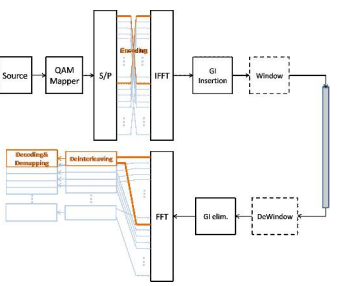


Abstract

Broadband PLC channels represent from the transmission point of view an highly hostile environment due to their high frequency selectivity and the high RMS delay spread, the presence of impulsive noise and the narrow band interferences from the radio channel. On the other hand they are almost static channels because the variations are mainly due to the insertion or removal of a node in the power network with a change in the state of switches and this kind of changes occurs in a slow time basis of the order of second to minutes. THYIA's research work aimed at the investigation of the effects of the introduction of a diversity technique such as the algebraic rotations, and windowed cosine OFDM (WC-OFDM) pulse shaping. Influence of PAR is investigated too. The implementation of 1Gbit/s PLC modem with turbo encoding is considered.

Tx & Rx simulation model



The implemented chain is represented in Figure 1. Algebraic Rotation and Component Interleaver is presented with the orange colored part in the picture. Cosine windowing and de/windowing is presented by dashed lines. The Decoding & Demapping phase has been realized through Sphere Decoder algorithm of the dimension of the matrix R of the rotation.

Figure 1: The simulation model.

The key concept of algebraic rotations is a coded modulation with high Hamming distance and product distance among codewords in order to improve diversity and coding gain. The key features of these codes include full diversity (i.e. Hamming distance equal to the space dimension) and minimum product distance independent of the constellation size. It allows to achieve ML decoding on this dimension and so the full diversity offered by the code with a lower complexity with respect to the straightforward ML detection. Sphere decoder algorithm has also demonstrated its strength for fixed point implementation and little dimension as the number proposed for this purpose is perfectly feasible for hardware implementation.

Algebraic Diversity Rotation

The PLC channel with WC-OFDM can be considered as a fading channel and modeled as a set of n parallel AWGN channels with individual complex channel gains h_i each one represented by the different sub-carriers. In such a case we say the channel has a diversity order of n . We can model *underground* channels by a covariance matrix:

$$R = [R_{ij}] \text{ for } i, j = 0, \dots, n-1$$

The effect of this correlation is to reduce the effective channel diversity below n . We assume that each of the n QAM symbols s_0, s_1, \dots, s_{n-1} corresponding an OFDM symbol $x = [s_0, s_1, \dots, s_{n-1}]$ is encoded in a codeword ε as:

$$\begin{bmatrix} \text{Re}(\varepsilon_i) \\ \text{Im}(\varepsilon_i) \end{bmatrix} = \begin{bmatrix} \text{Re}(s_i) \\ \text{Im}(s_i) \end{bmatrix} \text{ for } i = 0, \dots, n-1$$

Given a pair of codewords ε and w , we define the modulation diversity L as the Hamming distance between the vectors ε and w and the L -minimum product distance is:

$$d_{\min}^L(\varepsilon, w) = \prod_{i=1}^L |v_i - w_i|$$

The n codeword ε are then assigned to nN groups, where N is the interleaver degree, so that the subcarriers in each group are as far as possible in order to guarantee the statistical independence of their fading factors, a simple method can be in a comb fashion. The sent signal on the i -th subcarrier of the j -th group would then be:

$$P^j = \text{Re}(X^j) + j * \text{Im}(X^j) \text{ for } i = 0, \dots, N-1, j = 0, \dots, \frac{N}{n}-1$$

The received signal on the i -th subcarrier of the j -th group is given by:

$$Y_i^j = h_i P^j$$

We assume coherent detection, i.e., the channel coefficients $h_i = |h_i| e^{j\theta_i}$ are known to the receiver, then the receiver can remove the channel phase rotations by equalization and obtain:

$$\tilde{Y}_i^j = h_i^* Y_i^j / |h_i| = |h_i| P^j$$

In order to perform the detection the signal must be reconstructed with his two original parts:

$$M^j = \begin{bmatrix} \text{Re}(\tilde{Y}_i^j) \\ \text{Im}(\tilde{Y}_i^j) \end{bmatrix}$$

The maximum likelihood detection can then be obtained solving, as an example with the use of a 2-level sphere decoder on each symbol, as we did for our simulations the following expression:

$$\begin{bmatrix} \text{Re}(\tilde{Y}_i^j) \\ \text{Im}(\tilde{Y}_i^j) \end{bmatrix} = \underset{s_{opt}}{\text{argmin}} \begin{bmatrix} |h_i| & 0 \\ 0 & |h_i| \end{bmatrix} \begin{bmatrix} s_{opt} \\ s_{opt} \end{bmatrix} \text{ RLS}$$

