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In-Home Power Line Communications Local Area Network Based on Uniform Discrete Multitone Transceiver

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Abstract: Cyclic prefix based channel equalization employed in the Discrete Multitone (DMT) modulation offers the advantage of simplified implementation. However, this method has the disadvantage of amplifying channel noise for channels having deep nulls in the frequency response. The in-home power line channel is one such channel that has high noise content, in addition to deep frequency nulls. Enhancement of channel noise degrades bit error rate (BER), at the receiver. In order to improve the BER and the signal-to-noise ratio (SNR), for the in-home power line channel, a novel Uniform DMT transceiver is proposed. It divides the channel spectrum into uniform bandwidth sub-bands, and allocates variable power to each sub-band, according to the modified Fischer's power loading algorithm. The proposed Uniform DMT transceiver shows BER improvement in comparison with the conventional DMT system, for the in-home power line channel.

Key words: In-home power line communication · Discrete Multitone modulation · Uniform DMT · Wavelet filter banks · power-loading algorithms

INTRODUCTION

For many decades, power lines have been used to communicate at lower frequencies, mostly for applications such as telemetering and control of electrical equipment by the power utilities. In recent past, a new application of the indoor power lines was envisaged, which employed the ubiquitously available power lines for an in-home, high speed communication network [1]. The in-home power line communication (PLC) network offers the advantages of ubiquitous node availability, easy installation, and cost effectiveness. However, a PLC based home network has some limitations, due to the fact that power lines represent a harsh communication channel, which is plagued by different kinds of noise [2]. The transmitted signal is distorted by the presence of coloured background noise, narrowband noise and impulse noise in PLC [3]. It is for this reason that robust multicarrier modulation techniques, such as orthogonal frequency division multiplexing (OFDM), which help mitigate inter-symbol interference (ISI) have been adopted for communication in PLC [1].

In 2001, the HomePlug Powerline Alliance released the HomePlug 1.0 protocol, for the interconnection of computers and other electronic devices within a home or small building, utilizing the in-home power lines [4]. This standard employs OFDM, at the physical layer and can achieve data rates up to 14 Mbps [4]. HomePlug AV is another standard for PLC based home-network, that is also based on OFDM and supports a high data rate of 100 Mbps, for applications such as multistream video and audio, high definition television (HDTV) [5]. IEEE P1901is the only global PLC standard approved by IEEE, which supports two physical layers, based on DFT-OFDM as well as wavelet OFDM [6].

DMT is a variant of multicarrier modulation, which like OFDM employs the cyclic prefix based channel equalization. This gives the advantage of computationally simple implementation. DMT works on the divide and conquer approach. It splits the frequency-selective fading channel into a number of sub-channels, thereby making each sub-channel flat faded within its small frequency band [7]. Each of these sub-channels can be much more easily equalized with a single-tap equalizer to cancel out the channel effect, as compared to a complex equalizer required by a single carrier consisting of a large number of taps. If the additive noise present in the channel is not considered, then the linear zero-forcing (ZF) equalization

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technique in DMT modulation, completely removes ISI, due to the communication channel. Nevertheless, when the additive channel noise is taken into consideration, ZF equalization causes noise amplification at frequencies, where the channel has nulls or it has lower gain [8]. This noise amplification increases the BER and also reduces the post equalization signal-to-noise ratio (SNR).

A novel Uniform DMT modulation technique, with variable power allocation for different sub-bands is proposed here for the in-home power line channel, in order to counter the aforementioned problems of noise amplification, and the signal distortion resulting in greater BER and also to improve the post equalization SNR. It was shown in a previous work, that the proposed technique of the Uniform DMT gives improvement in SNR for the same BER over the conventional DMT system in the digital subscriber line (DSL) [9]. However, the Uniform DMT modulation transceiver proposed here is novel with respect to its application for the power line channel.

We utilize the wavelet packet filter banks in combination with a conventional DMT system for the Uniform DMT structure. Uniform DMT modulation splits the channel into equal bandwidth sub-bands and employs modified form of Fischer's power loading algorithm [10], in order to allocate variable power to each sub-band. The Uniform DMT modulated system's BER performance is assessed for the in- home power line channel, in the presence of additive white Gaussian noise (AWGN). In Section II, the system model for the implementation of the Uniform DMT transceiver is presented.

