A Low-Complexity Spectral Shaping Method for OFDM Signals with Dynamically Defined Emission Mask: Optimization Procedure

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***Abstract*—The low spectral confinement of orthogonal frequency division multiplexing (OFDM) signals obliges OFDM-based power line communications (PLC) systems to use out-of-band emissions (OOBE) reduction methods in order to comply with electromagnetic compatibility (EMC) regulations. This work proposes a computationally simple optimization procedure that yields a versatile set of solutions to shape the spectrum of OFDM signals regardless of the location and width of its passbands.**

I. INTRODUCTION

In-home broadband power line communications (PLC) systems in Europe have to comply with the EN 50561-1 [1], which defines multiple permanent and dynamically excluded subbands. Most PLC systems employ orthogonal frequency division multiplexing (OFDM) and need to null a significant number of data carriers by the edges of these subbands to comply with [1], which penalizes the data rate.

Among the pleiad of methods that have been proposed to reduce the out-of-band emissions (OOBE) of OFDM signals, pulse-shaping, active interference cancellation (AIC) and adaptive symbol transition (AST) are of particular interest as they do not require modifying the receiver's operation [2] [3].

In [4] the aforesaid techniques were combined yielding a pulse, referred to as generalized pulse, that is designed offline and that yields larger OOBE reductions than other methods of the same kind. The work in [5] proposed a modified version of the generalized pulses and an optimization strategy that allows computing a solution that can be adapted online, by means of computationally simple transformations, to comply with dynamic changes in the emission mask.

This work uses the modified version of the generalized pulses and the transformations in [5] and proposes an alternative optimization method for the calculation of its coefficients.

II. BACKGROUND

The discrete-time low-pass expression of an OFDM signal can be expressed as

$$x(n) = \sum_{u=-\infty}^{\infty} \sum_{k\in\mathcal{D}} p_k(n-uN_\mathrm{s})s_k(u) \tag{1}$$

where $s_k(u)$ is the data symbol and $N_\mathrm{s} = N + N_\mathrm{GI}$ is the OFDM symbol period, being N the size of the discrete Fourier transform (DFT) and N_GI the number of samples in the guard interval. Using matrix notation, the basic pulse can be expressed as $\mathbf{p}_k = [p_k(0), \ldots,\ p_k(L-1)]^\mathrm{T}$, where $L = N_\mathrm{s} + \beta$, with β being the number of tapered samples at the beginning and at the end of $p_k(n)$.

To reduce the OOBE of (1), the basic pulse is replaced with the modified generalized pulse proposed in [5] in those data carriers located by the borders of the passbands. The indices of these data carriers are in the set $\mathcal{D}^\mathrm{h} \subset \mathcal{D}$. The expression of the modified generalized pulse is,

$$\mathbf{h}_k^{(i,j)} = \mathbf{p}_k + \underbrace{\mathbf{C}_{k-i}^{+}\boldsymbol{\alpha}_k^{(i)} + \mathbf{t}_k^{(i)}}_{\mathbf{r}_k^{(i)}} + \underbrace{\mathbf{C}_{k-j}^{-}\boldsymbol{\alpha}_k^{(j)} + \mathbf{t}_k^{(j)}}_{\mathbf{r}_k^{(j)}},\quad \begin{matrix} i>0, \\ j<0 \end{matrix} \tag{2}$$

where the superindex $i > 0$ denotes that carrier k is the i-th one above the left edge (located at $k-i$) of the passband and $j < 0$ that it is the j-th one below the right edge (located at $k-j$). The matrix $\mathbf{C}_l^{+} = [\mathbf{p}_{l-N_\mathrm{co}}, \ldots, \mathbf{p}_l, \ldots, \mathbf{p}_{l+N_\mathrm{ci}}]$ is an $L \times N_\mathrm{CC}$ matrix comprising the set of cancellation carriers (CC) placed around the left edge of the passband. The matrix $\mathbf{C}_l^{-}$ is the conterpart of $\mathbf{C}_l^{+}$ for the right edge of the passband. The AST terms $\mathbf{t}_k^{(i)}$ and $\mathbf{t}_k^{(j)}$, referred to as transition pulses, are vectors of L samples used to shape the initial and final time-domain samples of the pulse.

