Spectrum Monitoring Scheme for Filter Bank Based Cognitive Radios

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Abstract: This paper focuses on the spectrum monitoring problem, i.e., detecting reappearing primary users during secondary transmissions in cognitive radio systems. The filter bank multicarrier (FBMC) concept is used as the basis as it facilitates simultaneous spectrum sensing and reception of secondary transmissions using the same device. With FBMC it is possible to support, in a spectrally efficient manner, narrow subcarrier-wide gaps in the spectrum of the transmitted signal for monitoring purposes. Such scheme allows fast reaction to reappearing primary users and it needs minimum amount of coordination between independent secondary systems operating in the same frequency band. We analyze the effect of the filter bank frequency response on energy detection based spectrum sensing. We also evaluate the impact of spectral regrowth due to transmitter power amplifiers, which is a critical issue in the proposed scheme.

Keywords: Cognitive radio, spectrum sensing, energy detection, filter bank, multicarrier.

1. Introduction

The primary goal of the spectrum sensing module of a cognitive radio is to detect the spectrum occupancy in the local area in which the system operates, and identify the spaces which are free of primary users (PUs) and other secondary users (SUs), the so-called spectrum holes. Spectrum holes are also referred to as white spaces and the target is to achieve pre-determined false alarm and missed detection probabilities, $P_{FA}$ and $P_{MD}$, when identifying white spaces. We will make a distinction between two modes of PU sensing: (1) Spectrum hole acquisition is carried out before local secondary transmission has been started or in other situations where the particular frequency band is not used for secondary transmission. (2) Spectrum monitoring takes place in parallel with secondary transmission and its main target is to detect reappearing primary users in the used frequency channel. Here we focus on the latter functionality.

The main challenge in developing the spectrum monitoring schemes is to reach short reaction time with minimum overhead to the simultaneously on-going secondary transmissions. A common approach for spectrum monitoring is based on quiet blocks in the time-frequency plane [1], e.g., in the form of time-domain gaps between transmission frames or continuous empty subbands in frequency domain. Obviously, in the context of multicarrier modulation techniques, there is a lot of flexibility in defining the quiet blocks.

On the other hand, the spectrum sensing scheme has to match the characteristics of the opportunistic, dynamic spectrum access (DSA) scheme which is employed by the

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1 This research was supported by the European Commission under Project PHYDYAS (FP7-ICT-2007-211887).
secondary systems. One general idea is that the DSA scheme should be able to support independent SU systems operating in the same white space, with minimum coordination between the different systems [2]. In any case, it is necessary that there exists coarse frequency synchronization between different SUs. However, reaching time synchronous operation of different opportunistic secondary systems would require higher level of coordination between them. This leads to the idea of leaving narrow parts of the spectrum unused in secondary transmission, allowing them to be utilized for spectrum sensing purposes in a continuous manner. In the multicarrier context, the spectrum sensing bands would mean one or a few subcarriers.

Due to the spectral leakage characteristics, filter bank multicarrier (FBMC) transmission schemes are much more favourable for this approach than OFDM [3, 4]. In FBMC, one subcarrier is sufficient to isolate a sensing subcarrier from active subcarriers of the adjacent secondary systems. This paper focuses on evaluation of this sensing subcarrier scheme taking into account various practical issues, especially the effect of spectral regrowth due to transmitter power amplifier nonlinearity, which increases the effective noise level on the sensing subcarrier. In Section 2, we briefly review the FBMC concept. In Section 3, energy detection principle is summarized and spectrum monitoring schemes for FBMC are discussed. In Section 4, the effects of spectral regrowth in the proposed sensing subcarrier scheme are analyzed.

2. FBMC transmission scheme

In this section, we shortly review the principles of the FBMC transmission scheme based on offset QAM subcarrier modulation [5] to facilitate the forthcoming analysis of the spectrum monitoring functionality in the data-receiving secondary receiver. Figures 1a) and 1b) show the block diagrams of FBMC/OQAM synthesis filter bank (SFB) and analysis filter bank (AFB), respectively. These are the fundamental baseband processing elements implementing the modulator and demodulator functions in the transmitter and receiver side, respectively, of the overall transceiver structure (a.k.a transmultiplexer).

