Performance Analysis of DWMT Transceiver for ADSL Channel with Overlap FDE in Presence of AWGN, Crosstalk and Impulse Noise

Arsla Khan, Sobia Baig, and Soo Y. Shin

***Abstract*—Discrete wavelet Multi-tone (DWMT) was proposed to overcome the problems of Discrete Multi-tone (DMT) for wireline channels. DWMT based system poses more resistance against inter-symbol interference (ISI) because of tight filters and more spectral efficiency due to absence of cyclic prefix as compared to DMT based system. However, no equalization technique has been standardized yet for DWMT transceiver. In this paper, we are proposing Overlap frequency domain equalization (FDE) for DWMT transceiver for ADSL channel in presence of additive white Gaussian noise (AWGN), crosstalk and impulse noise (IN). From simulations results, we can analyze that Bit error rate (*BER*) performance of Time domain equalization (TDE) is comparable with Overlap FDE but the main advantage lies in lower computational complexity.**

***Index Terms*—ADSL, AWGN, DMT, DWMT, FEXT, impulse noise, NEXT, overlap FDE.**

I. Introduction

Orthogonal division multiplexing (OFDM) has come forward as a competent multi-carrier modulation (MCM) technique. It mitigates the effect of frequency selective channels by dividing the entire wide band into small sub-bands [1]. DMT, which is considered as a variant of OFDM was proposed by Chew and Cioffi for wired channels like Asymmetrical digital subscriber loop (ADSL) signaling [2]. Just like OFDM, DMT uses Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) at transmitting and receiving sides respectively. Although DMT exhibits significant advantages, which have proved its potential in digital communication, however it still has some drawbacks such as redundant cyclic prefix (CP), higher peak to average power ratio (PAPR), and spectral leakage which results in higher side lobes.

To overcome these draw backs, an alternative approach based on discrete wavelet transform (DWT) was proposed [3]. This new scheme which was proposed by Sandberg and Tzannes in 1995 is called DWMT for wired channels [4]. Wavelet transform (WT) based DMT systems are considered spectrally efficient because it does not use CP. Spectral containment of channels is better in DWMT as compared to DMT [5]. FFT based systems have high energy containment in side lobes as compared to DWT based systems, which makes DWT systems more robust against narrowband interference and multipath fading affects [6]. WT based MCM technique has been standardized for power line communication (PLC) in IEEE P1901 [7].

Wavelet based filters can reduce ISI but they are not able to eliminate it completely. In order to reduce ISI and undo channel affects, several signal processing techniques may be used, which are collectively known as equalization techniques. Despite all advantages, DWMT based systems require computationally efficient and less complex channel equalization techniques for dispersive channels like ADSL [8]. But problem arises because of the overlapping nature of DWMT symbols in time domain. Few works are available in literature, which proposes various TDE and FDE techniques for wavelet based multi-carrier systems. These techniques are discussed in [9]-[12]. However, the equalization of DWMT modulation technique with less complexity and efficiency is still an open research area. Thus, in this paper, a new technique Overlap FDE proposed by Tomeba, Takeda and Adachi in [13] is applied on DWMT based ADSL channel. To the best of our knowledge, Overlap FDE has not been used for DWMT systems for ADSL downlink channel in presence of AWGN, crosstalk and IN.

In this paper, we have simulated the DWMT transceiver for ADSL channel with TDE and Overlap FDE. Performance of the system is analyzed in presence of AWGN, crosstalk and IN in terms of BER along with comparison in computational complexity. From simulation results, we can deduce that the BER performance of both equalization techniques is comparable, but the computational complexity of Overlap FDE is much less than the TDE techniques.

This paper is organized into different sections. Section II is about the basic DWMT transceiver structure. Section III describes the ADSL channel along with different channel impairments like cross talk and IN. Section IV presents TDE and Overlap FDE for DWMT transceiver over ADSL channel in detail. Simulation results are shown in Section V. Section VI gives computational complexity comparison of both TDE and overlap FDE techniques whereas Section VII draws the conclusions.

