An Efficient Technique for OFDM Systems over Fading Channels Impaired by Impulsive Noise

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***Abstract*—In this work, an elegant interleaving process is used not only to mitigate the impact of bursty impulsive noise on the performance of orthogonal frequency division multiplexing (OFDM) systems but also to break bursty multipath fading channel errors. While, conventional OFDM systems implement the interleaving process in the frequency domain, the system proposed here uses a block interleaver of size N^2 samples in the time domain. As a result, time diversity has been exploited through the use of the interleaver by spreading the samples contaminated by impulsive noise over the impulse-free OFDM symbols and breaking the correlated behaviour of the multipath fading channel. Nevertheless, the results, given in this work, have shown that the performance of the proposed system depends on the kind of equalization process used. A serious degradation in the performance is noticed when zero forcing (ZF) equalizer is utilized. However, a simple and low complexity solution to improve the ZF equalizer performance is also proposed. On the other hand, utilizing a minimum mean square error (MMSE) equalizer demonstrates better performance than the ZF equalizer. The simulation results have confirmed the validity of the proposed system over different scenarios of the channels considered in this work.**

I. INTRODUCTION

The increased demand for a high data rate and spectra-efficient modulation techniques has led to the widespread adoption of orthogonal frequency division multiplexing (OFDM) systems with various communication standards, e.g. digital video broadcasting - satellite services to handhelds (DVB-SH) [1]. However, the conventional OFDM systems have a poor bit error rate (BER) performance, since these systems do not exploit either frequency diversity or time diversity. Linear precoding techniques are one of the most important techniques that have been extensively used to improve the conventional OFDM system performance by exploiting the multipath channel frequency diversity [2] and [3]. These techniques have shown a remarkable improvement in the performance of the OFDM systems over multipath fading channels. For example, [3] has split the total number of subcarriers into small blocks and spread the data symbols over these blocks by using a unitary matrices in order to gain frequency diversity over each block. Unfortunately, this improvement comes at the cost of an increase in system computational complexity. Moreover, these techniques have failed to show an improvement over the impulsive noise environment, which forms another source of disturbance for many digital communication systems. Due to the long symbol time of the OFDM signal, it is more robust against the impulsive noise effect than the single carrier transmission [4]. Accordingly, the OFDM has been considered in many wired technologies, such as asymmetric digital subscriber line (ADSL) and home networking over power line communications (PLC) [5] and [6] . However, with harsh impulsive noise channels, the OFDM performance might be significantly degraded [7]. In the literature, several schemes have been suggested to reduce the impact of the impulsive noise on the OFDM performance [7]-[9]. The work in [7] is basically designed to elevate the impact of the impulsive noise on the DVB-T systems, where the impulsive noise is estimated in the frequency domain and subtracted from the equalizer output. Nevertheless, the main limitation of this work is its high computational complexity. The schemes in [8] and [9] are optimized for weak impulsive noise environments. The work in [10] did not consider the effect of the multipath fading channel.

In this work, a time domain interleaving (TDI) technique is utilized to improve the OFDM immunity over multipath fading channels impaired by impulsive noise without a sacrifice in bandwidth or an increase in the transmit power. However, the performance of the TDI combined with the OFDM system over multipath fading channels is sensitive to the zero forcing (ZF) equalization process. Accordingly, an approach to improve the TDI-OFDM performance over multipath fading channels is proposed as well.

The sections of this paper are organized as follows. The TDI-OFDM system and the channel model are presented in Section II. Numerical results and conclusions are given in Sections III and IV, respectively.

