RC Windowing Scheme for Cognitive Radio OFDM Systems

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Abstract*— Current spectrum allocation policies have led to an inefficient use of the spectrum. Indeed, several measurement campaigns confirm that observation indicating that there is space to greatly improve the spectrum utilization and efficiency. To achieve this goal the concept of cognitive radio (CR) has emerged. A CR system needs to be highly flexible with respect to the spectral shape of the transmitted signal. Orthogonal Frequency Division Multiplexing (OFDM) is the favorite air-interface for CR systems; we can easily shape the spectrum. An OFDM signal is composed of a sum of many sinusoidal carriers modulated by the data symbols and windowed by raised cosine function. A Raised Cosine soft-window is designed based on the characteristics of functions with vestigial symmetry which are common in digital data transmission. By using the vestigial symmetry and requiring at the extremes of the window several null derivatives, it is possible to control a fast out-of-band decay. It will be shown that by using a lower roll-off factor the proposed window can achieve the performance of raised-cosine with around more overhead savings, making it of interest for OFDM cognitive radio.

***Keywords*—cognitive radio, OFDM, spectral leakage, windowing, vestigial symmetry.**

I. Introduction

A CR system needs to be highly flexible with respect to the spectral shape of the transmitted signal. Orthogonal Frequency Division Multiplexing (OFDM) is the favorite air-interface for CR systems, since by nulling some subcarriers we can easily shape the spectrum [1]. An OFDM signal is composed of a sum of many sinusoidal carriers modulated by the data symbols and windowed by a Raised cosine function. The application of a raised cosine window in the time domain is equivalent to the spectral shaping by the sinc pulse which leads to a spectral spreading of the transmitted signal, causing interference to systems working at adjacent channels[1,4]. To alleviate this problem several algorithms have been proposed that reduce the out-of-band radiation. The simplest is to apply a low pass filter to the transmit signal. However, this requires a very high order digital filter, which results in a high computational complexity [4]. Other techniques have been proposed, including the insertion of cancellation carriers [5], subcarrier weighting [6], adaptive symbol transition [7] Spectral precoding [8,9] and windowing [10], just to name a few. All previous schemes, with the exception of spectral precoding and windowing, resort to optimization methods to reduce the spectral leakage of OFDM and the optimization task is run in a frame by frame basis leading to a high computational overhead. In the spectral precoding technique [8, 9] a data-independent matrix is used to precode the data symbols and reduce the spectral leakage[11].

Nonetheless, the matrix operations required in both transmitter and receiver will also bring a considerable computation burden to implementation [8]. On the contrary, the time windowing technique is simpler and more computational efficient, but since the signal is extended in time domain the resulting spectral efficiency is lower[10]. In this paper we propose to design a soft-window based on the characteristics of functions with vestigial symmetry which are common in digital data transmission[12]. By using the vestigial symmetry and requiring at the extremes of the window several null derivatives, it is possible to control a fast out-of-band decay.

II. System Model

A. Scenario

Let us consider a scenario where opportunistic users share the spectrum with incumbents and both employ OFDM techniques for transmission of information. The opportunistic terminals make use of the subcarriers that are momentarily unused by the incumbents. Nevertheless, since it is assumed that the opportunistic users transmit signal is asynchronous relative to the incumbent, the subcarriers orthogonality is lost, resulting into spectral leakage from the opportunistic user into the incumbent. To avoid harmful interference of opportunistic users on the incumbent it is desirable that the power spectral density (PSD) of the incumbents' subcarriers exhibits a quick decay when out of band. The same principle applies to the interference of the incumbent over the opportunistic users, but since the incumbent is the license, it is the opportunistic user who has to guarantee non-harmful interference. To reduce the spectral leakage we propose an enhancement to conventional OFDM, where modification from a rectangular to a smooth window allows high and controlled out-of band roll-off[6].

B. Transmitter block diagram

The block diagram of the incumbent transmitter is shown in Fig. 1, where it can be seen the similarity with conventional OFDM, the only replacement being the windowing at the end of the chain, which requires a length of $(1+\beta)T_0$ for the symbol instead of T_0 in the conventional OFDM using a rectangular window[9]. β is the roll-off factor of the window. This symbol period extension implies a reduction of the transmission bit-rate.

