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Performance Comparison of Time-Domain Equalization (TEQ) Techniques in a Discrete Wavelet Multitone (DWMT) System for Asymmetric Digital Subscriber Line (ADSL)

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Abstract: A Discrete Wavelet Multitone (DWMT) transceiver is proposed for the Asymmetrical Digital Subscriber Line (ADSL) channel, which promises greater subchannel spectral containment, as compared to the Fourier transform based conventional Discrete Multitone (DMT) system. Wavelet packet transform applied in DWMT system is robust against narrowband interference and impulse noise. It is also spectrally efficient, since it does not require cyclic prefixing. However, with a dispersive channel like ADSL, DWMT system requires an efficient equalization technique. A linear transversal filter based on zero-forcing (ZF) and minimum mean squared error (MMSE) algorithms are applied for equalizing the channel effect and performance of the proposed transceiver is compared to a DMT system with ZF-time domain equalizer. Moreover, the non-linear MMSE-Decision Feedback Equalizer (MMSE-DFE) is applied to the system. It is shown that the wavelet-packet based DWMT system with MMSE equalizer gives improved results in comparison with ZF equalizer in DWMT and DMT systems. On the other hand, MMSE-DFE outperforms all the other equalization techniques, regarding bit error rate for ADSL in the presence of additive white Gaussian noise (AWGN) and channel crosstalk.

Key words: Wavelet Packet Transform · Discrete Wavelet Multitone · Water-Filling bit-loading · Zero-Forcing Equalization · MMSE Equalization · MMSE-DFE Equalization

INTRODUCTION

Digital Subscriber Line (DSL) is used as a ubiquitous access network for data communication for residential applications. A multi-carrier modulation technique typically referred to as Discrete Multitone (DMT) has been adopted as a standard for high-rate transmission over ADSL [1]. DMT systems have the property to convert a multipath and frequency-selective channel into numerous flat-fading sub-channels, requiring simpler channel equalization [2]. DMT systems take bit-loading into account and therefore the system can easily adapt to the wireline channel and bits can be allocated according to the sub-channel signal-to-noise ratio (SNR) [3].

A problem that remains associated with Fourier transform-based DMT systems is the rectangular pulse shapes of the sinusoidal carriers, having high side-lobes [4]. The high-level side-lobes in DMT transceivers can cause increased sensitivity to channel distortion and consequently result in increased inter-symbol interference (ISI) and inter-channel interference (ICI) [1]. In wireless communications, a system based on Discrete Wavelet Multitone (DWMT) for modulating and demodulating the transmitted signal using Discrete Wavelet Transform (DWT) has been suggested as a possible solution [5]. On similar lines, a DWMT system can be used for wireline channels, using a maximally decimated filter bank, with its overlapping symbols in time-domain. This structure therefore, does not require the addition of Cyclic Prefix (CP) [6]. However, application of the DWMT systems in a dispersive channel like ADSL necessitates a robust channel equalization technique [7].

In this article, we have applied the time-domain equalization through a transversal filter. This technique utilizes Zero-Forcing (Z-F), minimum mean squared error (MMSE) algorithms and non-linear Decision Feedback Equalizer (DFE) based on MMSE (MMSE-DFE), to a wavelet-packet based DWMT transceiver for a wireline ADSL channel. The DWMT system's performance is then compared with a DMT system. The MMSE-DFE has been identified as the best among the suboptimal (compared to MLSE) receivers for wireless applications and has been the subject of extensive theoretical studies [8].

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For a fair comparison between the two systems, the DMT system also utilizes the same time-domain Z-F equalization. We have also evaluated the performance of the proposed wavelet-packet based transceiver in the presence of near-end crosstalk (NEXT) and far-end crosstalk (FEXT) for downstream ADSL. It is shown that the DWMT system conserves bandwidth by not utilizing any CP and gives improvement in bit error rate (BER) performance over the DMT system with time-domain equalization (TEQ).