II. THE TDI-OFDM SYSTEM AND CHANNEL MODEL

The main parts of the standard OFDM system and the TDI-OFDM system are shown in Fig. 1 and Fig. 2, respectively. As shown by the figures, the transmitter part of the TDI-OFDM system is similar to that of the standard OFDM system except, that the TDI-OFDM system implements the interleaving process after the inverse fast Fourier transform (IFFT). However, at the receiver side, the deinterleaving is performed after the equalization process in both systems. The role of the interleaver in the standard OFDM is to randomize the encoder output to break the channel bursty error. However, the TDI-OFDM, in addition to this, exploits the time diversity to elevate both the multipath effect and the impulsive noise effect on the OFDM system performance. In the following, we will focus on the TDI-OFDM system details.

A. Transmitter

Let N denote the number of subcarriers in the TDI-OFDM system modulated by a sequence of N complex data symbols $d = [d_0, d1, \cdots, d_{N-1}]^T$. The data symbols are selected uniformly from a constellation with constant modulus, such as M-ary phase shift keying (MPSK) or M-ary quadrature amplitude modulation (MQAM). We assume that the data symbols are independent and identically distributed (iid) with zero mean and variance $\sigma_d^2 = E\{|d_i|^2\}$ where $E\{.\}$ denotes the expectation operator. The modulation process can be implemented efficiently using N-points IFFT. The output of the IFFT process is given by

$$\mathbf{x} = \mathbf{W}\mathbf{d}, \tag{1}$$

where $\mathbf{W}$ is the normalized $N \times N$ IFFT matrix. The elements of $\mathbf{W}$ are defined as $W_{i,k} = (1/\sqrt{N})e^{j2\pi ik/N}$, i and k denote the row and column numbers $\{i,k\} = 0, 1, \cdots, N-1$, respectively. Consequently, the nth sample in the sequence $\bar{\mathbf{x}}$ can be expressed as

$$x_n = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} d_i e^{j2\pi in/N}, \quad n = 0, 1, \cdots, N-1. \tag{2}$$

The IFFT output is converted from serial to parallel and delivered to an interleaver of size N^2 as shown in Fig. 2 (for simplicity the serial to parallel and parallel to serial conversions are not shown). The interleaver is filled in row fashion, and then read in column. Consequently, the first transmitted symbol consists of the first subcarriers of the N OFDM symbols, the second transmitted symbol is consisting of the second subcarriers of the N OFDM symbols, and so on. Thus, the interleaved OFDM symbols during the signalling period $\ell \rightarrow \ell + N - 1$ can be expressed as

$$\begin{aligned}
\bar{\mathbf{x}}(\ell) = & \ [x_0(\ell), x_0(\ell+1), \cdots, x_0(\ell+N-1)]^T \\
\bar{\mathbf{x}}(\ell+1) = & \ [x_1(\ell), x_1(\ell+1), \cdots, x_{k1}(\ell+N-1)]^T \\
& \ \vdots \\
\bar{\mathbf{x}}(\ell+N-1) = & \ [x_{N-1}(\ell), x_{N-1}(\ell+1), \cdots, x_{N-1}(\ell+N-1)]^T,
\end{aligned}$$

where T denotes the transpose function. To eliminate the inter-symbol interference (ISI) between consecutive interleaved OFDM symbols, and to maintain the subcarriers' orthogonality in frequency selective multipath fading channels, a cyclic prefix (CP) of length P samples no less than the channel delay spread (L_h) is formed by copying the last P samples of $\bar{\mathbf{x}}(\ell)$ and appending them at the beginning of $\bar{\mathbf{x}}(\ell)$ to compose the interleaved transmitted symbol with a total length $N_t = N+P$ samples and a duration of T_t seconds. Hence, the complex baseband interleaved OFDM symbol during the ℓth signalling period can be expressed as

$$\begin{aligned}
\bar{\mathbf{x}}_{cp}(\ell) = & [x_k(\ell+N-P), \cdots, x_k(\ell+N-1), \\
& x_k(\ell), x_k(\ell+1), \cdots, x_k(\ell+N-1)]^T,
\end{aligned}$$

where $0 \leq k, \ell \leq N-1$. The sequence $\bar{\mathbf{x}}_{cp}(\ell)$ is upsampled, filtered, up-converted to a radio frequency centred at carrier frequency, and propagated through the channel.