Fig. 1. Block diagram of the transmitter with rc window

The operation performed in the windowing block, includes two main steps, as shown in Fig. 2 (upper part). Let us consider one data block (Bn). This block can be represented as the concatenation of two sub-blocksB1n and B2n , where B1n has a duration βT_0 and B2n$(1-\beta)\,T_0$. Bn is extended by appendingB1n, which leads to a block of duration $(1+\beta)\,T_0$. This extended block is then multiplied by the window which for the same roll-off β has the same duration[10]. To overcome the eventual multipath effects a time guard filled with zeros is added[8] .

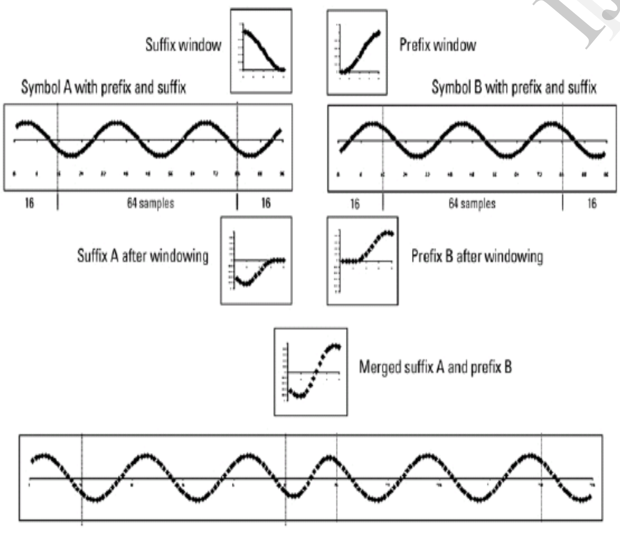

Fig. 2. Windowed OFDM processing steps in time domain.

C. Incumbent Receiver Block Diagram

At the CR receiver the operations are as illustrated in Fig. 2 (lower part). After removal of the zero prefix , the extended block is appended with zeros to meet a duration of $2T_0$ and then the second part of the block is summed to the first half, leading to the block transmitted[5]. Following these split and add operations we then have the FFT and all the conventional OFDM processing.

III. RAISED COSINE WINDOW DESIGN

As referred in the previous section, the design of the soft window is based on the characteristics of functions with vestigial symmetry[9]. The use of vestigial symmetry is motivated by the fact that these constitute orthogonal waveforms and therefore with the correct synchronization we can recover the data symbols without interference[7]. Furthermore, by requiring at the extremes of the window several null derivatives, it is possible to control a fast out-of-band decay[10]. If a limited pulse (in time or frequency according to the domain we are dealing) has its first P derivatives at the extreme points equal to zero, then the asymptotic slope in the transform domain is (by using the final value theorem) at least of the order x−2P−2 [11].

The assumptions for the signal (and consequently the window) design are:

• The normalized duration of the window is1+β, i.e. there is an extension by β of the window length compared to the conventional rectangular in order to ensure fast roll-off[9]. the function can be decomposed in a cosine series of Period 1+β,i.e.

$$\omega(t) = \begin{cases} \sum_{k=0}^{N} a_k, & |t| \le \frac{1-\beta}{2} \\ \sum_{k=0}^{N} a_k \cos\left(\frac{k\pi}{\beta}\left(|t| - \frac{1-\beta}{2}\right)\right), & \frac{1-\beta}{2} < |t| \le \frac{1+\beta}{2} \\ 0, & otherwise \end{cases} \qquad (1)$$

It is clear from (1) that for $N = 1$ and $a_0 = a_1 = 1/2$ this reduces to the RC with a roll-off of β.

The vestigial symmetry condition

$$\omega(t) + \omega(t-1) = 1, \quad \forall\ t \in]0, 1[\qquad (2)$$

implies $a_0 = 1/2$ and $a_{2k} = 0$ k ≥ 1.
It is easy to conclude from (2) that as long as $a_0 = 1/2$ and $a_{2k} = 0$ the vestigial condition is verified irrespective of the odd coefficients. Then

$$\omega(t) = \frac{1}{2} + \sum_{k=0}^{L} a_{uk} \cos\left(\frac{\pi uk}{\beta}(t - \Delta)\right), \frac{1-\beta}{2} < |t| \le \frac{1+\beta}{2} \qquad (3)$$