The remainder of this article has the following distribution. Section-II discusses the system model of DWMT based on discreat wavelet packet transform (DWPT). It also presents the ADSL channel and it gives the ZF, MMSE and MMSE-DFE equalization techniques used for channel-equalization of DWMT transceiver. Simulation results are evaluated after this section, followed by the conclusions drawn in the end.

System Model of DWMT Transceiver: The proposed DWMT system's block diagram is shown in Fig. 1. It starts by dividing the input data bit-stream into multiple parallel bit-streams. Bit loading is usually applied to DMT modulated systems having wireline channels, by first estimating the SNR of each subchannel by channel estimation and then the distribution of bits to those sub-channels according to their respective SNR [3,4]. A discrete version of the water-filling bit-loading algorithm is applied, in which the bit-loading procedure starts by determining which sub-channels should be turned off [9]. The bits allocated along with the subchannel SNR using water-filling bit-loading algorithm are shown in Fig. 2 (a) and (b) for an ADSL channel [4].

The proposed DWMT transceiver is based on discrete wavelet packet transform. The DWPT is implemented through a reverse order perfect reconstruction filter bank, known as a transmultiplexer. Wavelet packets can be implemented as a set of FIR filters, which leads to the filter bank realization of the wavelet transform, according to Mallat's algorithm [10]. The blocked version of the input signal $x_k(n)$, is mapped to a variable QAM constellation according to the number of bits loaded. This is interpolated and filtered by the *kth* branch synthesis filter $F_k(z)$. The combined signal is sent through the channel and the received signal is filtered by an equalizer filter. The equalized signal is passed through the corresponding analysis filter $H_k(z)$ and decimated to retrieve the QAM encoded version of the transmitted signal. The transmitted signal is recovered after QAM decoding. In the proposed system, the signal transmission is considered through the wireline ADSL channel with the addition of crosstalk, NEXT and FEXT in the downstream ADSL system.

ADSL Channel: Digital Subscriber Loop (DSL) is a ubiquitous communication channel, consisting of an unshielded twisted pair of wires, connecting residential areas to a telephone company's central office. Twisted pair copper cables attenuate signals proportional to length and frequency [1].

In addition to attenuation, ADSL channel is characterized by the crosstalk and impulse noise. In this article, we will evaluate the effect of crosstalk on the performance of DWMT and DMT in the downstream ADSL channel. For this purpose, the NEXT and FEXT are modeled using the ADSL standard G.992.1/G.992.2 [11].

The DWPT transmultiplexer in the proposed DWMT transceiver gives perfect reconstruction of the transmitted signal, if ideal channel conditions are assumed. However, an actual channel like ADSL is far from ideal and therefore requires some form of equalization to reliably retrieve the transmitted signal.

Time Domain Equalization: In order to equalize the signal after it has passed through a dispersive ADSL channel, time domain equalization is proposed, by employing a linear transversal filter and non-linear DFE.

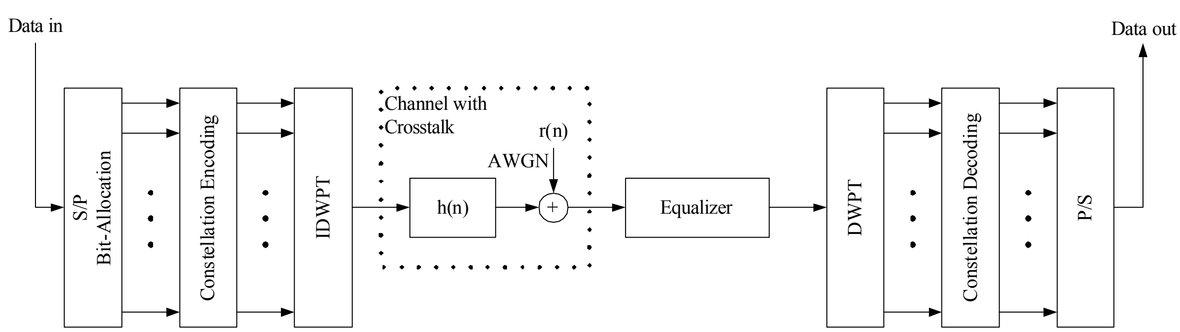

Fig. 1: Functional Block diagram of DWMT system.