II. Basic DWMT Transceiver Structure

The functional block diagram of DWMT transceiver is shown in Fig. 1. Transmitter accepts the data in the form of

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high data rate bit stream which is serial in nature. This serial bit stream is then divided into multiple parallel bit streams of low data rate after passing through serial/parallel converter. During serial to parallel conversion, instead of fixed loading, adaptive bit loading is implemented. These parallel streams are then sent to constellation encoder. Here bit streams are mapped onto QAM constellation according to the number of bits loaded and converted into sequences. These sequences are modulated through WT. The Inverse Discrete Wavelet transform (IDWT) is implemented at the transmitter. With the help of IDWT, not only frequency but also time information can be estimated [14]. Parallel streams are then combined together into serial stream and then sent to receiver through channel.

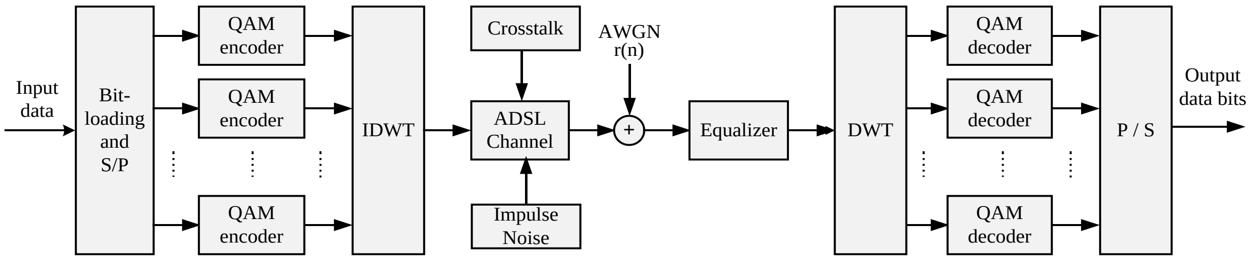

Fig. 1. Block diagram of DWMT transceiver.

On the receiver side, the serial stream is passed through an equalizer to undo the channel effects. After equalizer, the stream is passed through the DWT block. After DWT block, serial stream is again converted back into parallel streams. These parallel streams are then sent to QAM decoder for constellation demapping. After demapping, the sequence is converted back into bits and then these bits of parallel stream are combined together to get the final output bit stream.

Water Filling Adaptive Bit Loading Algorithm

In communication channels, to perform better in fading environment all sub-channels are loaded with different number of bits which is called adaptive bit loading. One of the its obvious advantage is less probability of error.

In our proposed system, water filling bit loading algorithm is used for bit loading. Bits will be loaded according to the SNR of each sub-channel. First of all it is decided as to which tones are to be turned off due to low SNR values. Bits are then assigned to sub-channels according to the value of SNR. These allocated bits are given by the formula [15].

$$b_n = \frac{1}{2}\log_2\left[1 + \frac{SNR}{\Gamma.\gamma_m}\right] \tag{1}$$

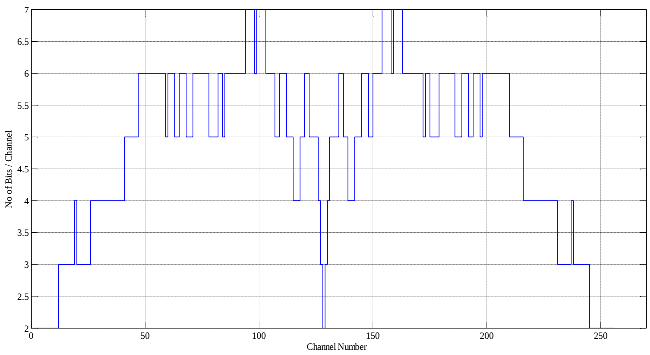

Fig. 2. Variable bit loading on ADSL channel.

where b_n is the number of bits on n^{th} sub-channel, SNR is equal to $\epsilon_n.g_n$ It is the SNR of each sub-channel. ϵ_n is the sub- channel energy. g_n is the gain of sub–channel. Γ is SNR gap which presents the difference between channel capacity and target bit rate. γ_m is performance margin. g_n can be calculated by the formula written in (2),

$$g_n = \frac{|H_n|^2}{\sigma^2} \tag{2}$$

where H_n is the channel and σ^2 is the noise power. A major drawback of water-filling algorithm is rounding off of values which results in performance degradation. This drawback is called granularity [16]. Fig. 2. shows the variable bit loading phenomena for ADSL channel whose impulse response is shown in Fig. 3.