where L = _(N − 1)/2_, u_k = (2k + 1) |designates the floor function. The value of Δ depends on the value of t. $\Delta = \frac{1-\beta}{2}$ for $\frac{1-\beta}{2} < t \le \frac{1+\beta}{2}$ and $\Delta = -\frac{1-\beta}{2}$ for $-\frac{1-\beta}{2} < t \le -\frac{1+\beta}{2}$.
Computing the derivatives, at the extremes, using previous equation we get for the p th order

$$\omega^{(p)}(t) = \begin{cases} (-1)^{\frac{p+1}{2}} \sum_{k=0}^{L} a_{u_k} c_k^p \sin(c_k(t-\Delta)), & p \text{ odd} \\ (-1)^{\frac{p}{2}} \sum_{k=0}^{L} a_{u_k} c_k^p \cos(c_k(t-\Delta)), & p \text{ even} \end{cases} \quad (4)$$

where $c_k = \frac{\pi u_k}{\beta}$. At the endpoints $\left(t = \pm\frac{1+\beta}{2}\right)$, one gets the values

$$\omega^{(p)}\left(\pm\frac{1+\beta}{2}\right) = \begin{cases} (-1)^{1+\frac{p}{2}} \sum_{k=0}^{L} a_{u_k} (\pi u_k)^p & ,p \text{ even} \\ 0 & ,p \text{ odd} \end{cases} \quad (5)$$

Therefore to have the first M derivatives null at the endpoints one needs to ensure that the series coefficients are chosen so that they verify (Subject to the conditions that ω(0) = 1)

$$\sum_{k=0}^{L} a_{2k+1}(2k+1)^p = 0\ , p = 2,4,\ldots,2[M\backslash 2] \quad (6)$$

Note that the design conditions of equation (6)are independent
of β. As a design example, let us consider that we want the first two derivatives equal to zero (the third will also be null) and therefore design with two cosine terms. Then the conditions will be

$$\begin{cases} \frac{1}{2} + a_1 + a_3 = 1 \\ a_1 + 9a_3 = 0 \end{cases} \Leftrightarrow \begin{cases} a_1 = \frac{9}{16} \\ a_3 = -\frac{1}{16} \end{cases} \quad (7)$$

These conditions define a new pulse (NP) whose frequency domain characteristics are illustrated in Fig. 3. From this figure it is clear the out-of-band decay at 90 dB/dec, of the NP with a roll-off factor of 100%, compared to the 20 dB/dec achieved with the rectangular and 60 dB/dec with RC 100%.

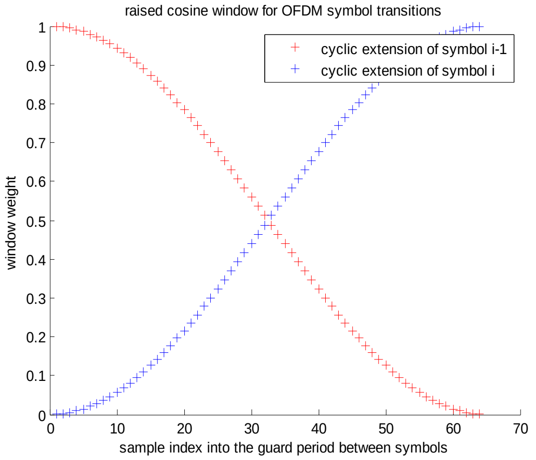

Fig. 3. Sample index into the guard period between symbols.

IV. Link-Level Performance with RC Windowing

In this section we analyze the asymptotic performance of an OFDM link with windowing included. Let us first consider the asymptotic performance with RC β[4] . To compensate for the extended length of the window one has to increase the modulation cardinality if one wants to preserve the bit rate. For a roll-off factor β the rate is decreased by a factor $1 + \beta$. If, for example, $\beta = 1$ the modulation order should be doubled so that the bit-rate is preserved, i.e. if one assumes a QPSK modulation for the rectangular window, then with the new window, with double duration, the new modulation scheme should be one with 16 symbols e.g. 16-QAM[6].

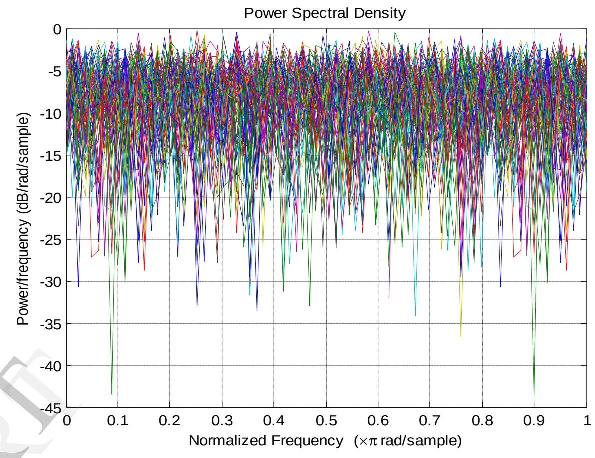

Fig . 4. Power Spectrum density of Cognitive Radio OFDM systems.