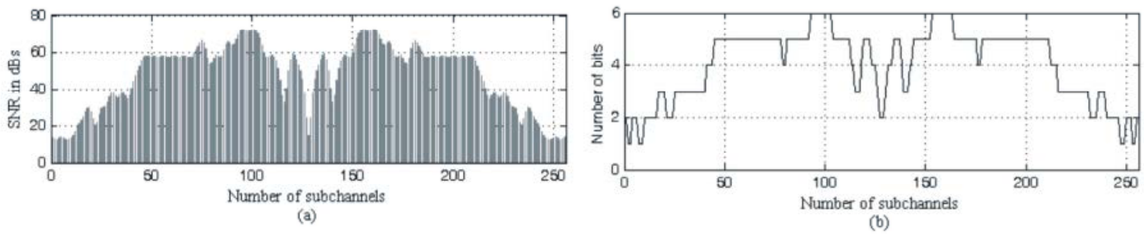

Fig. 2: ADSL channel frequency response and number of bits loaded according to discrete water-filling bit-loading algorithm.

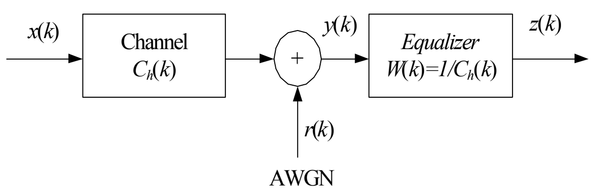

Fig. 3: A Linear transversal equalizer with coefficients optimized by Zero-Forcing criterion.

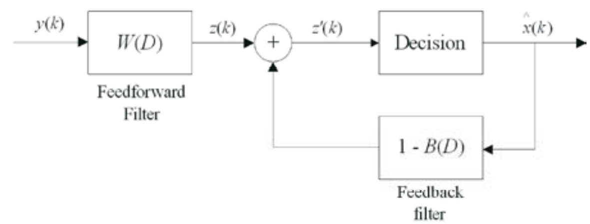

Fig. 4: A Decision Feedback Equalizer (DFE).

The equalizer filter is a linear function of the channel length L and the filter coefficients are optimized using the zero-forcing (ZF) and mean squared error (MSE) criterion [4,12,13]. Also the MMSE-DFE is applied to the system. The Decision Feedback Equalizer (DFE) is a well established and effective approach for the mitigation of the ISI effects. Therefore, MMSE-DFE along with linear ZF and MMSE equalizers is applied and proposed in time domain for Discrete Wavelet Multitone (DWMT) transceiver for the ADSL.

ZF Finite Length Equalizer: The ZF solution cancels out the channel effect completely by multiplying the received signal with the inverse of the channel, as shown in Fig. 3. With an infinite length equalizer filter, it would be possible to force the system impulse response to zero at all sampling points other than the desired sample point [14]. It is a known fact that an infinite length filter is unrealizable, therefore a finite length filter is considered that approximates the infinite length filter [14]. The receiver is set by ZF Equalizer (ZFE), as shown in Fig. 3, to a linear time-invariant filter with discrete impulse response w_k that performs action on y_k to produce the ZFE output z_k, which is actually an estimate of x_k [15]. According to Nyquist's Criterion symbol-by-symbol detection remains optimal if $c_k = \delta_k$. The ZFE facilitates restoration of this Nyquist pulse character to the channel. In order to perform this process, ZFE ignores the channel noise and shapes the signal y_k so that it is free of ISI. The received distorted signal is written in Eq. 1 and it can shown in Fig. 3,

$$y_k = x_k * c_k + r_k \qquad (1)$$

In ZFE solution, r_k is initially viewed as being zero. The *D*-transform of y_k is,

$$Y(D) = X(D) \bullet C(D) \qquad (2)$$

The ZFE output and the D-transform of z_k is

$$Z(D) = W(D) \bullet Y(D) = W(D) \bullet C(D) \bullet X(D) \qquad (3)$$

and this output from ZFE will be free of ISI if $Z(D) = X(D)$. The transfer characteristic of ZFE becomes as follows:

$$W(D) = \frac{1}{C(D)} \qquad (4)$$

The name ZFE is given to this equalizer's type of algorithm because it forces ISI to zero at all sampling instances kT except k = 0. The receiver detects the symbols using decision regions for constellation defined by xk at the output of ZFE [15].