The values of the $N_\mathrm{CC} \times 1$ vectors $\boldsymbol{\alpha}_k^{(i)}$ and $\boldsymbol{\alpha}_k^{(j)}$ and of $\mathbf{t}_k^{(i)}$ and $\mathbf{t}_k^{(j)}$ are optimized to minimize the OOBE of the compound pulse. The optimization is accomplished offline to lower the OOBE in a predefined subband and can be adapted online to changes in the emission mask by means of the simple transformations in [5, Expr. (22) and (24)].

III. PROPOSED OPTIMIZATION

This section proposes an optimization procedure of the terms in (2), alternative to the one in [5]. The coefficients of the OOBE reduction terms $\mathbf{r}_k^{(i)}$ and $\mathbf{r}_k^{(j)}$ are independently optimized. Moreover, since the coefficients of both terms are related through [5, Expr. (22) and (24)], only one optimization process has to be performed. In the following, only the steps corresponding to the optimization of $\mathbf{r}_k^{(i)}$ are described.

Let us consider an OFDM signal with carriers indexed from $k \in \{-\frac{N}{2}, \dots, \frac{N}{2}-1\}$. The number of active carriers is N_{D}, starting at index $k=1$. The OOBE is to be lowered in the two notched bands defined as *contiguous notched band*, denoted by $\mathcal{B}_{\mathrm{c}} = \left\{-\frac{N}{2}, \dots, 0\right\}$, and *opposite notched band*, denoted by $\mathcal{B}_{\mathrm{o}} = \left\{N_{\mathrm{D}}+1, \dots, \frac{N}{2}-1\right\}$. To this end, N_{h} consecutive carriers use the modified generalized pulse by each edge of the passband.

The proposed procedure starts by considering a passband with a minimum bandwidth of $N_{\mathrm{D\_min}}$ carriers and by determining the optimum coefficients of $\boldsymbol{\alpha}_k^{(i)}$ and $\mathbf{t}_k^{(i)}$ that minimize the OOBE of $\mathbf{p}_k + \mathbf{r}_k^{(i)}$ in $\mathcal{B}_{\mathrm{c}}$ and the one of $\mathbf{r}_k^{(i)}$ in $\mathcal{B}_{\mathrm{o}}$,

$$\begin{bmatrix} \widehat{\boldsymbol{\alpha}}_k^{(i)} \\ \widehat{\mathbf{t}}_k^{(i)} \end{bmatrix} = \arg \min_{\boldsymbol{\alpha}_k^{(i)}, \mathbf{t}_k^{(i)}} \left\{(1-a)E_{k,\mathcal{B}_{\mathrm{c}}}^{(i)} + aE_{k,\mathcal{B}_{\mathrm{o}}}^{(i)}\right\}, \tag{3}$$

where a has to be tuned to attain the best performance, and

$$E_{k,\mathcal{B}_{\mathrm{c}}}^{(i)} = \int_{\mathcal{B}_{\mathrm{c}}} \left|P_k(f) + R_k^{(i)}\right|^2 df, \quad E_{k,\mathcal{B}_{\mathrm{o}}}^{(i)} = \int_{\mathcal{B}_{\mathrm{o}}} \left|R_k^{(i)}(f)\right|^2 df. \tag{4}$$

Hence, $\mathbf{r}_k^{(i)}$ is designed to reduce the OOBE of the basic pulse in $\mathcal{B}_{\mathrm{c}}$ while generating no additional emissions in $\mathcal{B}_{\mathrm{o}}$. Provided that there are N_{ci} CC inside the passband (in-band CC) by each end on the passband, $N_{\mathrm{h\_min}} = N_{\mathrm{D\_min}} - 2N_{\mathrm{ci}}$ modified generalized pulses are optimized in the first step and the resulting coefficients are stored. Then, the passband width is increased in one carrier (to the right) and the minimization in (3) is performed for the new data carrier. The process continues until the rightmost data carrier in the passband would yield an OOBE below the required level when using the basic pulse.