Complexity considerations

- Turbo**
 - Beside the performances of the code
 - Absolutely requested parameters:
 - Number of states of the convolutionals
 - Turbo structure (Binary / Duo-binary)
 - Interleaver law
 - Block length
 - Number of Iterations
 - Maximum rate
- Example: Duo-binary turbo (I)**
 - Some speculation on a duo-binary turbo as that used in FT simulation
 - Asymptotic throughput with one SISO:

$$\frac{1}{\log_2 \left(\frac{1 + \sqrt{1 + 4P}}{2} \right)} \approx \frac{1}{\log_2 2} = 1$$
 - Coarse evaluation of the number of parallel SISO to achieve 1Gbit/s imposing $f_{ch} = 100$ MHz, at least 80 SISO
 - Throughput with more SISO's in parallel
- Turbo parameter (I)**
 - Number of state: usually a small number 4-8
 - Turbo structure and kind (serial vs. parallel, binary vs. non-binary)
 - A serial rather than a parallel structure seems not to affect too much the complexity and the throughput
 - Binary structure has approx. 1/3 of the complexity of a duo-binary, duo binary allow to double the throughput with the same frequency
- Example: Duo-binary turbo (II)**
 - Memories
 - Input/output and communication buffers:
 - Linear with block-length and data representation bit #
 - SISO buffers.
 - Depend also on window dimension
 - Example with max. BL=2400, bit #=8, window=32, P=1 => 1.163 Mbit
 - SISO area
 - Example each SISO employs 37KGate
 - This area must be multiplied by P (parallelism)
 - FFT choices
 - Different choices for internal processor architecture (depend also on the subcarrier #)
 - Radix 2
 - Radix 4
 - Radix 8
 - Split radix
 - ...
 - Different pipeline processor architectures
 - Multi-path delay combinator
 - Single-path delay feedback
 - Equalization
 - The presence of this block is dependent on the multicarrier modulation technique that will be employed
 - Its complexity could be relevant in the development of the receiver
 - PAR consideration
 - Peak to average ratio (PAR) is a parameter of high importance for hardware implementation of a PLC modem due to energy savings with a tolerable PAR that is offered by WC-OFDM.
- Turbo parameter (II)**
 - Interleaver law: very critic parameter
 - It must be performable on the fly
 - It must guarantee a collision free access into memories
 - Block length:
 - It affects linearly the dimensions of the memories
 - It affects the number of SISO which can be placed to work in parallel
 - Number of Iterations
 - Obviously it affects the throughput of the Turbo decoder
 - Feasibility analysis: open issues
 - Great request of details in the outlined blocks and in the overall architecture (algorithmic choices etc. - Some details that can come also from higher levels):
 - FEQ type and parameters
 - # of subcarriers
 - Presence of ARQ, HARQ etc.
 - maximum latency of the system, maximum round-trip time if ARQ
 - Update frequency of the channel estimation and consequently of the power allocation
 - Fixed-point simulation

The simulation results

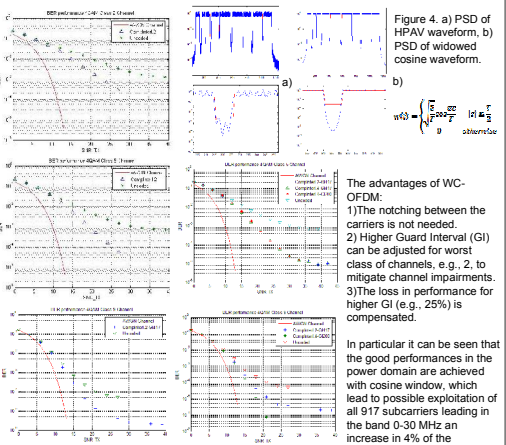


Figure 2. BER curves with rotated QAM and CI on 2 subcarrier for three class of channels, 2, 5 and 9.
 Figure 3. BER curves with rotated QAM and CI on 4 subcarrier for two class of channels 5 and 9.
 Figure 4. a) PSD of HPAV waveform, b) PSD of windowed cosine waveform.

The advantages of WC-OFDM:
 1) The notching between the carriers is not needed.
 2) Higher Guard Interval (GI) can be adjusted for worst class of channels, e.g., 2, to mitigate channel impairments.
 3) The loss in performance for higher GI (e.g., 25%) is compensated.

In particular it can be seen that the good performances in the power domain are achieved with cosine window, which lead to possible exploitation of all 917 subcarriers leading in the band 0-30 MHz an increase in 4% of the throughput with respect to the HPAV window.