![Figure 1. Synthesis and analysis filter banks for FBMC.](image)

The discrete-time complex I/Q baseband signal at the SFB output can be expressed as [6]

\[ s[m] = \sum_{k=0}^{M-1} \sum_{n=-\infty}^{\infty} d_{k,n} \theta_{k,n} \beta_{k,n} p[m - n \frac{M}{2}] e^{j \frac{2\pi}{M} km}, \]

where \( \theta_{k,n} = e^{j \frac{2\pi}{M} (k+n)} = \) \( j^{k+n} \) defines the phase mapping between the real-valued symbol sequence \( d_{k,n} \) and the complex-valued input samples of the synthesis bank, whereas \( \beta_{k,n} = (-1)^{kn} \cdot e^{-j \frac{2\pi k}{M} \frac{(n-1)}{2}} \) denotes a filter length dependent multiplier. Moreover, \( m, M, \)
and \( I_p \) denote the high-rate sample index, the overall number of subchannels in the system band, and the length of the prototype filter \( p[n] \), respectively. Symbols \( d_{k,n} \) are modulated on the \( k \)th subcarrier at the rate of \( 2/T \), where the signalling interval \( T \) is defined as the inverse of the subcarrier spacing, i.e., \( T = 1/\Delta f \). The \( C2\mathbb{R} \)-blocks represent the conversion from the real and imaginary parts of a complex-valued symbol \( c_{k,n} \) (from a QAM alphabet) into real-valued data. Symbols \( d_{k,n} \) and \( d_{k,n+1} \) can be interpreted to carry the in-phase and quadrature components, in an interleaved manner, with a relative time offset of \( T/2 \). The synthesis and analysis subchannel filters of the uniformly modulated filter bank are obtained by frequency shifting the real-valued symmetric lowpass prototype filter as

\[
g_k[n] = p[n]e^{j\frac{2\pi}{M}k(m \mod M - \frac{L_p}{2})} \quad \text{and} \quad f_k[n] = g_k[L_p - 1 - n],
\]

where \( m = 0, 1, \ldots, L_p - 1 \) and \((\cdot)^*\) denotes complex conjugation. The receiver implements the inverse operations in the reversed order to recover estimates of the transmitted data.

In the FBMC receiver, subchannel processing (e.g., fractionally-spaced equalization / frequency-domain fine synchronization) is carried out at 2x oversampled rate. In other words, complex-valued subchannel samples are processed instead of the real-valued ones, which are finally sufficient for data reception at the end subchannel processing chain. The 2x oversampled OQAM-subsymbol rate sequence at the input of the subchannel processing block writes \( y_{k,n} = (r[m] * f_k[m]) \downarrow M \) where \( r[m] \), \(*\), and \( \downarrow M \) denote the high rate signal at the input of the AFB, the convolution operation, and downsampling by \( M \), respectively. These subcarrier sample sequences can be used for the spectrum monitoring in the secondary receiver, as will be discussed in the following.

3. Spectrum sensing schemes

3.1 Energy detection principle

We consider spectrum sensing in a multicarrier receiver, where energy detection (radiometer) is carried out at subchannel level at the output of the analysis bank. In energy detection, the test statistic is obtained as

\[
T(Y) = \frac{1}{N} \sum_{n=1}^{N} |Y[n]|^2,
\]

where \( Y[n], n = 1, \ldots, N \), are complex independent (uncorrelated) observations. Binary hypothesis testing is carried out based on the test statistic. Using Gaussian approximation, the distributions in the absence \((\mathcal{H}_0)\) and presence \((\mathcal{H}_1)\) of the PU signal can be written as:

\[
T(Y)|_{\mathcal{H}_0} \sim \mathcal{N}(\sigma^2, \frac{1}{N} \sigma^2) \\
T(Y)|_{\mathcal{H}_1} \sim \mathcal{N}(P + \sigma^2, \frac{1}{N}(P + \sigma^2)^2)
\]

Here \( P \) and \( \sigma^2 \) are the signal and noise variances, respectively.