The use of a window that when normalized has values between 0 and 1 implies reduction of power. In order to obtain the values for the asymptotic performance, we consider the expression of the analogue multicarrier signal, where f_0 represents the frequency of the first carrier

$$x(t) = \sum_{k=0}^{N-1} a_k e^{j2\pi\left(f_0+\frac{k}{NT}\right)^t} \omega(t) \quad (8)$$

it is easy to deduce that by using the NP with a roll-off factor β the performance is improved by $-10\log_{10}((128-3\beta)/128)$ dB if the same modulation is used, but in this case we have a rate reduction of $(1+\beta)^{-1}$ compared to the conventional rectangular. Deciding to go from QPSK to 16-QAM we get the penalty 4+ $10\log_{10}((128-23\beta)/128)$, but gain in terms of rate by a factor of 2/(1+β). Relatively to the conventional RC with β the NP has a penalty $10\log_{10}(32(4-\beta)/(128-23\beta))$, which for β < 30% is lower than 0.1 dB and we gain an asymptotic decay going from 60 dB/dec to 90 dB/dec.

V. NUMERICAL RESULTS

In the simulations it was considered QPSK modulation, at the primary user, and 16-QAM modulation, at the secondary user. We assume a roll-off factor of 10% for the proposed pulse and have used the **G**2 matrix, from , for the spectral precoding scheme[8].

The main parameters used in the simulations, for both primary and secondary users are, FFT size of 1024; sampling frequency set to 15.36 MHz; cyclic prefix duration is 5.21 μs (80 samples); sub-carrier separation is 15 kHz. We used the ITU pedestrian channel model B, with the modified taps delays according to the sampling frequency defined on LTE standard and for comparison we also considered an AWGN channel.

In all simulations presented in this section it was assumed a delay between primary and secondary users of 8.33 μs and that the primary user uses subcarriers 1 to 256 and 769 to 1024. The ones used by the opportunistic user are from 256+GB to 768 − GB, where GB denotes the length of the

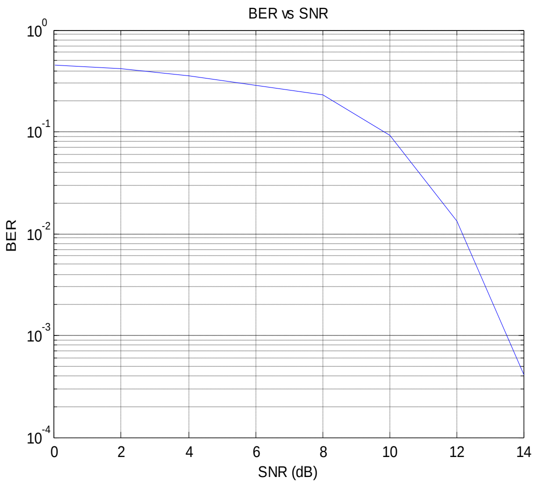

Fig. 5. BER vs SNR

guard band. It was also considered that the incumbent receiver filters the received signal with a low pass max flat FIR filter of order 30 and cutoff frequency of 0.77 MHz This filter has the function of cutting off the power of subcarriers used by opportunistic user, such that the application of a Raised Cosine window for FFT processing does not introduce power leakage into the used subcarriers, at the primary. Additionally, the filter must be designed such that its length (30 Samples) plus the channel impulse response length (39 samples) is lower than the used CP length (80 Samples).

VI. CONCLUSION

The design principles for RC windowed OFDM technique considered in this article have shown that in a simple modification of the OFDM conventional chain through a different windowing allows to control the out of band roll-off of the pulse. That is of interest for the incumbent opportunistic user paradigm, where the opportunistic user should not cause harmful interference on the primary. The combination of OFDM which is useful to identify vacant carriers, and controlled windowing which ensures no spill over of energy over used carriers, is a good solution to reuse significant part of the design used in conventional OFDM with the goal of very low energy leakage and low overhead.

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