Modulation Diversity in Wideband In-Home PLC

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Abstract

The power line channel is characterized by a multi-path behavior. A direct consequence is that Multi-Carrier Modulation (MCM) is generally retained for Power Line Communication (PLC). In addition to OFDM, or equivalently DMT, Wavelet OFDM and OFDM/OQAM have been recently proposed for PLC transmission. In fact, every scheme has its own pros and cons. The most effective way for PLC is to use a so-called unified modulation that can generate all of the above schemes, by which a “modulation diversity” can be provided to the PLC. In this paper we introduce this unified modulator and its functions in PLC.

Index Terms

Diversity, IEEE P1901, Multi-carrier modulation, OFDM/DMT, OFDM/OQAM, Wavelet OFDM

I. INTRODUCTION

MULTI-CARRIER modulation has been proven to be a good means for wideband PLC. Among all the possible ones, OFDM/DMT has absorbed a large attention due to its great reputation in wireless communications. Besides DMT, WOFDM and HS-OQAM have also been proposed to PLC by respectively Koga et al. [1] and Lin et al. [2]. The advantages of those schemes, compared with DMT, are: First, a prototype filter that provides both orthogonality and good time-frequency localization can be obtained; Second, cyclic prefix (CP) is not required such that we can have a full spectrum efficiency. Moreover, we also revealed that this threshold varies with the changing of the transmission environment. Therefore, in order to always get a maximum capacity, it would be judicious to cognitively switch between HS-OQAM and DMT schemes w.r.t.

Threshold for HS-OQAM vs. DMT, i.e. if the desired transmission throughput is below this threshold, using HS-OQAM scheme, rather than DMT, gives us a higher capacity. But, a reverse situation occurs if the desired throughput goes beyond that threshold.

II. THROUGHPUT THRESHOLD

In our previous work [3], we recall that the inter-symbol plus inter-carrier interference (ISI+ICI) power, at \( m \)-th subcarrier, of DMT system, using a one-tap zero-forcing (ZF) equalizer, can be calculated as [3]

\[
P_{\text{ZF} \text{DMT}}(m) = \frac{2\sigma_m^2}{\sum_{l=1}^{L_h} \left| \sum_{\mu=1}^{M} h[l] e^{-j2\pi\mu m} \right|^2},
\]

where \( \sigma_m^2 \) denotes the complex-valued QAM symbol variance and \( h \) stands for the channel impulse response (CIR) with \( L_h \) length; \( M \) the number of carriers; \( L \) the CP length; \( H_m \) the equalizer coefficient, at \( m \)-th subcarrier, obtained by \( H_m = \sum_{l=0}^{L_h-1} h[l] e^{-j2\pi lm} \). Assuming the background noise is white gaussian with zero mean and variance \( \sigma_n^2 \), the \( m \)-th subcarrier signal-to-interference-plus-noise ratio (SINR) of DMT system yields

\[
\text{SINR}^{\text{DMT}}(m) = \frac{\sigma_m^2}{\sum_{l=1}^{L_h} \left| \sum_{\mu=1}^{M} h[l] e^{-j2\pi\mu m} \right|^2 + \frac{\sigma_n^2}{H_m^2}}.
\]

On the other hand, the ISI+ICI power, at \( m \)-th subcarrier, of HS-OQAM system can be written as [3]

\[
P_{\text{ISI+ICI} \text{HS-OQAM}}(m) = \sigma_m^2 \sum_{(p,q)\neq(0,0)} \left\{ \left| e^{j\frac{\pi}{2} (p+q+pq)} H_{p,q}(m) \right|^2 \right\}^2,
\]

where \( (p, q) \) are integers and \( A_g[l,k] = A_g(lT_s, kF_0) \), with \( (T_s = T_0/M, T_0 F_0 = 1) \), is the sampled ambiguity function \( A_g(\tau, \mu) \) of \( g(t) \) given by

\[
A_g(\tau, \mu) = \int_{-\infty}^{\infty} g(t + \tau/2)g^*(t - \tau/2) e^{j2\pi\mu t} dt.
\]

