LDPC Coded TDS-OFDM for PLC Systems*

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Abstract: Powerline communications (PLC) have drawn great interest in recent years. However, most PLC standards such as HomePlug AV use the cyclic-prefix OFDM (CP-OFDM) technology. This paper presents a broadband PLC system using low density parity check (LDPC) coded time domain synchronous OFDM (TDS-OFDM), whose spectrum efficiency is about 10% higher than that of CP-OFDM. With the same bandwidth and the ability to combat the time delay spread as HomePlug AV, this system can provide a maximum throughput of 199.7 Mbps physical layer data rate. Simulations over the measured practical powerline channel in Beijing, China, show that LDPC in the TDS-OFDM system dramatically improves the bit error rate performance, and verify the feasibility and performance of the TDS-OFDM technology for PLC systems.

Key words: powerline communications (PLC); time domain synchronous OFDM (TDS-OFDM); low density parity check (LDPC); HomePlug AV; channel measurement

Introduction

With availability in every building and in every room on earth, powerline communications (PLC) has great potential in applications like last-mile access, in-home networking, and command and control. Power transmission towers and lines are some of the most robust structures ever built. Since the communication signal (with working frequencies much higher than 50/60 Hz) can be carried by the power cables, there is no need to build new networks which reduces not only costs but also the time to provide services to customers not covered by existing communication networks but who receive service from the electrical utility company.

Another advantage is the widespread coverage since there are no existing networks that link more customers in very different areas than the electrical grids.

Therefore, powerline communications have drawn great interest recently due to new technical developments in information technology[1,2]. Now we are witnessing the possibility of PLC being acclaimed universally as the prime method for long-haul data communications.

Orthogonal frequency division multiplexing (OFDM) modulation techniques are widely utilized in PLC systems for various applications due to the frequency selective spectrum of the power line channel. Recently developed broadband PLC standards, such as HomePlug AV[3] and Opera[4], all use the OFDM technology. HomePlug AV employs advanced physical (PHY) and MAC technologies that provide a 200 Mbps class powerline network for video, audio, and data. The PHY layer utilizes this 200 Mbps channel rate to provide a 150 Mbps information rate with robust, near-capacity communications over noisy powerline channels.

As with most of the OFDM-based communication systems, the main worldwide standards for PLC use the cyclic prefix-OFDM (CP-OFDM) technique. The CP serves the guard interval (GI) to combat multi-path
distortion and inter-symbol interference (ISI). The time domain synchronous-OFDM (TDS-OFDM), which is the key technology of the Chinese national digital television terrestrial broadcasting (DTTB) standard\cite{5}, inserts pseudo random noise (PN) sequences between OFDM blocks as the GI instead of CP. The PN sequences are also used for synchronization and channel estimation (CE)\cite{6}. The lack of pilot insertion significantly improves the spectral efficiency. It has also been demonstrated that TDS-OFDM can provide higher spectral efficiency and lower outage probability than CP-OFDM\cite{7}.

As another solution for PLC, this paper describes the use of TDS-OFDM over powerlines, together with the system design and performance evaluation.

1 PLC Channel Model

1.1 Typical PLC channel model

Unlike communication cables, which are quite stable and are rarely affected by other systems, PLC systems are vulnerable to environmental interference and noise. Thus, channel modeling is quite critical for PLC systems. With many papers giving very good insights, the channel model can be given as\cite{8-10}:

$$H(f) = \sum_{i=1}^{N} g_i(f) e^{-j(a_i+a_if^k)}d_i e^{-j2\pi f \xi_i}$$

(1)

where $N$ is the total number of multiple paths, $|g_i(f)|e^{a_i}e^{-j(a_i+a_if^k)d_i}$ is the attenuation, and $e^{-j2\pi f \xi_i}$ is the delay.

Studies have showed that the weighting factor has little relationship with the frequency\cite{10}, so $g_i$ can be treated as a real number in practice. For multiple paths, $g_i$ is the weighting factor for the $i$-th path. Therefore, the channel model can be expressed as:

$$H(f) = \sum_{i=1}^{N} g_i e^{-j(a_i+a_if^k)d_i} e^{-j2\pi f \xi_i}$$

(2)

where $\xi_i = \frac{d_i}{c_0} \sqrt{\zeta_i} = \frac{d_i}{v_p}$.