B. Receiver

At the receiver front-end, the received signal is down-converted to baseband and sampled at a rate $T_s = T_t/N_t$. In this work, we assume that the multipath channel is Rayleigh fading composed of $L_h + 1$ independent multipath components each of which has a gain h_i and delay $i \times T_s$, where $i \in 0, 1, \cdots, L_h$. Moreover, the channel coefficients satisfy $h_i = 0, \forall \ i < 0$ and $i > L_h$, and are normalized i.e. $\sum_{i=0}^{L_h} E\{|h_i|^2\} = 1$. Furthermore, a slow fading environment is assumed, so that the channel taps are assumed to remain constant over one block of interleaved OFDM symbols, varying from one block to another. In addition to the multipath distortion, additive white Gaussian noise and impulsive noise are added to the transmitted signal. Therefore, the received ℓth interleaved sequence after discarding the CP samples, assuming perfect knowledge of the channel coefficients, h_i, and ideal synchronization, can be expressed as

$$\bar{\mathbf{y}}(\ell) = \tilde{\mathbb{H}}\bar{\mathbf{x}}(\ell) + \mathbf{z}(\ell) + \rho\mathbf{b}\mathbf{v}(\ell) \tag{3}$$

where the channel matrix $\tilde{\mathbb{H}}$ is an $N \times N$ circulant matrix, $\mathbf{z}$ is the noise vector of N samples modelled as a white Gaussian noise process with zero mean and variance σ_z^2. The impulsive noise is modelled as a gated Gaussian noise process [11], where $\rho \in \{0, 1\}$ is the impulsive noise gating factor. If the ℓth symbol is hit by the impulsive burst, then $\rho = 1$, otherwise $\rho = 0$. The vector $\mathbf{b}$ consists of Bernoulli random variables with $Pr(b_i = 1) = p$, and $\mathbf{v} = [v_0, v_1, \cdots, v_{N-1}]^T$ are complex Gaussian noise samples with zero mean and variance σ_v^2. Then, the signal is passed to a frequency domain equalizer (FDE) which consists of N- point FFT, equalizer, and N-point IFFT. Accordingly, the FFT output of the sequence $\bar{\mathbf{y}}(\ell)$ can be computed as follows

$$\bar{\mathbf{s}}(\ell) = \mathbf{H}\bar{\mathbf{x}}(\ell) + \mathbf{Z}(\ell) + \rho\mathbf{V}(\ell), \tag{4}$$

where the last equation follows from linearity property of the discrete Fourier transform (DFT). The $\mathbf{Z}(\ell)$ and $\mathbf{V}(\ell)$ are the FFT outputs of the Gaussian noise and the impulsive noise, respectively. The matrix $\mathbf{H}$ is a $N \times N$ diagonal represents the channel frequency response which should be estimated and compensated before the deinterleaving process. Given that the kth element in the diagonal matrix $\mathbf{H}$ and in the impulsive noise vector $\mathbf{V}$, respectively, are

$$H_k = \frac{1}{\sqrt{N}} \sum_{i=0}^{L_h} h_i e^{-j2\pi ik/N}, \quad k = 0, 1, \cdots, N-1 \tag{5}$$

and

$$V_k = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} b_n v_n e^{-j2\pi ik/N}, \quad k = 0, 1, \cdots, N-1. \tag{6}$$

Then, the equalized signal is converted to the time domain via N-point IFFT. The discrete time domain samples are delivered