MMSE Criterion: The MMSE criterion represents a more robust solution than the ZF since it considers the effect of additive channel noise [14-16]. The MMSE algorithm using transversal equalizer filter coefficients optimizes the mean squared error of all the ISI terms plus the noise at the equalizer output. A set of over determined equations is formed, in order to derive a MMSE solution of the equalizer filter [16].

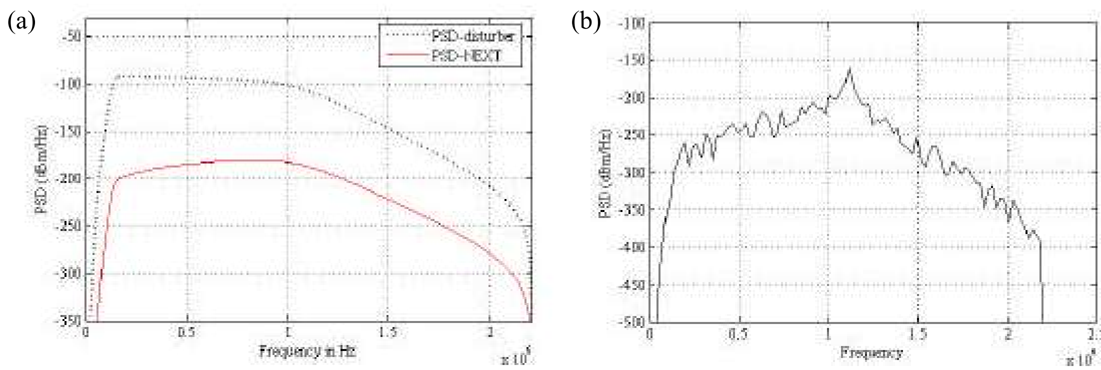

Fig. 5: (a) PSD-disturber & PSD-NEXT for downstream ADSL in G.992.1/G.992.2 standard (b) PSD-FEXT for downstream ADSL in G.992.1/G.992.2 standard.

Decision Feedback Equalizer (MMSE-DFE): A decision feedback equalizer (DFE) is a non-linear equalizer that uses previous detector decisions to eliminate ISI on the current received symbol [17]. In principle, if a number of source symbols are properly detected and the channel impulse response is known, then the ISI from these symbols can be reconstructed and cancelled out from the current received symbol [17].

The DFE is a non-linear equalizer due to feedback path. However, if one assumes all previous decisions are correct then it can be analyzed using linear techniques. MMSE diminishes the noise factor and improves the overall SNR. Therefore, MMSE-DFE solution is presented and proposed here for DWPT based ADSL.

The block diagram for a DFE is shown in Fig. 4. The configuration of MMSE-DFE contains a linear feedforward equalizer *W* (*D*), augmented by a linear, causal, feedback filter, 1-*B* (*D*), where $b_0 = 1$ [15]. The feedback filter receives the decision from the previous symbol period as input. Therefore, the name "decision feedback" is given to this type of equalizer. The output of the feedforward filter is denoted by *Z* (*D*) and the input to the decision element by *Z′* (*D*) [15].