III. ADSL Channel Model with Channel Impairments

ADSL is an asymmetric channel where downstream and upstream data rates are different. Stimulated ADSL channel is a finite Impulse Response (FIR) filter, having length equal to 101 coefficients as shown in Fig. 3. ADSL channels are plagued by many disturbances such as crosstalk, radio frequency interference and IN [17]. Due to these impairments, the rate at which data is to be transmitted gets limited.

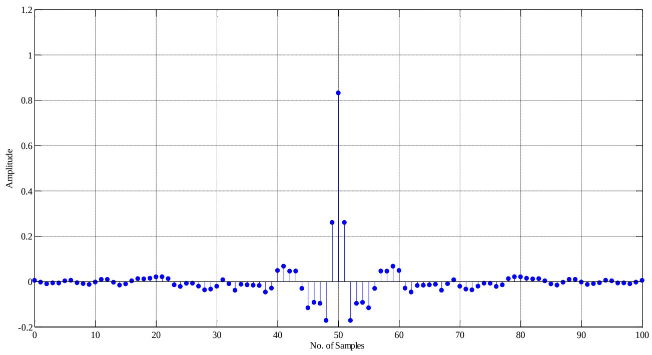

Fig. 3. Impulse response of telephone channel [7].

A. *Crosstalk-Capacity Limiting Noise*

Crosstalk is considered as a capacity limiting noise for DSL channels [18]. It generates because of the coupling between different unshielded twisted pairs (UTP). Based on interference location, it can be divided into two types i.e. Far end crosstalk (FEXT) and near end cross talk (NEXT). NEXT coupling is the ability of transmitting signals to interfere with signals of other wires within same cables [19]. FEXT appears on another pair at the opposite end or far end of cable as compared to the source of interference. For our simulations, modeling of FEXT and NEXT is performed according to the parameters documented in G.992.1/G.922.2 [20]. These parameters are listed in the Table I.

TABLE I: MODELING PARAMETERS FOR NEXT AND FEXT

Parameters	Notations	Values
No. of Disturbers	n	24
Sampling Frequency	f_s	2.208 MHz
Low pass cut-off frequency	f_{LP3dB}	$f_s/2$
High pass cut-off frequency	f_{HP3dB}	138 KHz
Coupling constant	K_{ADSL}	0.1104 watts
NEXT frequency	f_{NXT}	160 KHz
NEXT power sum loss	NPSL	47 dB
FEXT frequency	f_{FXT}	160 Khz
Distance	d_{FXT}	1.0 km
FEXT power sum loss	FPSL	45 dB

Power spectral densities (PSD) for disturber noise (downstream), disturber noise (upstream), ADSL downstream NEXT and ADSL downstream FEXT are given below respectively [20],

$$PSD_{d\_DST} = K_{DST} \frac{2\left(sin\left(\frac{\pi f}{fo}\right)^2\right)}{\left(fo\left(\frac{\pi f}{f_o}\right)^2\right)\left(1+\left(\frac{f}{f_{LP3dB}}\right)^{12}\right)\left(1+\left(\frac{f_{HP3dB}}{f}\right)^{16}\right)} \quad (3)$$
$$0 \leq f < \infty$$

$$PSD_{u\_DST} = K_{DST} \frac{2\left(sin\left(\frac{\pi f}{fo}\right)^2\right)}{\left(fo\left(\frac{\pi f}{f_o}\right)^2\right)\left(1+\left(\frac{f}{f_{LP3dB}}\right)^{16}\right)\left(1+\left(\frac{f_{HP3dB}}{f}\right)^{8}\right)} \quad (4)$$
$$0 \leq f < \infty$$

$$PSD_{NXT} = PSD_{d\_DST} \left(10^{-\frac{NPSL_n}{10}} \times f_{NXT}^{-3/2}\right) f^{3/2} \quad (5)$$
$$0 \leq f < \infty$$

$$PSD_{FXT} = PSD_{d-DST} |H_{CH}|^2 \left(10^{-\frac{FPSL_n}{10}} d_{FXT}^{-1} f_{FXT}^{-2}\right) df^2 \quad (6)$$
$$0 \leq f < \infty$$

where H_{CH} is the channel transfer function. $NPSL_n$ and $FPSL_n$ are power sum losses for NEXT and FEXT for n disturbers.