For a PLC transmission medium whose dielectric constant $\zeta_i = 4$, $v_p$ is 150 000 km/s, half the velocity of light, $c_0$.

This model, with only a few parameters, describes the complicated frequency response of typical PLC channel in terms of the total transmission characteristics of the channel ranging from 500 kHz to 50 MHz.

The frequency response of a channel model with 6 paths with the parameters shown in Table 1 ($k=1$, $a_0=-2.1\times10^{-7}$ s/m, and $a_1=8.11\times10^{-10}$ s/m), is depicted in Fig. 1.

| path | Theoretical PLC channel parameters for each path |
|-----------------|-----------------|-----------------|-----------------|
| $i$ | $g_i$ | $d_i$/m | $i$ | $g_i$ | $d_i$/m |
| 1 | 0.54 | 200 | 4 | 0.08 | 259 |
| 2 | 0.28 | 221 | 5 | -0.03 | 266 |
| 3 | -0.15 | 242 | 6 | -0.02 | 530 |

**Fig. 1** Frequency response of the channel model in Table 1

1.2 Measured actual PLC channel

Since the system performance heavily depends on the channel characteristics, channel measurements as well as channel modeling are of great importance for PLC systems. The feasibility of the PLC channel model mentioned given by Eq. (2) and more importantly the PLC system performance in a real environment was studied by Liu et al.\cite{12} and Song et al.\cite{13} in field tests of the practical transmission characteristics in a medium-voltage (MV) power supply network in Beijing, China. The solid line in Fig. 2 shows the average characteristics of the measured channel.

A Gauss-Newton algorithm was used to fit a curve as shown by the dashed line in Fig. 2 to compare with the theoretical model in Eq. (2). The fit parameters for the practical channel are listed in Table 2 ($k=1$, $a_0=0$, and $a_1=1.64\times10^{-10}$ s/m).
The impulse response of the measured channel is shown in Fig. 3.

The theoretical and measured results show that:

1. The theoretical channel model actually presents the measured PLC channel response;
2. The PLC channel is frequency elective and the overall attenuation increases drastically with increasing frequency. Therefore, the OFDM technique, which is well suited for the frequency-selective channel, is a promising PLC technique;
3. The typical time spread for the PLC channel is $\mu s \cdot 2 \mu s$. Therefore, the requirement on the guard interval duration in OFDM systems is not very strict.

2 TDS-OFDM System for PLC

The PLC channel characteristics described in Section 1 show that the frequency selective channels can effectively use OFDM modulation techniques for various PLC applications, such as the recently developed broadband PLC standard HomePlug AV[3].

The tone (or carrier) masks define the set of tones that can be used in a given regulatory jurisdiction or a given application of HomePlug AV. Certain tones need to be turned off to comply with the spectral mask requirements of the region or application. The tone mask that complies with the current North American regulations is shown in Fig. 4.

Thus, the TDS-OFDM can be used as the basic physical layer for PLC applications, rather than the CP-OFDM adopted by HomePlug AV.

2.1 TDS-OFDM system model

Figure 5 compares the CP-OFDM and TDS-OFDM frame structures. Instead of inserting the CP, TDS-OFDM uses known PN sequences as the guard intervals, providing multi-path protection similar to CP-OFDM. The PN sequences can also be used as the training symbols in the signal to facilitate CE as well as synchronization. Therefore, its spectrum efficiency is about 10% greater than CP-OFDM, since no pilot is needed.
A diagram of the TDS-OFDM transmitter is shown in Fig. 6. The input payload data stream passes through a scrambler, a forward error correction (FEC) encoder, and an interleaver. The FEC output binary sequence is converted to an $M$-ary quadrature amplitude modulation (M-QAM) symbol stream. A convolutional interleaver is then utilized across many OFDM signal frames with frequency interleaving in each OFDM frame. The frame body after an inverse fast Fourier transform (IFFT) processor is combined with the frame head (PN sequence) to form a signal frame. A square root raised cosine (SRRC) filter is used to shape the baseband signal which is fed to the analog front end (AFE) module that couples the signal to the powerline medium.

