On Spectrally Efficient Multiplexing in Cognitive Radio Systems

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Abstract—Recently, spectrum agile radios have been proposed for resolving the challenge of spectrum shortage in future wireless communications. These smart radios would monitor and sense their radio environment in order to identify spectral resources temporarily and/or spatially unused by their primary (licensed) users. This would enable opportunistic spectrum access for the secondary (unlicensed) users in case their transmissions cause no harmful interference to the primary systems. In this paper, the trade-off between the level of interference caused by secondary transmission to primary user and the spectral efficiency of secondary user is discussed in the context of cognitive radio. In particular, we analyze the influence of the choice of pulleshape used for the multicarrier modulation based overlay secondary transmission. It is shown that, with a proper choice of multicarrier scheme, spectrally efficient secondary multiplexing is possible while simultaneously minimizing the interference caused to the primary system.

I. INTRODUCTION

The future wireless communications is expected to fulfill the ever growing demands for ubiquitous broadband wireless connectivity. This seems very challenging due to apparent shortage of available spectrum, especially on lower frequencies where the signal propagation characteristics are most favorable. On the other hand, recent studies on the licensed frequency bands allocated to existing systems reveal that the conception of spectrum scarcity is mostly delusion as reports show very poor temporal and/or spatial utilization of the assigned spectral resources. To improve the efficiency of spectrum usage, an innovative dynamic spectrum access strategy, named spectrum pooling, has been proposed [1], [2]. In the concept of spectrum pooling, secondary user devices, that is cognitive radios (CRs), are allowed to transmit and receive data over portions of spectra where/when primary users are inactive provided that secondary transmissions cause no harmful interference to the licensed systems. In order to facilitate this, CRs have to regularly perform reliable radio scene analysis to detect potential primary user signals with high detection and low false alarm probability. A failure to fulfill these requirements would result in bandwidth efficiency loss in primary or secondary transmission, respectively.

In the literature, a number of spectrum sensing techniques have been discussed, which can coarsely be classified as cooperative or non-cooperative detection methods based on whether or not information from multiple CRs are incorporated for primary user detection. The different spectrum awareness schemes can further be categorized into matched filter detection, energy detection, and cyclostationary feature detection techniques, each with their individual pros and cons [3]. Approaches differ from each other in terms of implementation complexity, amount of prior knowledge required, processing gain obtained, and detection time required. In this paper, we assume that the secondary user terminals can reliably detect the spectral opportunities, spectrum holes, using one or some combination of the sensing methods mentioned. The question of interest is then how to best exploit the identified time-frequency resource slot(s) available; maximizing the spectral efficiency of the secondary transmission while simultaneously fulfilling the constraints on the level of interference to the primary bands.

The content of this paper is organized as follows: Section II defines the problem in hand. Section III briefly reviews the principles of filter bank based multicarrier modulation. In section IV, the characteristics of different prototype filters are presented. Moreover, the frequency domain model used in the interference / spectral efficiency analysis is explained. A simulation based performance evaluation of different multicarrier schemes is discussed in Section V and finally conclusions are drawn in Section VI.

II. PROBLEM STATEMENT

Multicarrier modulation techniques have been identified as a very potential choice for the physical layer implementation / design of the spectrum agile radios. The fundamental reason for the attraction is the evident flexibility to control the transmission parameters in the frequency domain. From the secondary user terminal point of view, the most crucial characteristic is the ability to perform adaptive wideband multiplexing which allows to focus the transmission power to frequency bands identified as spectrum holes.
Recently, a modulation scheme based on orthogonal frequency division multiplexing (OFDM) has been proposed as the baseband processing core to CRs [2]. In the CR context, OFDM provides means to perform the required dynamic overlay wideband transmission where parts of the bandwidth occupied by the primary and/or other secondary users can be protected simply by turning off the transmission on the respective subcarriers. The concept of opportunistic spectrum sharing using multicarrier modulation based secondary transmission is illustrated in Fig. 1.