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The SINR at \( m \)-th subcarrier can be calculated as

\[
\text{SINR}_{m}^{\text{HS-OQAM}} = \frac{\rho_{m}^{2}\sigma_{c}^{2}}{\sigma_{n}^{2}}, \text{ with } \rho_{m} = \Re \left\{ \alpha_{m}^H \right\}, \text{ and } \alpha_{m} = \sum_{l=0}^{L_{A}-1} h[l] e^{-j \frac{2\pi m l}{M}} a_{g}[-l, 0].
\] (5)

Knowing the SINR expression, the system capacity for DMT and HS-OQAM can be respectively written as

\[
R_{\text{DMT}} = M F_{0} \sum_{m=0}^{M-1} \log_{2} \left( 1 + \frac{\text{SINR}_{m}^{\text{DMT}}}{\Gamma} \right), \text{ and } R_{\text{HS-OQAM}} = F_{0} \sum_{m=0}^{M-1} \log_{2} \left( 1 + \frac{\text{SINR}_{m}^{\text{HS-OQAM}}}{\Gamma} \right),
\]

where the SNR gap is \( \Gamma = \frac{1}{3} \left( Q^{-1} \left( \frac{\text{SER}_{4}}{2} \right) \right)^{2} \). Thus, using the above capacity expressions, we can find a SNR threshold for a given channel environment for judging the preference of choosing HS-OQAM or DMT and this SNR threshold is further corresponding to a throughput threshold. The resulting thresholds are layout in Tab. I, where the calculation parameters are based on HomePlug AV specifications [4] (the notches are not taken into account), i.e. \( M = 3072 \); sampling frequency 75 Mhz; CP length for DMT 417 samples. Furthermore, we consider the realistic in-home PLC channel models, presented in [5], from channel class 2 to 9. Note that the SNR in Tab. I is in corresponding to the received SNR value.

<table>
<thead>
<tr>
<th>Throughput (Mbits/s)</th>
<th>class 2</th>
<th>class 3</th>
<th>class 4</th>
<th>class 5</th>
<th>class 6</th>
<th>class 7</th>
<th>class 8</th>
<th>class 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR (dB)</td>
<td>236.8</td>
<td>243.5</td>
<td>260</td>
<td>294.9</td>
<td>322.3</td>
<td>454.7</td>
<td>500.4</td>
<td>591.6</td>
</tr>
</tbody>
</table>

**TABLE I**

THRESHOLD LOOKUP TABLE W.R.T. IN-HOME PLC CHANNELS.

III. **Unified Modulator**

So far, we have shown the throughput/SNR threshold value. Now the question is how to find a way to arbitrarily switch from HS-OQAM to DMT or reverse? Fortunately, in our recent paper [6], we proposed a unified transceiver that can generate DMT, HS-OQAM and WOFDM using the fast cosine/sine transform with type I (FCT/FST-I). The advantages of this system are that it can not only provide the modulation diversity as we discussed above but also can solve the dual physical layer controversy occurred in IEEE P1901 draft standard. The transform kernel of our unified modulator uses FCT/FST-I writing as

\[
[FCT]_{k,n} = \cos \left( \frac{kn \pi}{2N} \right) \text{ and } [\text{FST}]_{k,n} = \sin \left( \frac{kn \pi}{2N} \right),
\] (6)

the idea of using FCT and FST kernel was inspired by the paper [7] where the authors showed that, thanks to the Lee’s fast algorithm [8], using FCT and FST can reduce around 80% the complexity of the case when using traditional Cooley-Tukey algorithm of FFT. The unified modulator structure is depicted in Fig. 1, where a modulation select (MODSEL) parameter is introduced for controlling the desired modulation scheme and the selection rule can refer to the above lookup table. For each modulation scheme chain, it consists of a pre-processing block, a transform kernel block and a post-processing block. Each block has its particular function and the mathematical derivation of each block can be found in [6]. In Fig. 2, we plot the throughput comparisons for PLC channel class 2, 6 and 9 when the unified modulator is utilized compared with individual DMT or HS-OQAM scheme. The results give us a clear view of the modulation diversity gain.
Fig. 2. Throughput comparison among DMT, HS-OQAM and Unified modulator for class 2, 6 and 9.

REFERENCES