B. Impulse Noise-Performance Limiting Noise

IN is a non–stationary interference which consists of energy spikes. These spikes are random in nature with random amplitudes [21]. Different surveys have been performed by telephone companies to study the behavior of IN [22]-[24]. However, it is not possible to present a complete model for IN [17]. Among different models, IN models presented in [25] and [26] are most popular. DMT systems performance in presence of IN is discussed in [27]. Middleton proposed three models for IN [28]. Middleton noise model A is used for the generation of IN in our simulation system, as it was used in [27].

$$f_x(x) = e^{-A} \sum_{k=0}^{\infty} \frac{A^k}{k! \sqrt{2\pi\sigma_k^2}} e^{-\frac{x^2}{2\sigma_k^2}} \quad (7)$$

where $\sigma_k^2 = \frac{\frac{k}{A}+\Gamma}{1+\Gamma}$ is the noise variance. A is the impulse noise index, where A is defined as [28],

$$A = v_t T_s \quad (8)$$

v_t is the mean impulse rate and T_s the is mean impulse duration or its length. Class A noise samples can therefore be described as [10],

$$n = x_g + \sqrt{K_k}\, y \quad (9)$$

where x_g represents white Gaussian background noise with mean zero and variance σ_g^2. K_k is a Poisson random variable with mean A. y is another Gaussian sequence having zero mean and variance equal to $\frac{\sigma_i^2}{A}$. Here σ_i^2 is the variance of impulse noise. Cross talk and impulse noise degrades ADSL system performance so to improve it, an appropriate equalization technique is required.

IV. EQUALIZATION TECHNIQUES FOR DWMT TRANSCEIVER OVER ADSL CHANNEL

Inter block interference (IBI) and Inter Carrier Interference (ICI) is a big problem in delivering high data rates. Receivers have equalizer filters that are designed to compensate IBI and ICI. Channel equalization has been studied to improve the performance of filter banks based communication system by combating ISI [29].

In DWMT based systems, design of an optimal equalization technique is challenging because of the overlapping nature of DWMT symbols in time domain. Thus, it is necessary to avoid IBI and ICI for distortion-less and error free communication [30]-[32]. Though different equalization techniques have been examined in the past for DWMT based systems but a vigorous equalization technique with less complexity is still need to be standardized.

A. Time Domain and Frequency Domain Equalization

In DWMT transceiver, to combat IBI, TDE equalization has to be performed separately for each sub-channel. However, one of the main drawbacks of TDE approach is high complexity. As the length of channel increases, complexity of the equalizer also increases.

FDE is used in those cases where channel delay spread is very large. In case of large delay spread, TDE equalizer structure becomes complex, thus FDE is preferred because of its less complexity as compared to TDE [7].

B. Overlap Frequency Domain Equalization

To overcome the complexity of TDE techniques and inefficiency due to guard interval (GI) insertion of FDE techniques, a new technique overlap FDE was proposed.

Overlap FDE does not need any GI and improves the bandwidth efficiency of the system. For the first time, Overlap FDE was applied by Tomeba for MCM systems [13] and later used by Sohaib for wavelet OFDM [13]. In [7], authors showed its supremacy for ADSL systems for DWMT transceiver in presence of AWGN and FEXT, NEXT. In this paper, we are evaluating Overlap FDE performance for ADSL systems for DWMT transceiver in presence of AWGN, FEXT, NEXT and impulse noise.

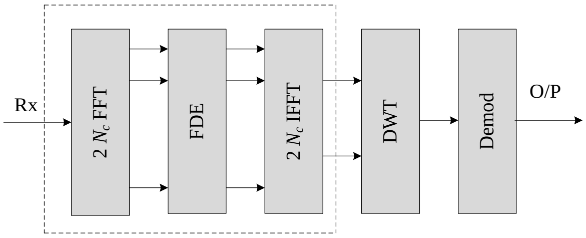

Fig. 4. DWMT receiver with overlap FDE.