Despite the fact that OFDM provides a number of advantages, such as inherent multiple access mechanism, robustness to multipath propagation, and benefits of frequency diversity, it might not be the optimal choice in the CR setting. In [4], the authors name a few potentially crucial limitations. These shortcomings originate from the large sidelobes of the frequency response of the subcarrier filters (the first sidelobe of a subchannel response is only 13 dB below the mainlobe). In a CR system, this may lead to intolerable interference to primary users and other asynchronous secondary users unless specific frequency domain guard bands are introduced between different band allocations. However, these guard bands would effectively reduce the bandwidth efficiency and the throughput of the secondary system, resulting in a condition which is in contradiction with the fundamental goal of CR.

Interestingly, there exist multicarrier modulation techniques based on filter banks that could inherently provide means to overcome the limitations of FFT-based OFDM in a CR environment [5]. The performance gain of the filter banks is based on the improved frequency concentration of the prototype filter, a property which is inherited also by the constructed multicarrier signal. This will enable allocation of the filter bank synthesized secondary multiplexes closer to the active primary user and/or other secondary user bands while fulfilling the constraints of the interference level.

III. FILTER BANK BASED MULTICARRIER MODULATION

Filter bank based multicarrier modulation techniques utilize modulated transmultiplexers to channelize the wide signal band. Synthesis and analysis filter banks are used to implement the modulator and the demodulator at the transmitter and receiver side of the communication link, respectively. The distinctive feature, with respect to IFFT/FFT blocks utilized in the conventional OFDM, is the ability to introduce efficient pulse shaping through the use of non-rectangular prototype filter, length of which extends over multiple symbol periods.

Here, our analysis focuses on critically sampled \(M\)-subchannel transmultiplexers since they enable both maximal spectral efficiency and efficient implementation. Moreover, when combined with a prototype filter designed for \(M/2\)-subchannel cosine modulated filter bank, so-called perfect reconstruction (PR) condition can be fulfilled (i.e., the output signals are just delayed versions of the corresponding input signals). The critically sampled transmultiplexers based on the modified DFT (MDFT) filter banks [6], [7] and the exponentially modulated filter banks (EMFBs) [8] can be observed to be very closely related. The main differences are in the subchannel stacking arrangements and the required pre/post-processing.

In a MDFT transmultiplexer, the subchannel filters are obtained by uniformly frequency shifting a single symmetric lowpass prototype filter \(h_p[n]\), i.e., the synthesis and analysis filters are defined according to

\[
    f_k[n] = h_p[n]e^{j\left(\frac{2\pi k}{N}(n-\frac{1}{2})\right)} \quad (1)
\]

and

\[
    h_k[n] = f_k^*[N - n] = h_p[n]e^{j\left(\frac{2\pi k}{N}(n-\frac{1}{2})\right)}, \quad (2)
\]

where \(k = 0, 1, \ldots, M - 1\) and \(n = 0, 1, \ldots, N\). Here, \(M\) and \(N\) are the number of subcarriers and the filter order, respectively. An efficient synthesis filter bank structure is shown in Fig. 2. It can be noticed that the pre-processing section is structurally similar to an offset QAM (OQAM) modulation [7]. Therefore, the MDFT filter bank based multicarrier scheme is also referred to as OFDM/OQAM. The additional multipliers \(\beta_k = e^{-j\left(\frac{2\pi k}{N}\right)}\) are due to the utilized modulation sequence in (1) and the polyphase filter section is based on type-1 polyphase filters, i.e., \(g_k(m) = h_p(mM + k)\).

IV. INTERFERENCE ANALYSIS

Here, we analyze the following multicarrier schemes in the CR setting based on the used prototype filters:

1) **OFDM without a cyclic prefix (CP)**

The prototype filter is a rectangular window

\[
    h_{p1}[n] = 1, \quad n = 0, 1, \ldots, M - 1. \quad (3)
\]

2) **OFDM with a CP**

The prototype filter is a temporally extended version of \(h_{p1}[n]\), i.e.,

\[
    h_{p2}[n] = 1, \quad n = 0, 1, \ldots, T - 1, \quad (4)
\]
where $T = L_{CP} + M$ with $L_{CP}$ being the length of the CP in samples.