We make use of the equations in [7], that relate the sample complexity to the false alarm probability \( P_{FA} \), the misdetection probability \( P_{MD} \), and the operating SNR = \( P/\sigma^2 \). In case there is no uncertainty and the noise variance is completely known, the required sensing time in samples, \( N_D \), to achieve target \( P_{FA} \) and \( P_{MD} \) is:

\[
N_D = \left[ \frac{\Phi^{-1}(P_{FA}) - \Phi^{-1}(1-P_{MD})(1+\text{SNR})}{\text{SNR}^2} \right]^2,
\]

where \( \Phi \) denotes the standard Gaussian complementary CDF. On the other hand, when the energy detector is assumed to operate under a noise level uncertainty of \( \sigma = 10\log_{10}\sigma^2 \) dB, the sample complexity can be approximated [7] as
\[ N_D \approx \left[ \frac{\Phi^{-1}(P_{FA}) - \Phi^{-1}(1 - P_{MD})}{\text{SNR} - \left(\frac{1}{\rho}\right)} \right]^2. \]  

This introduces the so-called SNR wall [7]: For example, with 0.1 dB uncertainty of the noise variance, the sensing time grows without limits when the SNR approaches $-13.3$ dB.

3.2 Spectrum monitoring schemes

In multicarrier systems, subchannel sample-wise energy values can be integrated both in time and frequency directions. This gives the possibility to utilize filter banks with subchannel spacing much smaller than the bandwidth of the signal to be detected. Furthermore, a filter bank with suitable subchannel spacing can be used flexibly in the detection of different types of primary signals and different SNR values by adjusting the integration range. The requirement is that the sensing block contains at least \( N_D \) independent elements in the time-frequency plane. Here we assume for simplicity that both noise and the possible PU signals have constant power spectral density in the region used for sensing; the extension of this study to frequency selective and fading PU channels is a topic for future studies.

Figure 2 shows two basic structures for introducing quiet blocks in multicarrier transmission, either as time-domain quiet periods (i.e., all-zero multicarrier symbols) or as continuous sensing subcarriers. It is obvious that the latter approach is not feasible in case of OFDM, due to the energy leakage from active subcarriers to the nearby unused ones. However, in FBMC with sufficiently sharp prototype filter frequency response, one guard subcarrier is sufficient to isolate the sensing subcarrier from the active ones. Figure 3 shows the subcarrier frequency responses in case of the PHYDYAS prototype filter [6] with overlapping factor \( K = 4 \).

Let us now consider the spectrum monitoring schemes of Figure 2 from the secondary system operation point of view. The main idea of opportunistic spectrum use is that the same white space can be used in different, not very distant, locations independently, in an un-coordinated manner. Therefore, co-channel interference between different secondary systems utilizing overlapping frequency channels can always be expected. To reach time-synchronous operation between different SU systems, especially regarding the quiet sensing period, a common stable time-base should be available. Furthermore, the length of the sensing period should be long compared to the signal propagation delays in those signal paths between different SU systems, which are not attenuated well below the targeted PU sensitivity level. In conclusion, it seems to be very difficult to reach sufficiently quiet time-domain sensing blocks in opportunistic spectrum usage scenarios.
On the other hand, some level of coarse frequency synchronization between nearby SU systems must exist, and it is easier to reach than precise time synchronization. The absolute sensing subcarrier locations could be a parameter of an FBMC-based secondary access scheme, and then it would be possible for all the secondary systems to leave the sensing subcarriers unused at all times.

The main challenge in the proposed approach is to keep the sensing subcarriers clean enough also with practical analog RF implementations of the transmission chain. Especially, the spectral regrowth due to transmitter power amplifier nonlinearities should be kept at a low-enough level. This issue is considered in Section 4. Before that, we will consider the energy detection in FBMC systems in some more details.