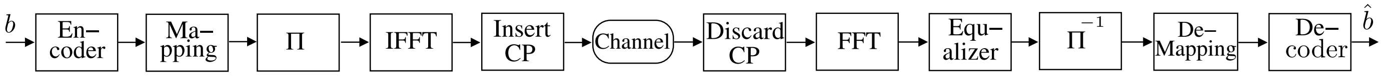

Fig. 1. Block diagram of the standard OFDM system

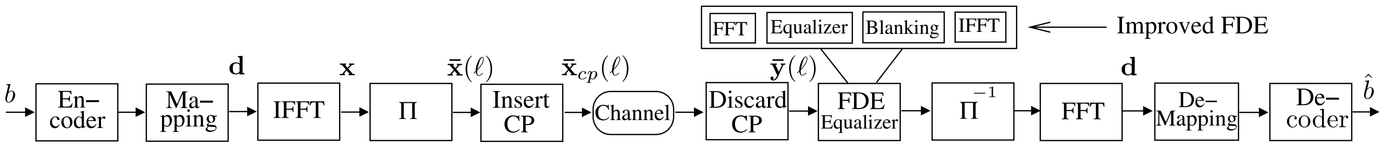

Fig. 2. Block diagram of the TDI-OFDM system

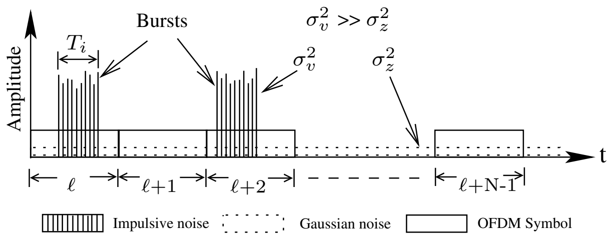

Fig. 3. Bursty impulsive noise model

serially to the deinterleaver. The deinterleaver is filled in a column fashion and read in a row. Finally, the transmitted data symbols can be recovered by the demodulation process and achieved efficiently by N-point FFT applied on the deinterleaver output samples after serial to parallel conversion. The aforementioned processes can be expressed mathematically as

$$\hat{\mathbf{d}} = \mathbf{W}^H \, \Pi^{-1}[\mathbf{W}\mathbf{C}\bar{\mathbf{s}}(\ell)], \tag{7}$$

where $\mathbf{C}$ is the equalizer coefficients denoted as $\mathbf{C}^{ZF} = \frac{\mathbf{H}^*}{\mathbf{H}\mathbf{H}^*}$ and $\mathbf{C}^{MMSE} = \frac{\mathbf{H}^*}{\mathbf{H}\mathbf{H}^* + \frac{1}{\gamma}}$ where $\gamma = \frac{\sigma_d^2}{\sigma_Z^2}$ for zero forcing (ZF) and minimum mean square error (MMSE) equalizer, respectively. Note that $\mathbf{W}^{-1} = \mathbf{W}^H$ because $\mathbf{W}$ is a symmetrical and unitary matrix.

C. Impulsive Noise Model and TDI-Mitigation

As mentioned above, the impulsive noise model is assumed to be a gated Gaussian noise model with burst width T_i, as demonstrated in Fig. 3. The impulsive noise measured in the 2.4 GHz band, due to the process of the switching transistor circuits in microwave oven, can be considered as an example of this kind of impulsive noise model [12]. The arrival of the impulsive bursts is usually following Poisson distribution. Consequently, the occurrence of δ arrivals in t seconds with a rate of λ units per second, has a distribution [13]

$$P_\delta(t) = \frac{(\lambda t)^\delta}{\delta!} \, e^{-\lambda t} \qquad \delta = 0, 1, 2, \cdots . \tag{8}$$