3) Raised cosine (RC) windowed OFDM

The adjacent channel leakage can be reduced by multiplying the OFDM symbols with a RC window before transmission. For simplicity, this extra windowing is modeled here with the prototype filter defined in [4]

$$h_{p3}[n] = \begin{cases} \frac{1}{2} + \frac{1}{2} \cos \left( \pi + \frac{\pi n}{T} \right), & 0 \leq n < \beta T \\ 1, & \beta T \leq n < T \\ \frac{1}{2} + \frac{1}{2} \cos \left( \frac{\pi (n-T)}{T} \right), & T \leq n < (1 + \beta)T. \end{cases} \quad (5)$$

The considered rolloff values are $\beta = \{0.1, 0.25, 0.50, 0.75, 1.0\}$ that correspond to the prototype filters $h_{p3a}[n]$, $h_{p3b}[n]$, $h_{p3c}[n]$, $h_{p3d}[n]$, and $h_{p3e}[n]$, respectively.

4) PR MDFT transmultiplexer

An efficient method to design $KM$-length PR prototype filters is presented in [9] ($K$ denotes a positive integer called overlapping factor). The prototype filter is expressed using special lattice rotation angles. The lattice structure automatically guarantees the PR property leading to unconstrained optimization. The selected optimization criterion is the minimization of the stopband energy of the prototype filter. In the proposed multi-step technique, the number of subchannels is gradually increased and the result of the previous step is used as a start-up solution for the present step. The prototype filter $h_{p4}[n]$ can be generated using the optimized lattice rotation angles. Due to the recursive procedure, there is no simple closed-form representation for the prototype filter.

5) Nearly PR (NPR) MDFT transmultiplexer

An interesting design method for NPR prototype filters is presented in [10]. The coefficients of the prototype filter can be determined without optimization using the following equation:

$$h_{p5}[n] = 2 \sum_{\ell=0}^{K-1} A_{\ell} \cos \left( \frac{2\pi n \ell}{N} \right), \quad n = 0, 1, \ldots, N - 1, \quad (6)$$

Here, it is defined that $N = KM$. The reported frequency-weighting coefficients $A_{\ell}$ can provide prototype filters with low sidelobe levels. This results in significantly improved stopband performance while the resulting reconstruction errors remain relatively small. In [11], it is shown that the proposed design technique can also be interpreted as a frequency sampling method.

The overall spectral decay behavior of different prototype filters can be seen from Fig. 3, whereas Fig. 4 shows the details of the mainlobe, transition band, and some of the first sidelobes.

The interference caused by a secondary user transmission to a primary system is analyzed using the generic frequency domain model shown in Fig. 5. The principal idea is to use the frequency response(s) of the prototype filter $H_{pi}(e^{j\omega})$ and a frequency domain mask $F_{mask}(e^{j\omega})$ (with unity gain in the passband) to model the secondary user signal and the primary receiver, respectively. The normalized cumulative interference power leaking into the primary user band is obtained by numerically integrating over the mask-weighted power density spectrum (PDS) of the sidelobes within the receiver mask:

$$P_{I}(i, d, L) = \sum_{l=1}^{L} \int_{-\omega_s}^{\omega_s} \left| H_{pi}(e^{j(\omega + \frac{\omega_s}{2} + dl)}) F_{mask}(e^{j\omega}) \right|^2 d\omega, \quad (7)$$

where $i = 1, 2, \ldots, 5$ and the summation is done over all the active subcarriers in the interfering secondary signal multiplex. The overall power of the prototype filters is normalized to
unity, i.e., $\int_{-\pi}^{\pi} |H_{p,i}(e^{j\omega})|^2 = 1$, for all $i$. The model is generic in a sense that one has control on the following:

1) Selection of the prototype filter $h_{p,i}[n]$ to model different secondary multicarrier schemes.
2) Type of the receiver mask $F_{mask}(e^{j\omega})$ to model alternative primary systems.
3) The distance $d$ between the center frequency of the last active (band edge) subcarrier in the secondary signal multiplex and the reference point $f_r$ of the receiver mask to model the influence of the guard band. Here, $f_r$ is defined as the center frequency of the transition band between the passband edge and the first breakpoint of the receiver mask.
4) The number of active subcarriers $L$ to model the cumulative interference contribution from the neighboring subcarriers.