The MMSE-DFE jointly optimizes the settings of both the feedforward filter w_k and the feedback filter δ_k-b_k to minimize the MSE. The MMSE-DFE error signal is [15],

$$e_k = x_k - z_k^{'} \tag{5}$$

The MMSE for MMSE-DFE is [15]

$$\sigma^2_{MMSE-DFE} \overset{\Delta}{=} \min_{w_k, b_k} E\left[\left|\mathrm{x_k} - \mathrm{z_k^{'}}\right|^2\right] \tag{6}$$

The error sequence can be written in *D*-transform as [15]

$$\begin{aligned} E(D) &= X(D)\text{-}W(D) \bullet Y(D)\text{-}[1\text{-}B(D)]\,X(D) \\ &= B(D) \bullet X(D)\text{-}W(D) \bullet Y(D) \end{aligned} \tag{7}$$

The DFE has a clear advantage over linear equalizers since it has lower noise enhancement while it processes the received signal.

Simulation Results: A DWPT-transmultiplexer based multicarrier ADSL system with *M* = 256 subchannels and bit-loading algorithm for bit allocation in subchannels is investigated in channel environment based on ADSL along with crosstalk standard G.992.1/G.992.2 [11]. The two systems based on DWMT system and DMT transceiver, utilizing time-domain equalization (TEQ) techniques for ADSL channel with AWGN and crosstalk, are simulated. Matlab is used for simulation purpose and the system's simulation parameters are specified in Table 1.

Table 1: DWMT and DMT System Simulation Parameters

Parameter	WPT-DWMT	DFT-DMT
Data rate	1 Mbps	1 Mbps
Sampling Frequency	2.208 MHz	2.208 MHz
Modulation	*M*-QAM (2, 4, 8, 16, 32, 64)	*M*-QAM (2, 4, 8, 16, 32, 64)
Cyclic Prefix	None	20%
FFT size (N)	-	512
Wavelet-level	2	-
Number of bits/sub-channel	1 to 6	1 to 6

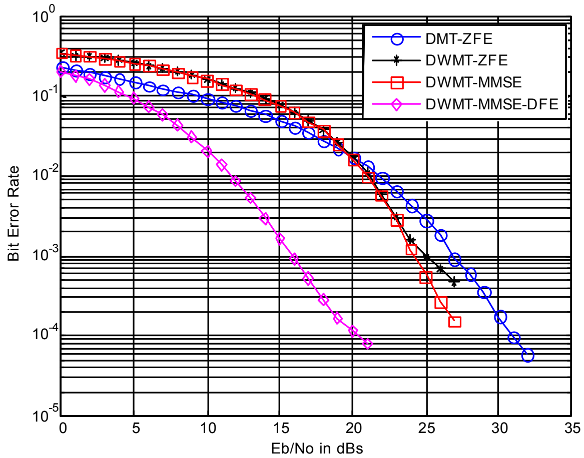

Fig. 6: BER Comparison of DWMT and DMT systems for ADSL channel with AWGN, NEXT and FEXT (Nff = 50, Nfb = 50 for MMSE-DFE)

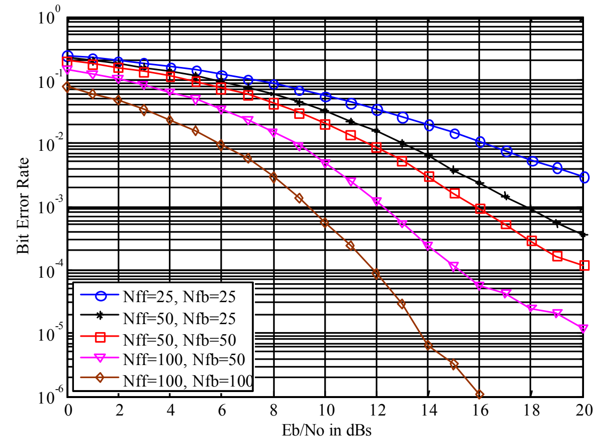

Fig. 7: BER Comparison of DWMT system for ADSL channel for different feedforward and feedback filter taps with AWGN, NEXT and FEXT