The value of λ and T_i are classified according to different applications, such as weak, moderate, and heavy distribution [11] and [14]. The overall additive noise sample is $\Psi_k = Z_k + \rho V_k$. Accordingly, the probability density function (PDF) of Ψ_k conditioned by ρ can be expressed as [4]

$$P(\Psi_k|_{\rho=1}) = \sum_{m=0}^{N} \binom{N}{m} p^m (1-p)^{N-m} G(\Psi_k, 0, \sigma_\Psi^2(m)), \tag{9}$$

where $\binom{N}{m} \triangleq \dfrac{N!}{(N-m)!}$ and

$$\sigma_\Psi^2(m) = \sigma_Z^2 + \frac{m}{N}\sigma_V^2. \tag{10}$$

The main idea of the TDI is to reduce the value of m in (10), which leads to a significant improvement in the BER performance of the OFDM system. To attain this improvement, we use a block interleaver at the transmitter after the IFFT process with depth of N samples and a block deinterleaver at the receiver after the equalization process, i.e. the FDE unit in Fig 2. As long as $\delta \ll N$, the samples contaminated by impulsive bursts can be spread over a large number of the impulsive-free OFDM symbols. Simply, if we assume one burst of size width N samples (i.e. $T_i = N$) hits N interleaved OFDM symbols, and then every OFDM symbol after the deinterleaver receives only one sample contaminated by impulsive noise.

III. Numerical results and discussion

In order to assess the performance of the TDI-OFDM system, Monte Carlo simulations have been used to evaluate the system BER performance over different types of channels. For both systems, the simulation parameters were set as follows. The number of subcarriers was chosen to be 1024 (i.e. N=1024) with $P = N/4$. The subcarriers were modulated using quadrature phase shift keying (QPSK) modulation.

A. Impulsive Noise Channel

The impulsive noise parameters were fixed as follows. The impulsive rate, λ, which determines the number of the OFDM symbols that might be hit by an impulsive burst within N OFDM symbols duration, was chosen to be 100, 150, and 250 which forming 10%, 15%, and 25% of one signalling period of N OFDM symbols, respectively. The bursts width, T_i, was fixed to 300 samples, forming about 30% of the symbol time, T_t. It is worth mentioning that, for both systems, the burst locations were assumed to be perfectly known at the receiver side, and therefore, could be ideally blanked.

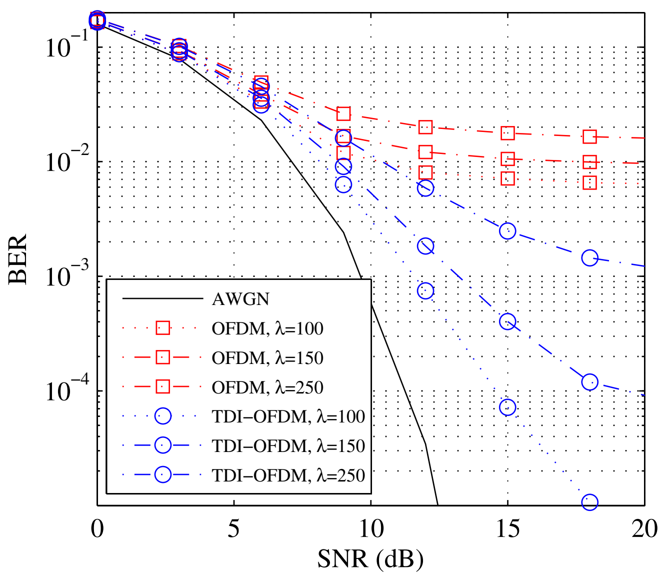

Fig. 4. BER performance of TDI-OFDM over impulsive noise and AWGN channel.

Moreover, to investigate the robustness of the TDI-OFDM, we assume that at most one impulsive burst would hit the useful part of the OFDM symbol. Fig. 4 presents the BER performance of the TDI-OFDM system as well as the OFDM system over AWGN with impulsive noise channel. It is obvious that the TDI-OFDM outperformed the standard OFDM, which suffers from error floors at high SNRs. For weak, and moderate impulsive noise distribution, the TDI-OFDM demonstrated a degradation in BER performance of about 3, 7.5 dB at BER 10^{-4}, respectively, compared to the AWGN case. However, for heavy distribution the TDI-OFDM suffered from error floors at BER 10^{-3} which is much below those of the standard OFDM.