In the forthcoming analysis, we consider (a) the ideally bandlimited mask of width equal to 312.5 kHz that corresponds to the subcarrier spacing in the OFDM based IEEE 802.11 standard, (b) the transmission emission mask defined in the DVB-T [12] and (c) in the WLAN [13] specifications (see Table I for details).

V. NUMERICAL RESULTS

The sampling rate of $F_s = 30$ MHz and a filter bank consisting of $M = 1024$ subcarriers was used in the simulations. This corresponds to a subcarrier spacing of $\Delta f = 29.3$ kHz. The number of active subcarriers was chosen as $L = 20$. The results are given in terms of the normalized interference power $P_I$ as a function of the normalized width of the guard band $d/\Delta f$. It should be noted, that in the analysis the potentially interfering secondary signal was located only on one side of the primary band. In practise, the primary band may be surrounded by secondary signals on both sides. A CP of length corresponding to 12.5 % of the useful symbol period was used in case of OFDM. The rolloff values of $\beta = \{0.1, 0.25, 0.5, 0.75, 1.0\}$ were tested for RC windowed OFDM. For the PR filter bank, a prototype filter with overlapping factor $K = 3$ and rolloff $\rho = 1.0$ was considered. For the NPR design $K = 3$ and parameters $A_0 = 0.5$, $A_1 = -0.91143783$, and $A_2 = 0.41143783$ were used. The obtained simulation results, with integration limits $\omega_L = \frac{-2f_r}{T_s}\pi$ and $\omega_H = \frac{2f_r}{T_s}\pi$, for the ideally bandlimited mask, DVB-T mask ($f_r = 4.0$ MHz), and WLAN mask ($f_r = 10.0$ MHz) are shown in Fig. 6, Fig. 7, and Fig. 8, respectively.

OFDM with rectangular prototype filter without a CP ($h_{p,i}[n]$) shows very slow decay of the interference power. The inclusion of the CP ($h_{p,2}[n]$) lowers the level of interference slightly, but very modest decay trend still holds. The RC windowing with increasing $\beta$ clearly pushes down the level of interference introduced by the OFDM. This is due to improved spectral concentration of the subcarrier filter response ($h_{p,3}[n]$). The filter bank with the PR prototype ($h_{p,4}[n]$) achieves fairly low interference power level with the normalized guard bandwidth of one. This corresponds to the situation in which the stopband edge of the (band edge) subcarrier response matches the reference point (the passband edge in ideally bandlimited case) of the receiver mask. With the NPR prototype ($h_{p,5}[n]$), a very fast and consistent decay of interference power can be obtained by allowing a limited amount of ISI and ICI.

How to interpret the obtained results? Given an interference power threshold of interest, say $-70$ dB, one can observe that the different multicarrier schemes reach the threshold with different widths of guard band. The reduction in the required guard bandwidth with NPR prototype, in comparison...
The above analysis shows that the selection of the pulse-shape (prototype filter), used as the basis of the multicarrier modulation in the overlay secondary transmission, plays an important role. With improved spectral concentration of the prototype filter, the level of interference power caused by the secondary transmission to the primary system can be controlled and the required frequency domain guard band can be minimized. The RC windowing enables this in the case of OFDM. However, this becomes at the price of increased symbol period (with increasing $\beta$) and thus results in the loss of spectral efficiency in the time domain. Using filter bank approach, a low-interference secondary transmission can be obtained without sacrificing the bandwidth efficiency. Therefore, the additional complexity of the FB approach, due to introduced pulse shaping, can be seen to be well profitable in the CR context.

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**REFERENCES**