The major problem of the TDS-OFDM is that the PN sequence and the frame body will cause inter-symbol-interference (ISI) with each other, creating a need for an iterative padding subtraction algorithm at the receiver to remove the ISI between PN sequence and frame body for CE and equalization\textsuperscript{[14]}. However, the ISI removal is not good if the channel is rapidly varying. Fortunately, the PLC channel does not change drastically with time, this major problem with the TDS-OFDM can be neglected when applied to PLC systems.

### 2.2 TDS-OFDM adaptation for PLC

Although TDS-OFDM was originally designed for terrestrial DTV systems with a working bandwidth of 8 MHz, this technology can be adapted for other wideband applications such as PLC. This section describes an OFDM system based on TDS-OFDM (called derivative TDS-OFDM), which occupies the same bandwidth as HomePlug AV and offers similar system throughput.

1. **System bandwidth (BW)**
   
The spectral mask in Fig. 4 implies that not all the sub-carriers can be used for HomePlug AV. Actually, a maximum of 917 sub-carriers can be used out of the total 1155 sub-carriers ranging from 1.8 MHz to 30 MHz, with a spacing of 24.416 kHz (28.2 MHz/1155=24.416 kHz). Thus the actually occupied bandwidth for HomePlug AV is 22.4 MHz. Since the PN sequence in the time domain for the TDS-OFDM system occupies the complete bandwidth, the total bandwidth for the derivative TDS-OFDM system is limited to 22.4 MHz.

2. **Symbol rate ($R_s$)**
   
   Unlike the CP-OFDM in HomePlug AV where the nonuse of certain sub-carriers will not affect the spectral efficiency, all the sub-carriers should be used for the TDS-OFDM system to guarantee the highest spectral efficiency, since the PN sequence in the time domain already occupies the whole bandwidth. Therefore, the symbol rate, both of the PN sequence and the frame body, is defined as 22.4 MS/s.

3. **IFFT length ($N$)**
   
   For best feasibility the IFFT length should be 2\textsuperscript{n} but this is not required. The number of symbols in each frame body should then be the same as the IFFT length in the derivative TDS-OFDM system. Thus the IFFT length is defined as 1024 and the IFFT period ($T$) is 45.71 $\mu$s, which is similar to the IFFT period for HomePlug AV, which is 40.96 $\mu$s (1/24.416 kHz = 40.96 $\mu$s).

4. **Number of sub-carriers ($K$)**
   
   Since all the sub-carriers should be used in the TDS-OFDM system, the number of sub-carriers $K$ should be equal to the IFFT length $N$, which is 1024.

5. **Sub-carrier spacing ($
\Delta f$)**
   
   Since the whole bandwidth is limited to 22.4 MHz and the number of sub-carriers is 1024, the sub-carrier spacing, $\Delta f$, for the derivative TDS-OFDM system is
The GI duration in OFDM systems depends on the time delay spread. As pointed out in Section 1, the typical time delay for a PLC channel is about 1 μs. Therefore, the GI period for the derivative TDS-OFDM is set to 5.56 μs, which is the same for HomePlug AV.

(7) OFDM symbol period (T_S)

The OFDM symbol is composed of IFFT data and the GI (either CP or PN). Thus the total OFDM symbol period is

$$T_S = T_U + T$$  \hspace{1cm} (4)

The total OFDM symbol period is 51.27 μs (45.71 μs + 5.56 μs = 51.27 μs) for the derivative TDS-OFDM system.

(8) Modulation

HomePlug AV can support binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-quadrature amplitude modulation (QAM), 16QAM, 64QAM, 256QAM, 1024QAM, depending on the channel conditions, while the conventional TDS-OFDM supports 64QAM, 32QAM, 16QAM, 4QAM, and 4QAM-NR (Nordstrom Robinson). The derivative TDS-OFDM system will be designed to support the same modulation schemes as HomePlug AV.

(9) Channel coding

Channel coding is of great importance for communication systems. The derivative TDS-OFDM system was designed with LDPC instead of the Turbo convolutional encoder used by HomePlug AV, since LDPC provides superior error correction capability for better sensitivity especially at higher code rates\[15\].