B. Multipath Channel

In order to bring the simulations closer to the reality, the performance of the TDI-OFDM system was evaluated according to the parameters used by the WiMAX standards. For mobile WiMAX applications, the channel parameters in [15] (fixed over one block of OFDM symbols duration) were implemented in the simulations, as defined by the international telecommunication union ITU. Accordingly, for the ITU-Pedestrian type B channel, the simulation parameters were chosen as follows. The number of subcarriers, N, was 1,024, with $P = N/4$, the system bandwidth 10 MHz, and the sample time 88 ns. Sufficient statistic realizations of the channel components was generated. For each realization the BER performance was evaluated, and the overall BER was the average over all these realizations. Accordingly, the Fig. 5 was generated by transmitting 10^4 OFDM blocks for each SNR value. From the figure, it is worth noting that the BER performance of the TDI-OFDM system with ZF equalizer is even worse than that of the standard OFDM system at low and moderate SNR cases. The reason for this is that, in the standard OFDM system, only one data symbol is affected when a particular subcarrier experienced a deep fade, i.e. the enhanced noise owing to the fading at each subcarrier is independent. However, in the TDI-OFDM system, due to the use of the interleaver the channel spectral nulls are spread over N data symbols. As a consequence, the noise enhancement arising from deeply faded subcarriers can not be averaged out completely using the ZF equalizer. As a result, the overall BER performance of the TDI-OFDM was dominated by the worst subchannels. In order to justify and prove this explanation, the performance of the ZF equalizer is improved by using a simple, low complexity blanking unit as follows. Since the performance of the TDI-OFDM is taken over by the worst subcarriers, blanking those subcarriers at the output of the ZF equalizer will improve the BER performance remarkably, as confirmed by Fig. 5. Consequently, we propose a blanking unit located at the output of the ZF equalizer as shown in Fig 2. The worst subcarriers are then blanked depending on their corresponding minimum values in the channel frequency response coefficients of $\mathbf{H}$.

Extensive simulation results for different numbers of subcarriers, N, showed that blanking no more than 1% of N (the worst subcarriers) ensures the suppression of the enhanced noise and improves the overall performance of the TDI-OFDM. In Fig. 5, the curves (the lines marked with " $\circ$ ") from right to left are obtained by blanking one worst subcarrier to ten worst subcarriers. It is obvious from the figure that blanking just one worst subcarrier reduces the degradation in the BER to 5 dB, compared to the MMSE equalizer. However, the improvement becomes trivial after blanking worst five subcarriers. On the other hand, utilizing the MMSE equalizer in the TDI-OFDM receiver is more robust against the channel spectral nulls compared to the ZF equalizer. As shown in the figure, the TDI-OFDM by utilizing MMSE equalizer achieves SNR gain about 9 dB at BER 10^{-3} compared to the standard OFDM system.

C. Multipath with Impulsive Noise Channel

Under the same conditions and assumptions of Fig 4 and Fig 5, the influence of both the impulsive noise and the multipath fading on TDI-OFDM performance is demonstrated in Fig. 6 by utilizing the MMSE equalizer. We can see from the figure that the standard OFDM suffered from error floors for all impulsive distributions. In contrast, the degradation in the performance of the TDI-OFDM at BER 10^{-4} was less than 2 and 4 dB compared to the impulsive-free case for weak, and moderate impulsive distributions, respectively. The reason for this is that, at weak and moderate impulsive distributions, the overall TDI-OFDM performance is taken over by the multipath effect not the impulsive noise. However, for heavily impulsive distribution the situation is inverted, so that TDI-OFDM suffers from error floor at BER 10^{-4} because the performance is dominated by the impulsive noise effect not the multipath. Although, the simulation results have been given here for QPSK modulation, the extension to modulation