System Model of the Uniform DMT Transceiver: In this work, the Uniform Discrete Multitone (DMT) modulation is proposed for in-home power line communication based local area network (LAN). The proposed modulation technique is a hybrid modulation technique, which is a combination of DMT modulation and wavelet packets based transmultiplexer, as shown in the generalized Uniform DMT system in Figure 1. The M branch Uniform DMT transceiver depicted here, splits the communication channel $C(z)$ into equal bandwidth sub-channels $C_k(z)$, where k=0,…M-1, by utilizing a maximally decimated filter bank. The transmultiplexer utilized in this structure consists of the analysis filters $F_k(z)$ in the transmitter and the synthesis filters $H_k(z)$. The input, serial bit-stream is split into parallel sub-streams, each having an equal bit-rate, which is 1/M times the input bit rate.

The $x_k(n)$ bit streams are DMT modulated, and the detailed structure of the DMT modulator is shown in Figure 2(a). The DMT modulation process starts with parsing, in which the B- bit blocks of the scalar bit-stream $x_k(n)$ are grouped to form N symbol streams, therefore this is known as the (B_k, N_k) parser. These groups of bits are mapped into a constellation using quadrature amplitude modulation (QAM) and transformed using Inverse Discrete Fourier Transform (IDFT). A part of each data symbol known as the cyclic prefix is appended at the start of the DMT symbol. This addition of redundant data in the guard interval helps counter the ISI. Cyclic prefix also plays a crucial role in frequency domain equalization of each DMT symbol, since it helps create a circulant channel matrix, which can be easily equalized.

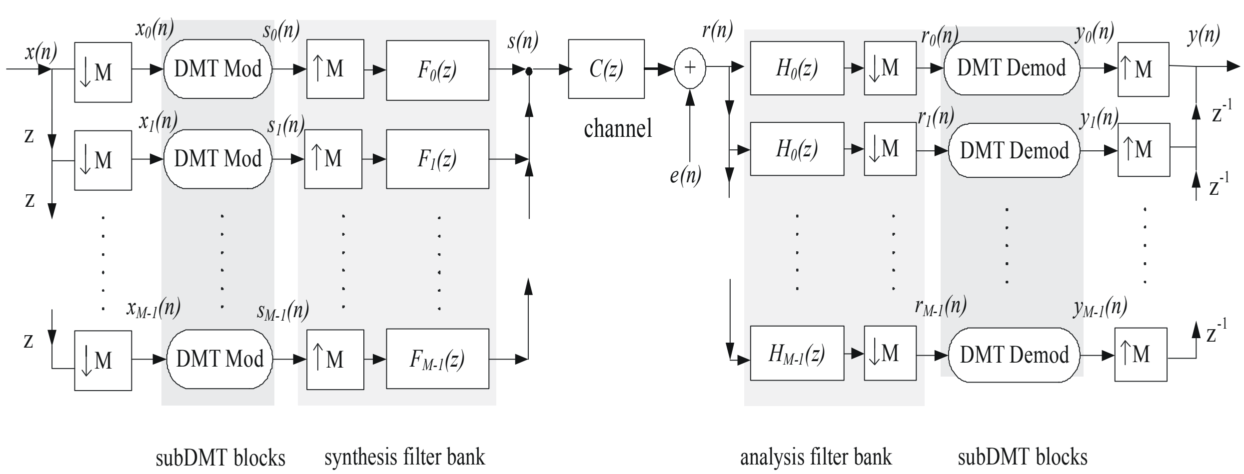

Fig. 1: The generalized structure of the M-branch Uniform DMT transceiver

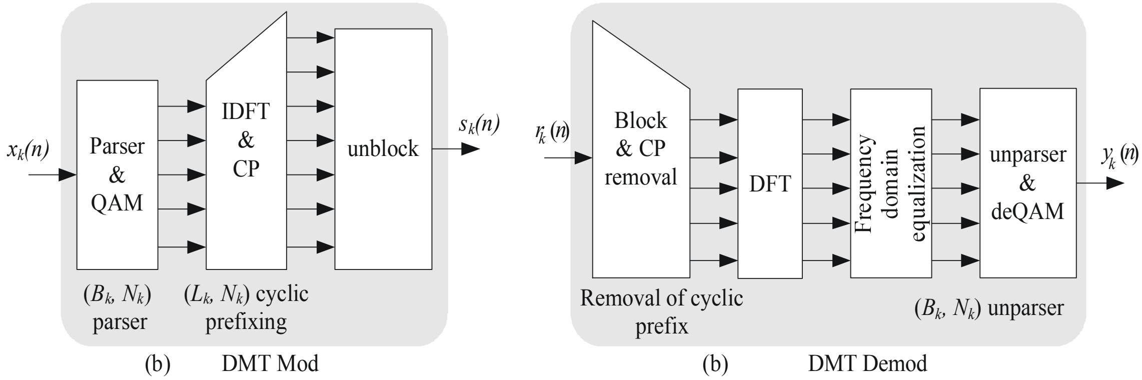

Fig. 2: (a)-Detailed structure of the DMT modulation block (b)-Detailed structure of the DMT demodulation block