DWMT transceiver with Overlap FDE is shown in Fig. 4. At the receiver side, the received signal R_x is first passed through the block of 2 N_c point FFT, where N_c is the number of sub-carriers used. Received signal $r_m(t)$ is in the time domain. After passing through FFT block, time domain signal $r_m(t)$ is converted into frequency domain signal $R_m(q)$. Received signal in frequency domain is given as [13],

$$R_m(q) = \frac{1}{2N_c} \sum_{t=0}^{2N_c-1} r_m(t) \exp(-j2\pi q \frac{t}{2N_c}) \quad (10)$$

Here the value of q varies from 0 to $2N_c - 1$. $R_m(q)$ can also be written in form of

$$R_m(q) = H(q)Y_m(q) + N_m(q) + \Pi_m(q) \quad (11)$$

Here, $Y_m(q)$ is the transmitted signal passing through the channel $H(q)$. During its transmission through channel, it gets affected due to IBI and AWGN. $N_m(q)$ is the AWGN added in the signal while $\Pi_m(q)$ is the IBI factor. In our case N_c = 256. Thus, due to 2 N_c point FFT, the received signal is decomposed into 512 frequency components for N_c = 256 sub-carriers. Equalization is performed according to the taps optimized by either zero forcing (ZF) and minimum mean square error (MMSE). FDE weights $c(q)$ are calculated by method given in [7].

$$c(q) = \begin{cases} \frac{H^*(q)}{|H(q)|^2} & ZF \\ \frac{H^*(q)}{|H(q)|^2 + \left(\frac{E_{avg}}{N_o}\right)^{-1}} & MMSE \end{cases} \quad (12)$$

where $H(q)$ is the channel impulse response. E_{avg} is the average energy per symbol while N_o is the AWGN. Equalized signal can be represented like,

$$R'(q) = R(q)c(q) \quad (13)$$

Equalized signal $R'(q)$ is then passed through 2 N_c point IFFT which will convert the frequency domain signal into time domain signal.

$$\hat{r}_m(t) = \sum_{q=0}^{2N_c-1} R'(q) \exp\left(j2\pi q \frac{t}{2N_c}\right) \quad (14)$$

The original length of our data was 256 but due to $2N_c$ point FFT and IFFT, it becomes double. We know that since IBI is present at the edges of all blocks so if we discard the samples present at corners of the block then IBI can be removed. Thus, IBI present at the corners are suppressed by simply removing the 256 samples present at the edges and by picking the central 256 samples. This data is then sent to the block of DWT. Demodulation is performed at the received data and then original signal is retrieved.

V. Simulation Results

DWMT transceiver is designed and simulated in MATLAB. Channel impairments like AWGN, FEXT, NEXT and impulse noise are introduced in DWMT system. TDE and overlap FDE are used to overcome the affects of channel spreading. For this purpose equalizer performance is analyzed with the help of two tap optimization methods i.e. ZF and MMSE. It is assumed that channel is known and there is no need of channel estimation. Perfect synchronization is considered between transmitter and receiver. Performance of both techniques is compared on the basis of BER and computational complexity. Detail of simulation parameters is given in Table II.

TABLE II: Modeling Simulation Parameters

Parameters	Values
Channel Bandwidth	1.104 MHz
Sampling Frequency	2.208 MHz
No. of Sub-channels	256
Symbol Length	256
Symbol Period	0.115942 msec
Symbol Rate	8625 symbols/sec
Channel Frequency Spacing	4.3125KHz
No. of bits per sub-channel	1 to 7
Modulation Scheme	*M-QAM*
Wavelet Level	2
Wavelet Family	Haar
Equalization Technique	TDE-ZF TDE-MMSE Overlap FDE - ZF Overlap FDE- MMSe

A. Comparison of TDE-ZF and TDE-MMSE with AWGN, FEXT NEXT and IN

Performance analysis regarding BER between TDE – ZF and TDE – MMSE for DWMT transceiver is performed and shown in Fig. 5. Simulations are performed in presence of AWGN, FEXT, NEXT and impulse noise simultaneously. Impulse noise index A is kept constant at 0.0001. For a BER of 5.68E-3, TDE – MMSE algorithm has $\frac{E_b}{N_o}$ = 22 dBs while ZF has $\frac{E_b}{N_o}$ = 24 dBs. It shows TDE - MMSE equalization algorithm outperforms with a gain of 2 dBs as compared to TDE – ZF.

B. Comparison of Overlap FDE-ZF and Overlap FDE-MMSE with AWGN, FEXT NEXT and IN

In this sub-section, simulations are performed on DWMT transceiver for ADSL channel with overlap FDE. Fig. 6 shows that if we fix BER equal to 1E-3, ZF technique gives $\frac{E_b}{N_o}$ equal to 32 dBs while MMSE outperform ZF criteria and we are getting a gain of 6 dBs.