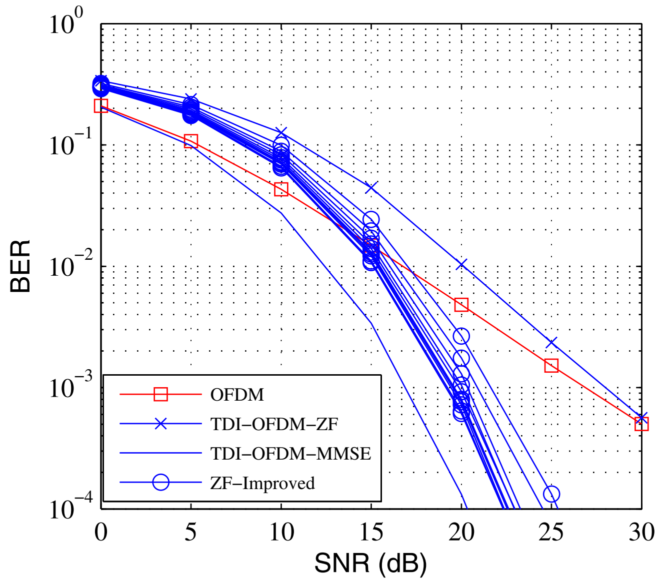

Fig. 5. Improving the ZF equalizer performance of the TDI-OFDM.

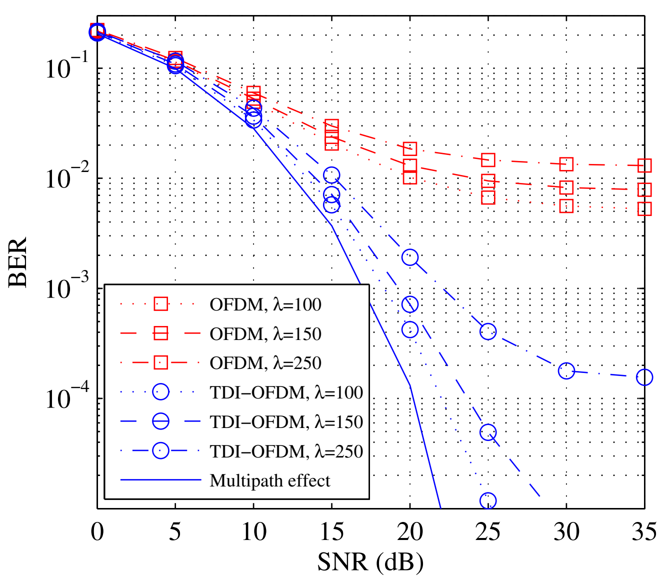

Fig. 6. BER performance of the TDI-OFDM system over multipath fading channel impaired by impulsive noise.

schemes other than QPSK is a straightforward.

IV. Conclusion

The performance of the OFDM system has been enhanced without sacrificing bandwidth or increasing transmit power. This enhancement was achieved by exploiting the time diversity which is ensured by the use of a block interleaver of depth N samples positioned after the IFFT process at the transmitter and a block deinterleaver located after the equalization process at the receiver. It has been shown that the use of the interleaver breaks the correlated behaviour of the multipath fading channel, and spreads the impulsive noise samples over the impulse-free OFDM symbols as well. Although the BER performance of the standard OFDM suffers from high error floors starting at SNR$\leqslant$ 10dB, the TDI-OFDM system has shown a substantial improvement in BER performance over different channels. The results showed that different equalizers, namely, ZF, and MMSE, lead to different performances for the TDI-OFDM system over multipath fading channels. The channel spectral nulls result in a large noise enhancement at the output of the ZF equalizer, which degrades its performance dramatically. A blanking process has been proposed to suppress the enhanced noise and improve the overall system performance. Another conclusion which can be drawn from these results is that the MMSE equalizer is recommended in the TDI-OFDM system design since it tackles the channel spectral nulls efficiently and boosts the BER performance of the TDI-OFDM system. Finally, the simulation results have affirmed the validity of the TDI-OFDM system to cope with multipath fading channels deteriorated by different impulsive noise distributions.

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