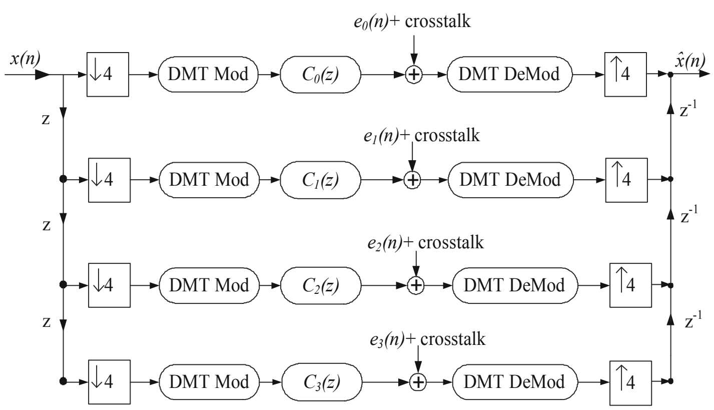

Fig. 3: Uniform DMT Transceiver with equivalent sub-channels $C_k(z)$ for k=1,..4

The wavelet packet filter bank in conjunction with the communication power line channel $C(z)$ can be represented by equivalent sub-channels $C_k(z)$. For example, employing a two-level wavelet packet transmultiplexer, which gives M=4, the Uniform DMT transceiver can have four uniform sub-channels. In the Uniform DMT transceiver, the equivalent sub-channels $C_k(e^{j\omega})$, are determined by the expression [11],

$$C_k(e^{j\omega})=\left[H_k(e^{j\omega})F_k(e^{j\omega})C(e^{j\omega})\right]_{\downarrow M} \quad (1)$$

The received signal in the k^{th} branch $R_k(z)$ can be is expressed in z-domain as,

$$R_k(z)=S_k(z)C_k(z)+E_k(z) \quad (2)$$

Where $C_k(z)$ is the z-domain description of the k^{th} sub-channel, defined in Eq. (1), $S_k(z)$ represents the transmitted signal of the k^{th} branch, and $E_k(z)$ represents the additive noise corresponding to the k^{th} branch, defined as,

$$E_k(z)=\left[H_k(z)E(z)\right]_{\downarrow M} \quad (3)$$

From Eq. (3), it may appear that the k^{th} branch noise $E_k(z)$ becomes coloured, however it can still be considered white with respect to the spectrum of the sub-channel $C_k(z)$, since $E(z)$ is also downsampled by M to get $E_k(z)$.

The received signal $R_k(z)$ in the k^{th} branch is DMT demodulated by the receiver counterpart of the DMT modulation process. The details of the DMT demodulation process block are shown in Figure 2(b). As a first step in DMT demodulation, the received signal is blocked or serial to parallel converted. Then the cyclic prefix is removed from the received signal $r_k(n)$, after which the (L_k+N_k) length received signal is reduced to N_k length signal. The next step involves, taking the discrete Fourier transform (DFT) of the received signal and converting the time-domain signal to frequency domain signal. This signal is then equalized in frequency domain to remove the channel affect. In order to equalize the channel attenuation, each of the data sub-streams is equalized by the inverse of the sub-channel frequency response $C_k(e^{j\omega})$. Therefore, the equalized signal $\hat{s}_k(z)$ is expressed as,

$$\hat{S}_k(z) = \frac{R_k(z)}{C_k(z)} \quad (4)$$

This expression can be also be written as,

$$\hat{S}_k(z) = S_k(z) + \frac{E_k(z)}{C_k(z)} \quad (5)$$

Therefore, the received signal is reduced to the recovered signal $S_k(z)$, plus the noise term, which is the enhanced version of the AWGN $E_k(z)$, and is represented as,

$$\hat{E}(z) = \frac{E_k(z)}{C(z)} \quad (6)$$

The mathematical description of the system model of the Uniform DMT transceiver implies that the equalized signal recovers the signal $S_k(z)$ perfectly, however the channel noise $E_k(z)$ is enhanced, depending on the zero-locations of the equivalent sub-channel $C_k(z)$.

