Digital Signal Processing ••• (••••) •••–•••

Contents lists available at ScienceDirect

Digital Signal Processing

www.elsevier.com/locate/dsp

Digital filters for clustered-OFDM-based PLC systems: Design and implementation

Vinícius Lagrota R. da Costa [a,b], Hugo Viveiros Schettino [a], Ândrei Camponogara [a], Fabrício P.V. de Campos [a,b], Moisés Vidal Ribeiro [a,b]

[a] LCom – Communications Laboratory, Electrical Engineering Department, Federal University of Juiz de Fora (UFJF), Brazil
[b] Smarti9 Ltda, Juiz de Fora, MG, Brazil

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Power line communication
Digital filters
Digital communication
Orthogonal frequency-division multiplexing

ABSTRACT

This work aims to investigate the design and implementation of digital filters for separating clusters in a clustered-orthogonal frequency-division multiplexing scheme for power line communication systems. In this regard, we formulate the mathematical problem and present a criterion which is capable of searching for digital filters that maximizes data rate. In the following, several finite impulse response and infinite impulse response digital filters are analyzed in order to validate the proposed criterion and to verify the best one which fulfills the given constraints. Furthermore, regarding only the best digital filters obtained, a finite precision and complexity analyses are carried out by using a field-programmable gate array device. Based on numerical results, we show that finite impulse response equiripple minimum phase and infinite impulse response Chebyshev type II digital filters yield the best data rates among the chosen digital filters. Moreover, we point out that equiripple minimum phase digital filters consume more hardware resources than Chebyshev type II digital filters, although the first one deal better with the field-programmable gate array constraints when more bits are used to implement the digital filter. Due to that, finite impulse response digital filters are more indicated to be implemented in a field-programmable gate array device.

1. Introduction

Power line communication (PLC) technologies have been widely investigated in the last few decades since they allow the use of electric power networks infrastructures as a medium for data communication [1–3,?,4–10,?]. However, they are a harsh medium, due to time-varying behavior provoked by loads dynamics; electromagnetic interference associated with the use of unshielded power cables; significant signal attenuation with the distance and frequency increases; channel frequency selectivity associated with multi-path signal propagation; impedance mismatching at the branching point and at the loading connection point; and high power impulsive noise yielded by switching devices [11].

To deal with some of these issues, orthogonal frequency-division multiplexing (OFDM) scheme has been successfully applied [12]. Also, the orthogonal frequency-division multiple access (OFDMA) scheme has been investigated [13–15]. A drawback of OFDMA is the high complexity of the transceiver at the physical layer because one OFDM symbol covers all the frequency bandwidth. In order to overcome this weakness of OFDMA, the clustered-OFDM scheme was investigated [16–21].

The clustered-OFDM scheme offers low computational complexity in the user's transceiver and in the PLC concentrator (PLC base station). The frequency bandwidth in the user's transceiver is much smaller than in the PLC concentrator, resulting in several advantages, such as the use of discrete Fourier transform (DFT) with short length and low clock frequency, see [20] for details. Besides, it needs only a single-channel analog-to-digital converter (ADC) and digital-to-analog converter (DAC) device to perform both baseband and passband data communication which is a remarkable advantage. Basically, the clustered-OFDM consists of several OFDM schemes operating in parallel so that each one occupies a distinct frequency bandwidth, named cluster, which may reduce the clock speed of a PLC transceiver. Also, the oscillators are not needed for both passband modulation and demodulation because they are implemented with very simple digital signal processing (DSP) tools.

E-mail addresses: vinicius.lagrota@engenharia.ufjf.br (V.L.R. da Costa), hugoschettino@gmail.com (H.V. Schettino), acamponogara@gmail.com (Â. Camponogara), fabricio.campos@ufjf.edu.br (F.P.V. de Campos), mribeiro@engenharia.ufjf.br (M.V. Ribeiro).

http://dx.doi.org/10.1016/j.dsp.2017.08.004

Base on that, [22] discussed a prototype of a broadband PLC system for outdoor application which uses the clustered-OFDM scheme.

As the clustered-OFDM is a new scheme for designing PLC systems, several issues such as symbol synchronization, clock frequency offset estimation and correction, carrier frequency offset estimation and correction, resource allocation, and digital filters design need to be deeply investigated. Regarding the design of digital filters, we point out the lack of works which address data rate maximization with minimum hardware complexity. In fact, the digital filter design has not been properly discussed in the literature yet, having in mind that it can directly affect the clustered-OFDM-based PLC system performance.

This work aims to discuss important issues related to the design of finite impulse response (FIR) and infinite impulse response (IIR) digital filters for clustered-OFDM scheme for PLC systems. Based on a proposed criterion, we investigated the influence of digital filters choice on data rate. Also, hardware constraints associated with the use of field-programmable gate array (FPGA) device are addressed [23]. A brief introduction of our research was firstly published in [21]. Different from [21], this work provides comprehensive descriptions and analyses that precisely address the necessity of correctly design digital filters for clustered-OFDM scheme. The main contributions of our work are summarized as follows:

- Introduction of a criterion that is capable of searching for the best digital filters for a clustered-OFDM-based PLC system in both indoor and low-voltage outdoor scenarios. To do so, the achievable data rate based on multichannel signal-to-noise ratio (mSNR) and length of cycled prefix are chosen for decision making.
- Cost analyses for the best digital filters comparing the use of resources versus gain in data rate in order to guide practitioners. Also, a hardware analyses and comparison between second-order sections (SOS) and Lattice structures for IIR digital filters, focusing mainly on the computational complexity cost. Furthermore, analyses and comparison between the hardware resource usage of digital filters implemented in an FPGA device.