3.3 Energy detection from FBMC subcarrier signals

In FBMC, subcarrier signals are obtained at a rate, which is two times the subcarrier bandwidth. The samples are correlated, but there remains the question whether there is some benefit from using all the samples instead of the ones at symbol rate. The effect of the
sensing filter frequency response is analyzed in general form in [8]. Assuming that the sensing filter frequency response is \( F(j\omega) \) and it is normalized in such a way that
\[
\frac{T}{\pi} \int |F(j\omega)|^2 d\omega = 1, \tag{7}
\]
the means of both test statistics of (4) remain the same but the variances of both test statistics are multiplied by the factor
\[
\beta = \frac{T}{\pi} \int |F(j\omega)|^4 d\omega. \tag{8}
\]

In FBMC context, \( F(j\omega) \) is the prototype filter frequency response. With the PHYDYAS prototype filter design [4, 6], \( \beta = 0.8228 \). The variance of the test statistic is reduced by this factor, under both hypotheses, and consequently the needed sample complexity is reduced by the same factor in subcarrier-wise sensing. On the other hand, when symbol-rate samples are used, aliasing results in effectively constant sensing filter frequency response over the subchannel, and \( \beta = 0.5 \). In summary, \( N \) samples at subcarrier symbol rate and \( 2\beta N = 1.65N \) samples at 2x oversampled rate result in the same \( P_{FA} \) and \( P_{MD} \). The needed time record length is reduced by the factor of 0.8228 in the latter case.

It should be emphasized that the gain from using fractionally-spaced samples is fully obtained only in the scheme of Figure 2(b), i.e., when using just one subcarrier for sensing. If several adjacent subcarriers are used, the additional samples (beyond critical sampling) in the inner subcarriers would be fully correlated with the other observations, and the benefit comes from the two edge subcarriers only.

This analytical model of the effects of the sensing filter is tested in Figure 4 in terms of complementary receiver operation characteristic (CROC) plots. We can see that the experimental data matches quite well with the analytical model, much better than with the simplistic basic model with \( \beta = 1 \).

3.4 Numerical examples

We consider an FBMC system where the subcarriers are allocated in groups of 18. The subcarrier spacing is 10 kHz. In the sensing subcarrier scheme, 3 all-zero subcarriers are inserted between such groups. In the time-domain quiet period scheme, just one all-zero subcarrier is used as a guard between adjacent groups. In the filter bank design, overlapping
factor of $K = 4$ is assumed, so the length of time-domain guards is 4 subcarrier samples. In
the quiet period scheme, the length of the quiet period is chosen in such a way that the total
overheads due to quiet periods and guards are the same in the two schemes. Then we can
calculate the effective size (including the effect of $\beta$ of (8)) of the decision statistics for
both schemes, as a function of the sensing interval. From this information, the sensitivity of
spectrum sensing can be plotted, as shown in Figure 5. Here perfect knowledge of the noise
level is assumed. The ‘best case’ and the ‘worst case’ refer to the PU center frequency in
relation to sensing subcarrier grid, which has an effect on the number of sensing subbands
hitting the PU band. It can be seen that the sensing subcarrier scheme is actually more
effective with short sensing intervals. With longer sensing intervals, the quiet period
scheme achieves approximately 1 dB better sensitivity, however, with reduced time
resolution in detecting reappearing PUs.

4. Spectral regrowth effects

One essential practical aspect influencing the performance of the sensing subcarrier scheme
is the SU transmitter power amplifier (PA). Running the PA in its nonlinear operation
region results in out-of-band spectral power leakage [9], which in turn will increase the
effective level of the noise experienced by the energy detector in the spectrum monitoring
subcarriers at the SU receiver. In the following analysis, we consider a PA model, which is
specified in details in [10]. The relative power levels of the spectral regrowth component
responding to different PA input back-off (IBO) values are shown in Table 1.

![Figure 5. Sensitivity as a function of sensing interval with the zero-symbols scheme and the sensing subcarrier
scheme. Groups of 18 subcarriers, the same overheads due to guards in both schemes.](image)

The effective PU signal-to-noise ratio (under $\mathcal{H}_i$) can be expressed as $P/\tilde{\sigma}^2$, where
$\tilde{\sigma}^2 = \sigma^2 + \sum_{j=1}^{2} 10^{SNR_j^{ib}/10} \cdot \sigma^2 \cdot 10^{\beta_j^{ib}/10}$. Here, $SNR_j^{ib}$ and $\beta_j^{ib}$ denote the power of the
SU $j$ (located next to the monitoring subcarrier in frequency) w.r.t. the noise floor and the
PA back-off –dependent relative (w.r.t. to the SU signal power) level of the spectral
regrowth component, respectively. Some example cases of $P/\tilde{\sigma}^2$ are listed in Table 2.

