variance of estimated noise to mitigate the effect of impulsive noise at the receiver in the frequency domain [10]. For the peak detection, a threshold value is estimated to recognize impulsive noise sequence $\hat{u} = [\hat{u}_0, \hat{u}_1, \ldots, \hat{u}_{N-1}]$:

$$\widehat{\sigma}^2 = \frac{1}{N}\sum_{k=0}^{N-1} \left|\hat{d}_k\right|^2, \quad k = 0, 1, \cdots, N-1, \tag{7}$$

$$\hat{u}_k = \begin{cases} d_k, & \text{if } \left|\hat{d}_k\right|^2 > C\hat{\sigma}^2, \quad k = 0, 1, \ldots, N-1 \\ 0, & \text{otherwise} \end{cases}, \tag{8}$$

where $\hat{d}_k$ is the integrated noise estimation in time domain, N is the number of $\hat{d}_k$, $\hat{u}_k$ is the estimated representation of impulsive noise, and C is the threshold value that corresponds to the probability of false detection.

Although these approaches provide an effective way to reduce the impact of impulsive noise, the evaluation of the threshold value does not respond to changes in the characteristics of the impulsive noise and does not assess any correlation between the additive noise components.

3. Our proposed approach

As expected, the value of the impulsive noise threshold affects the performance of the impulsive noise suppression methodology. If the threshold value is too small, a significant portion of the transmitted signal is replaced with zeros and the output signal-to-noise ratio (SNR) given by

$$\mathrm{SNR} = 10\log_{10}\frac{\sum x_k^2}{\sum n_k^2} \tag{9}$$