Based on the attained results and the chosen set of digital filters we point out that the effective length of the chosen digital filters is the main parameter that must be considered in order to maximize data rate because the SNR associated with distinct digital filters shows small differences. Also, we state that the best FIR and IIR digital filters are, among the chosen ones, equiripple minimum phase (EMP) and Chebyshev type II (CHII) digital filters, respectively. Furthermore, CHII digital filters achieve higher data rates than EMP digital filters. Regarding the hardware resource usage, IIR digital filters need less computational complexity to achieve the same data rate in the same conditions than FIR digital filters. Moreover, based on FPGA implementation analyses, we verify that due to its higher computational complexity, the SOS structure, used in CHII digital filters, needs more hardware resources than the type 1 and 2 linear-phase FIR digital filter, used to design the EMP. Because of that some CHII digital filters may not comply with restrictive hardware resource availability. Overall, we point out that the choice of digital filter for clustered-OFDM must be carefully based on a given criterion and hardware that will be used to implement it.

The rest of this paper is organized as follows: Section 2 addresses the problem formulation; Section 3 describes the design approach considered in this work; Section 4 discusses the numerical results; and, finally, Section 5 presents some concluding remarks.

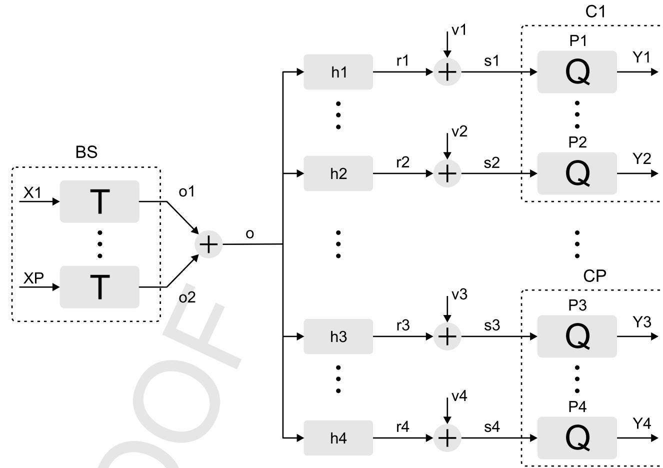

Fig. 1. Clustered HS-OFDM scheme: the downlink data communication.

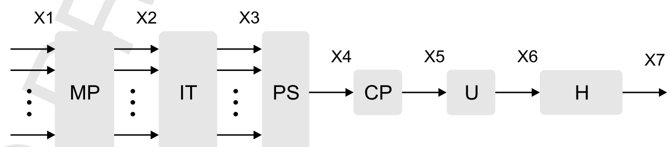

Fig. 2. Block diagram of the transmitter.

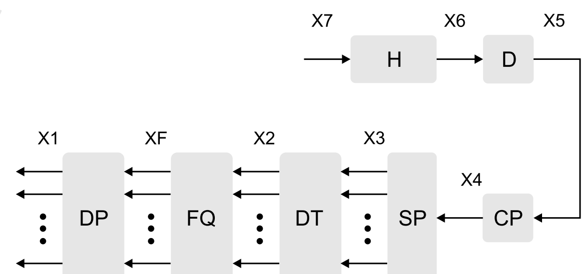

Fig. 3. Block diagram of the receiver.

2. Problem formulation

Let a clustered hermitian symmetric OFDM (HS-OFDM) scheme in the downlink direction be represented by the block diagram in Fig. 1 [20]. The PLC concentrator makes use of $P \in \mathbb{N}^+$ clusters to communicate with PQ users. A set of $Q \in \mathbb{N}^+$ users is allocated to each cluster, and each cluster occupies a frequency bandwidth B/P, where $B \in \mathbb{R}^+$ is the total bandwidth available for data communication. The transmitter $\mathcal{T}$ and the receiver $\mathcal{R}$ can be depicted by the block diagrams as shown in Figs. 2 and 3, respectively.

At the transmitter, $\mathbf{X}_p \in \mathbb{C}^{N\times 1}$ is the output of a digital modulator, in which p denotes the pth cluster, $N \in \mathbb{Z}_+$ is the number of sub-carriers of the HS-OFDM scheme. Before be processed by the inverse discrete Fourier transform (IDFT), $\mathbf{X}_p$ is mapped into a vector denoted by $\mathbf{X}_{map,p} = [X_{map,p}[0]\ X_{map,p}[1]\ \ldots\ X_{map,p}[2N-1]]^T$, according to the following rule:

$$X_{map,p}[k] = \begin{cases} X_p[k-1], & k = 1,\ldots,N-1 \\ \Re\{X_p[N-1]\}, & k = 0 \\ \Im\{X_p[N-1]\}, & k = N \\ X_p^*[2N-k-1], & k = N+1,\ldots,2N-1 \end{cases} \tag{1}$$

where $\Re\{\cdot\}$ and $\Im\{\cdot\}$ are the real and imaginary parts, respectively, of a given number, and $\{\cdot\}^*$ denotes the complex conjugate operator.

Please cite this article in press as: V.L.R. da Costa et al., Digital filters for clustered-OFDM-based PLC systems: Design and implementation, Digit. Signal Process. (2017), http://dx.doi.org/10.1016/j.dsp.2017.08.004