With 917 carriers active in the HomePlug AV tone mask in Fig. 4 with each modulated with 1024QAM (10-bit symbol), the channel bit rate $$R_1$$ is

$$R_1 = \frac{10 \times 917 \text{ bits}}{(40.96 + 5.56) \mu \text{s}} = 197.1 \text{ Mbps}$$  \hspace{1cm} (5)

For the conventional TDS-OFDM with the 64QAM modulation scheme, the channel bit rate $$R_2$$ is

$$R_2 = \frac{6 \times 3780 \text{ bits}}{(500 + 55.56) \mu \text{s}} = 40.8 \text{ Mbps}$$  \hspace{1cm} (6)

For the derivative TDS-OFDM system with the same modulation scheme, the channel bit rate $$R_3$$ is

$$R_3 = \frac{10 \times 1024 \text{ bits}}{(45.71 + 5.56) \mu \text{s}} = 199.7 \text{ Mbps}$$  \hspace{1cm} (7)

In a summary, the overall system parameters are listed in Table 3.

### Table 3  Summary of the system parameters

<table>
<thead>
<tr>
<th>Bandwidth (MHz)</th>
<th>Symbol rate (MSPS)</th>
<th>IFFT length</th>
<th>Sub-carriers</th>
<th>Sub-carrier spacing (kHz)</th>
<th>Used sub-carriers</th>
<th>GI period (μs)</th>
<th>OFDM period (μs)</th>
<th>Coding</th>
<th>Maximum data rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HomePlug AV</td>
<td>22.4</td>
<td>100</td>
<td>4096</td>
<td>40.96</td>
<td>1155</td>
<td>24.416</td>
<td>917</td>
<td>5.56</td>
<td>46.52 Turbo</td>
</tr>
<tr>
<td>Conventional</td>
<td>7.56</td>
<td>7.56</td>
<td>3780</td>
<td>500</td>
<td>3780</td>
<td>2.0</td>
<td>3780</td>
<td>55.56</td>
<td>555.56 LDPC</td>
</tr>
<tr>
<td>TDS-OFDM</td>
<td>22.4</td>
<td>22.4</td>
<td>1024</td>
<td>45.71</td>
<td>1024</td>
<td>21.875</td>
<td>1024</td>
<td>5.56</td>
<td>51.27 LDPC</td>
</tr>
</tbody>
</table>

### 3 Simulation Results

The feasibility and performance of the TDS-OFDM technology for a PLC system were evaluated for the actual PLC channel shown in Fig. 2, with the curve fit parameters in Table 2. The frequency and impulse responses of this channel are shown in Figs. 2 and 3, respectively. The modulation schemes include QPSK, 16QAM, 64QAM, and 256QAM.

Figure 7 shows the bit error rate (BER) performance for various signal-to-noise ratios (SNR) for the derivative TDS-OFDM system over a PLC channel without channel coding. The simulation results show that the BER decreases as the SNR increases for all the modulation schemes, with the QPSK scheme having the fastest decrease. For the QPSK scheme, the BER reaches $$10^{-3}$$ for SNR greater than 22 dB. The channel coding is of great importance for communication systems.

The performance of the LDPC for the derivative TDS-OFDM system is shown in Figs. 8-11 which compares the BER performance for various modulation schemes. The LDPC rate was set as 0.4 for these simulations. The results indicate that the channel coding dramatically improves the system BER performance. For example, the SNR requirement for 64QAM...
without LDPC coding for an expected BER of $10^{-3}$ is about 30 dB, while the requirement dramatically drops to about 17 dB with the LDPC coding. Similar conclusions hold for the other modulation schemes and coding rates. The SNR thresholds are about 2 dB for QPSK, 9 dB for 16QAM, 17 dB for 64QAM, 20 dB for 256QAM, respectively.

Thus, the simulations indicate the TDS-OFDM technology can be used over PLC channels with good performance which makes it a promising choice for PLC.

4 Conclusions

This paper describes the actual characteristics of the powerline networks in Beijing, China, with a theoretical channel model to evaluate the performance of a wideband PLC system based on the TDS-OFDM technology. With the same active bandwidth as HomePlug AV, the derivative TDS-OFDM system provides the maximum throughput of 199.7 Mbps physical layer data rate. Simulation results show that the use of LDPC in the derivative TDS-OFDM system dramatically improves the BER performance. Thus, TDS-OFDM is an interesting modulation scheme for PLC systems with limited bandwidth. Use of a notch filter to remove the negative impact of narrow-band noise and a power allocation algorithm to maximize
the throughput of the conventional TDS-OFDM technology will make it even more attractive for PLC applications.

References