Each of the sub-channels $C_k(z)$ of the communication channel $C(z)$ in the Uniform DMT system will show variable channel-noise enhancement, depending on the placement of zeros present in the channel transfer function. Therefore, in order to improve the BER, the Uniform DMT transceiver is aided by variable power allocation in each sub-band, which is performed according to the modified form of the Fischer's power-loading algorithm.

Power Loading Algorithm: Discrete Multitone modulation is characterized by various loading algorithms aimed at maximizing the signal-to-noise ratio (SNR), bit-rate or minimizing the BER. The Fischer's algorithm belongs to the margin-adaptive class of loading algorithms [12]. The main goal of this loading algorithm is to distribute data bits and transmit power in order to minimize the BER. Its main advantage is its computational efficiency, since it does not require extensive sorting and searching.

The Uniform DMT modulation constitutes various sub-bands, because of the wavelet-packet filter banks. Therefore, a modified Fischer's loading algorithm is applied to different sub-bands for variable power allocation. A modified Fischer's algorithm, which performs bit and power allocation in sub-bands instead of sub-channels is proposed in literature, so as to minimize the signaling overhead [10].

The successive sub-channels are grouped in various sub-bands and power is allocated to each sub-band, in accordance with each sub-band's channel gain $C_k(z)$. The number of bits Rk allocated to the k^{th} sub-band is expressed as [10],

$$R_k = \frac{R_{tot}}{N_B} + \frac{1}{N_B} log_2 \left[\frac{\left(|C_k|^2\right)^{N_B}}{\prod_{i \in \Psi} |C_i|^2} \right] \quad (7)$$

Where Ψ denotes the sub-band indices, i denotes the subcarrier indices, and R_{tot} are the total number of bits to be distributed into N_B number of sub-bands, for the k^{th} sub-band channel gain. The power allocated in each sub-band is given by [9],

$$P_k = \frac{P_{tot} \frac{2^{R_k}}{|C_k|^2}}{\sum_{i \in \Psi} \frac{2^{R_i}}{|C_i|^2}} \quad (8)$$

Where P_{tot} denotes the total power constraint and R_k stands for quantized number of bits in the k^{th} sub-band. With the subcarriers grouped into sub-bands, by the Uniform DMT system, we allow equal number of bits and equal amount of power to be allocated to each subcarrier in a sub-band, however, the power and bits may be variably allocated for various sub-bands.

Simulation Results: Utilizing the modified Fischer's power loading algorithm, performance of the Uniform DMT transceiver is evaluated for the in-home power line channel. The in-home power line channel utilized for the purpose of simulation and the simulation results are presented in this Section.

A LAN that is utilizing the existing power-line network as the communication medium consists of a transmission line having numerous branches and different loads with different impedances connected to them. Therefore, there is strong chance of the impedance mismatch at the couplings and different branches, due to which the channel causes creation of reflected versions of the transmitted signal. Thus a power line channel can be represented in mathematical derivations and simulation processes as an echo channel model, which gives rise to multipath transmission and narrowband fading [13].

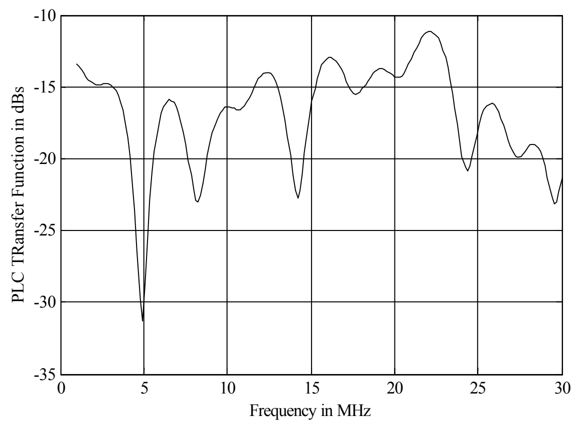

Fig. 4: In-home power line channel frequency response

Table 1: In-home Power Line Channel Parameters

No	$\lvert\rho\rvert$	φ in radians	τ in µs
1	0.151	0.691	0.110
2	0.047	-0.359	0.154
3	0.029	0.591	0.205
4	0.041	2.913	0.311
5	0.033	1.012	0.427