An analytical model for the test statistic in the monitoring subcarriers can be obtained
by substituting $\tilde{\sigma}^2$ for $\sigma^2$ in the expressions in (4) and including the factor $\beta = 0.8228$. The
CROC curve derived based on the experimental data is compared to that of the analytical
model in Figure 6, showing fairly accurate match.
5. Conclusions

We have presented a continuous spectrum monitoring scheme for FBMC based secondary transmission. The scheme is based on quiet sensing subcarriers, which are placed in-between active subcarriers used in secondary transmission. Improved analytical models were developed for energy detection using sensing subcarriers. They take into account the effect of the spectrum sensing filter response and spectral regrowth effects due to nonlinear transmitter power amplifier. The proposed scheme provides comparable spectrum sensing performance with an alternative scheme based on time-domain quiet periods, but it was argued to be a much better match for opportunistic secondary spectrum usage scenarios.

The main challenge of the proposed sensing subcarrier scheme is due to the spectral regrowth effects. As demonstrated in Table 2, if the power levels of different secondary users are well under control (e.g., 25 dB SU-SNR, 10 dB back-off), the spectral regrowth effect is comparable to the noise uncertainty always experienced in energy detection based spectrum sensing. When the dynamic range of secondary users grows (e.g., 40 dB SU-SNR, 10 dB back-off), the spectral regrowth effects become comparable to the channel noise level. The increased effective noise level can be compensated by larger integration range. However, in this case the estimation of the effective noise level becomes a challenging problem. In order to expand the feasible SU dynamic range further, effective PAPR mitigation and power amplifier linearization methods are of crucial importance.

In this paper we considered only the case of AWGN channel. In [8], it is shown how the analysis of Section 3.3 can be extended to the case of frequency selective channel between PU and the sensing receiver, and preliminary performance results and conclusions are given. A detailed investigation of this case remains a topic for future studies.

![Figure 6. Verification of the effective PU SNR analysis using CROC plots. PU SNR = −10 dB, SU SNRs = 15 dB, and SU IBOs = 6 dB.](image)

<table>
<thead>
<tr>
<th>SU SNRs</th>
<th>6.0 dB</th>
<th>7.5 dB</th>
<th>9.0 dB</th>
<th>12.0 dB</th>
<th>18.0 dB</th>
<th>No PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 dB</td>
<td>10.55</td>
<td>−10.21</td>
<td>−10.08</td>
<td>−10.01</td>
<td>−10.00</td>
<td>−10.00</td>
</tr>
<tr>
<td>25 dB</td>
<td>13.71</td>
<td>−11.77</td>
<td>−10.71</td>
<td>−10.08</td>
<td>−10.01</td>
<td>−10.00</td>
</tr>
<tr>
<td>35 dB</td>
<td>21.62</td>
<td>−17.80</td>
<td>−14.44</td>
<td>−10.76</td>
<td>−10.06</td>
<td>−10.02</td>
</tr>
<tr>
<td>45 dB</td>
<td>31.34</td>
<td>−27.10</td>
<td>−22.75</td>
<td>−14.70</td>
<td>−10.53</td>
<td>−10.19</td>
</tr>
<tr>
<td>55 dB</td>
<td>40.31</td>
<td>−37.02</td>
<td>−32.53</td>
<td>−23.13</td>
<td>−13.60</td>
<td>−11.61</td>
</tr>
</tbody>
</table>

Table 1. Spectral regrowth characteristics of the PHYDYAS PA model. Top row: input back-off. Bottom row: relative power level at two subcarrier spacings from the active band edge subcarrier.

Table 2. Effect of spectral regrowth on effective PU SNR in dB with nominal PU SNR of −10 dB.
Acknowledgements

The authors wish to acknowledge the help of Mr. Mathieu Huchard (LETI) in providing the power amplifier model.

References


Figure 7. Analytic performance results with spectral regrowth effects and different SU SNRs: (left) SU SNRs = 25 dB, (right) SU SNRs = 35 dB. PU SNR = –10 dB.