Table 2: NEXT and FEXT Simulation Parameters

Parameter	WPT-DWMT	DFT-DMT
Number of disturbers	24	24
f_{LP3dB}	fs/2	fs/2
f_{HP3dB}	138 kHz	138 kHz
K_{ADSL}	0.1104 watts	0.1104 watts
f_{NXT}	160 kHz	160 kHz
NPSL	47.0 dB	47.0 dB
f_{FXT}	160 kHz	160 kHz
d_{FXT}	1.0 km	1.0 km
FPSL	45.0 dB	45.0 dB

This corresponds to a system bandwidth of 2 MHz with data rate of 1 Mbps with discrete wavelet packet filter being used for transmitter and receiver end. The channel equalization is performed by applying a linear equalizing filter in time-domain, with the filter coefficients optimized by ZF algorithm, MMSE and non-linear MMSE-DFE criterion. The ADSL channel is simulated by an FIR filter of 100 taps.

The NEXT & FEXT represents the downstream crosstalk in ADSL channel according to the G.992.1/G.992.2 standard [11], with the simulation parameters as described in Table 2. Power spectral density (PSD) of 24 disturbers and NEXT is shown in Fig. 5 (a) and Fig. 5 (b) displays the FEXT PSD for downstream ADSL [11].

Fig. 6 shows the performance of DWMT and DMT systems in ADSL channel with AWGN, NEXT and FEXT (crosstalk), utilizing time-domain equalization (TEQ) techniques. DMT system is equalized by ZF-TEQ, while the DWMT transceiver is equalized by ZF-TEQ, time-domain MMSE (MMSE-TEQ) and time-domain MMSE-DFE (MMSE-DFE-TEQ) from previous section. The BER curves shown in Fig. 6 validate the fact that the wavelet packet transmultiplexer improves the performance of DWMT transceiver, having ZF-TEQ by E_b/N_o margin of 1.0 db for BER of 1E-4, over a DMT transceiver, having an identical equalizer. Moreover the MMSE-TEQ technique for DWMT system shows an improvement of 2 dBs in E_b/N_o over ZF-TEQ technique for DWMT and a 3 dB gain over the ZF-TEQ equalized DMT system, at a BER of 1E-4.

In comparison with other two equalization techniques for DMT and DWMT systems, simulation results depicted in Fig. 6 show the influence of MMSE-DFE-TEQ equalizer on bit error rate. It improves the gain margin of 9 dBs in E_b/N_o over ZF-TEQ and 7 dBs gain over MMSE-TEQ equalized DWMT system, at BER of 1E-4. It also shows the improvement of 10 dBs gain in E_b/N_o over the ZF-TEQ equalized DMT system, at BER of 1E-4.

The simulation results presented in Fig. 7 show that there is a major improvement of BER with the increase of feedforward and feedback filter taps. With the number of 100 feedforward ($N_{ff} = 100$) and feedback filter ($N_{fb} = 100$) taps, the system performance gives a gain of 18 dBs in E_b/N_o at BER of 1E-5 in comparison with DMT based ADSL using ZF equalization. On the other hand, it also gives improvement of 8 dBs gain in E_b/N_o at BER of 1E-5 in comparison with MMSE-DFE with the number of 50 feedforward and feedback ($N_{ff} = 50$, $N_{fb} = 50$) filter taps. It shows that with the increase of feedforward and feedback (N_{ff} and N_{fb}) filter taps, the system improves further as compared with lower filter taps in terms of bit error rate at the cost of complexity.

CONCLUSION

DWMT modulation based transceiver, appears to be an interesting choice, when utilizing multi-carrier modulation techniques in ADSL. It not only offers the unique time-frequency localization advantage over the conventional frequency localized DMT systems, but also conserves precious bandwidth in foregoing cyclic prefix. In this article, a novel WPT based DWMT transceiver is proposed for ADSL in place of conventional DMT modulation with ZF, MMSE and MMSE-DFE algorithm based time-domain equalization techniques. DWMT system based on WPT performs well in the presence of AWGN and crosstalk in comparison with the DMT system for ADSL. MMSE-DFE outperforms the other two equalization techniques (ZF and MMSE) for DWMT based ADSL.

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