Finally, the coefficients $\boldsymbol{\alpha}_k^{(j)}$ and $\mathbf{t}_k^{(j)}$, $j<0$, are obtained from $\boldsymbol{\alpha}_k^{(i)}$ and $\mathbf{t}_k^{(i)}$, $i>0$, by means of [5, Expr. (24)].

IV. NUMERICAL RESULTS

In this section the influence of the parameter $N_{\mathrm{D\_min}}$ on this performance is evaluated. To that end, the optimization is performed with the parameters $N_{\mathrm{D\_min}} \in \{5, \dots, 9\}$ and $N_{\mathrm{h\_max}} = 9$. An OFDM signal with $N = 4096$, $N_{\mathrm{GI}} = 1024$ and $\beta = 512$ is considered. The obtained coefficients are applied to two different scenarios: one consisting in a passband of width $N_{\mathrm{D\_min}}$ carriers (i.e., the narrowest one used in the optimization process) and a wider one of $N_{\mathrm{D}} = 13$ carriers. Two versions of the generalized pulse are also compared: one that only uses AIC tones and another that combines AIC and AST techniques. Three CC are used by each end of the passband: 2 inside the passband (in-band) and 1 in the notched band (out-of-band).

Fig. 1 shows the maximum value of the normalized power spectral density (PSD) attained by the proposed method in the aforementioned cases. First of all, it is clear that the combination of CC and transition pulses performs notably better than the CC alone, showing a difference that fluctuates between 6 and 12 dB.

Increasing the value of $N_{\mathrm{D\_min}}$ entails an enhancement in the obtained $\mathrm{PSD}_{\mathrm{max}}$. However, this reduces the range of passband widths where the computed pulses perform as expected, since using the pulses optimized for a range of passband widths starting at $N_{\mathrm{D\_min}}$ in narrower passbands yields larger values of $\mathrm{PSD}_{\mathrm{max}}$. Nonetheless, the solutions computed for $N_{\mathrm{D\_min}} = 7$ attain values of $\mathrm{PSD}_{\mathrm{max}}$ under -45 dB when applied to the same size of passband, which is lower than the limit of -43 dB specified for in-home broadband PLC systems in [1].

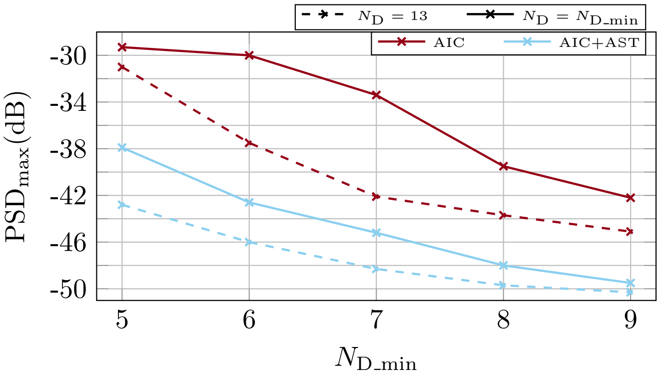

Fig. 1. $\mathrm{PSD}_{\mathrm{max}}$ in the notched band attained with the pulses in (2) when optimized with $N_{\mathrm{D\_min}} \in \{5, \dots, 9\}$ and $N_{\mathrm{h\_max}} = 9$. Two passband widths are considered: $N_{\mathrm{D}} = N_{\mathrm{D\_min}}$ and a wider one with $N_{\mathrm{D}} = 13$. Two types of modified generalized pulses are considered: one which only employs AIC and another which also includes the AST terms.

The proposed optimization method is considerably simpler than the one in [5] at the expense of a more limited performance in specially stringent situations. Nevertheless, for many applications the OOBE reduction attained by the proposed strategy is enough.

V. CONCLUSION

This work has proposed a spectral shaping method for OFDM signals that is transparent for the receiver and that can be dynamically adapted to changes in the emission mask. It is grounded in the pulses proposed in [5], for which an alternative optimization procedure has been proposed.

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