The frequency response of the in-home PLC channel transfer function model, as presented by H. Philipps is shown in Figure 4 [13]. The channel response displays deep narrowband notches in the channel frequency response, spread over the whole frequency range of 0-30 MHz. Each path for the impulse response $h_v(t)$ in the N-path model, is characterized by a delay τ_v, attenuation $|\rho_v|$ and phase shift φ_v. These parameters, which describe the multipath in-home PLC channel model are given in Table 1 for a 5 path channel model [13]. The channel impulse response is the sum of N Dirac pulses, each multiplied by the complex attenuation factor ρ_v and delayed by τ_v, and is expressed as,

$$h(t)=\sum_{v=1}^{N}\rho_v\delta(t-\tau_v) \tag{9}$$

Where the attenuation factor ρ_v is defined as,

$$\rho_v=|\rho_v|e^{j\varphi_v} \tag{10}$$

and the phase shift φ_v is expressed as,

$$\varphi_v=tan^{-1}\left(\frac{Im\{\rho_v\}}{Re\{\rho_v\}}\right) \tag{11}$$

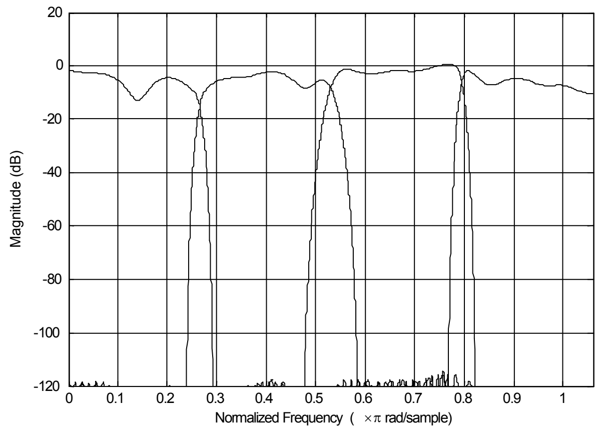

Fig. 5: Uniformly spaced sub-bands formed by the Uniform DMT modulation in the in-home power line channel.

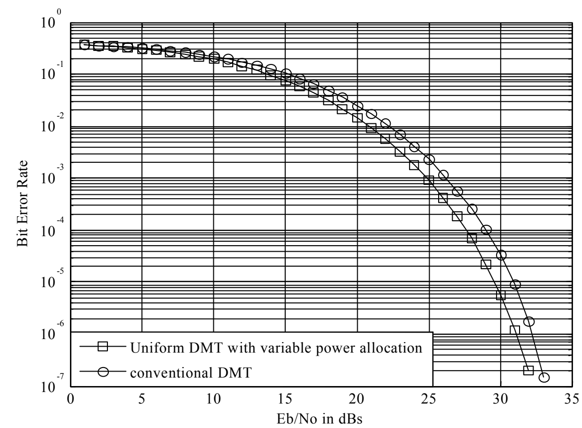

Fig. 6: BER Performance comparison of the Uniform DMT modulation with the conventional DMT system for the In-Home PLC channel.

Uniform DMT Transceiver-Simulation Results: The Uniform DMT transceiver and a conventional DMT system are simulated using Matlab and SIMULINK. The simulation parameters include a sampling frequency of 2.208 MHz, with 512 number of subcarrier. QAM modulation is applied, which varies from 2-ary to 16-ary.The simulation involves certain assumptions, one of which is that the PLC communication channel is a quasi-stationary channel. Moreover, it is also assumed that complete channel state information is available at the receiver.

Perfect synchronization between the transmitter and receiver is considered. A finite impulse response (FIR) filter of length 101 is used to simulate the in-home power line channel. The power line channel impulse response modeled as equivalent sub-channels, due to wavelet packet transmultiplexer is shown in Figure 5.

The BER evaluation versus the Eb/No for the Uniform DMT transceiver with power distributed according to modified Fischer's algorithm is shown in Figure 6, and compared with the BER for a conventional DMT system, for the in-home power line channel with AWGN. It is observed from Figure 6 that the Uniform DMT transceiver with variable power allocation gives an improvement of 0.9 dB in Eb/No at a BER of 2E-7, over the conventional DMT system.

CONCLUSIONS

Different power and bit loading algorithms have been applied in literature, in order to achieve improvement in the overall performance of a DMT transceiver, for the PLC environment. In this article, we have proposed a hybrid modulation technique that makes use of a wavelet packet filter banks, and distributes the in-home power line channel spectrum into uniform bandwidth sub-bands. A modified Fischer's power loading algorithm is then employed to allocate more power to the sub-band which has lower sub-channel gain, in order to minimize the BER. The Uniform DMT transceiver shows improvement in the BER performance in comparison with a conventional DMT system.

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