If we compare these results with TDE results, we can easily find that for TDE – MMSE $\frac{E_b}{N_o}$ has value equal to 28 dBs for BER of 1E-3, whereas in Overlap FDE, the same value of BER is achieved at 26 dBs. It means with MMSE-

Overlap FDE, we are getting 2dBs gain as compared to MMSE-TDE.

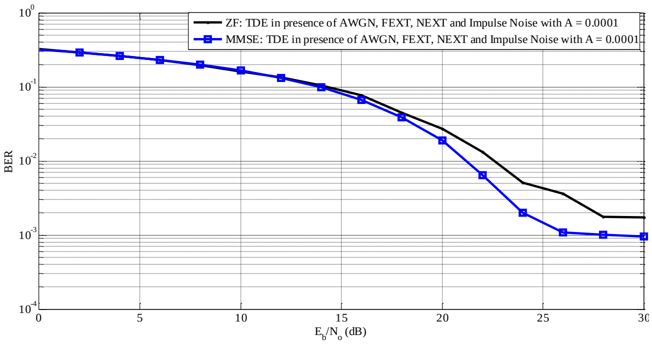

Fig. 5. *BER* comparison of TDE–ZF and TDE–MMSE for DWMT transceiver for ADSL channel in presence of AWGN, FEXT NEXT and IN with impulse noise index, *A* = 0.0001.

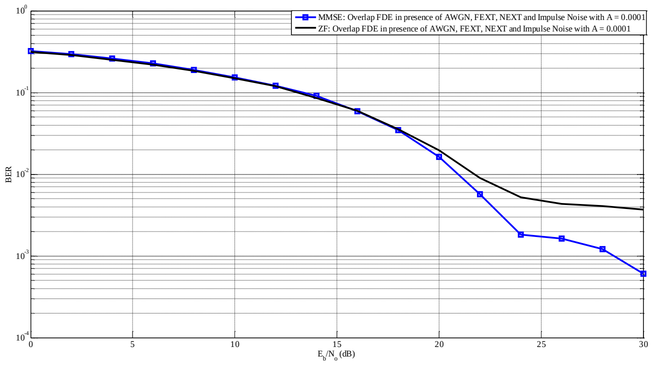

Fig. 6. *BER* comparison of Overlap FDE–ZF and Overlap FDE–MMSE for DWMT transceiver for ADSL channel in presence of AWGN, FEXT NEXT and IN with *A* = 0.0001.

VI. Computational Complexity Comparison

In DWMT based system, computation complexity is $O(N)$ where N is the length of the signal. For TDE, the complexity is given by, $O(N^3)$ [7]. Here N is dimension of the signal. For Overlap FDE, the complexity of $2N_s$ points is given by, $[2(2(N_s \log_2 N_s)) + 2N_s]$. N_s represents the size of IFFT/FFT [7]. Complexity comparison for TDE and Overlap FDE for DWMT transceiver is shown in Table III.

TABLE III: Complexity Comparison of TDE and Overlap FDE for DWMT Transceiver

Equalization Technique	TDE	Overlap FDE
Complexity of equalization technique	$O(N^3)$	$[2(2N_s log_2 2N_s) + 2N_s]$
System Complexity	$O(N)$	$O(N)$
Total Complexity	$O(N^3) + O(N)$	$[2(2N_s log_2 2N_s) + 2N_s] + O(N)$
If N and N_s = 256	$=O(256)+ O(256^3)$ = 16777472	$= O(256) + [(2 \times 256 \log_2 2 \times 256) + 2 \times 256] = 5376$

VII. Conclusions

DWMT based systems have proved incredible advantages over its counterpart DMT based systems in terms of lower side lobes, resistance against IBI and ICI due to its spectral containment. However, its equalization is not easy task because of complexity which comes due to overlapping of DWMT symbols in time domain. In this paper, overlap FDE is proposed for the first time for DWMT transceiver in presence of AWGN, FEXT, NEXT and impulse noise. Results obtained from simulating the system on MATLAB shows that *BER* performance of both system is comparable. However, supremacy of overlap FDE lies in its lower computational complexity. Therefore, overlap FDE is a good option to equalize DWMT transceiver even in the presence of different types of noises. For future work, authors are interested to apply overlap FDE for power line communication channel for smart grid communications.

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