A cognitive radio system for home theatre “5+1 audio” surround applications

Valeria Orani
University of Cagliari
Piazza D’Armi
09123 Cagliari / Italy
+39-070-6755907
valeria.orani@diee.unica.it

Vlad Popescu
Transilvania University of Brasov
Bdul Eroilor 29
500019 Brasov / Romania
+40-268-4785705
vladpop@unitbv.ro

Maurizio Murroni
University of Cagliari
Piazza D’Armi
09123 Cagliari / Italy
+39-070-6755907
murroni@diee.unica.it

ABSTRACT

This paper presents the application of cognitive algorithm for a stream diffusion in home theatre “5+1 audio” surround applications. We develop a wavelet-based method to efficiently estimate the spectrum and utilize its non-interference zones for unlicensed users transmission. We use the wavelet packet decomposition to detect frequency holes through power estimation of the subbands. Finally, we present an application scenario where audio information is coded by AC-3.

Categories and Subject Descriptors

E.4 [**Data**]: Formal models of communication

General Terms

Experimentation.

Keywords

Wireless data transmission, spectrum sensing, cognitive radio, wavelet transform.

1. INTRODUCTION

The increased demand for mobile communications and new wireless applications raises the need for new technologies to efficiently use the available spectrum resources. Because of the current static assignment of spectrum to specific users by regulatory bodies, the actual demand for transmission resources often exceeds the available bandwidth. In this context, new approaches to overcome static spectrum assignments have been come out to solve this problem. To provide the necessary bandwidth required by current and future wireless services and applications, a new concept of unlicensed users ”borrowing” spectrum from spectrum licensees, known as dynamic spectrum access (DSA) is born. Terminals in the secondary (unlicensed) systems must be able to detect an emerging primary (licensed) user (PU) immediately as well as reliably. These types of terminals are known as Cognitive Radios (CR), which can be defined as self-learning, adaptive and intelligent radios with the capacity to sense the radio environment and to adapt to the current conditions like available frequencies and channel properties [1]. The spectrum management rule of CR is that all new users for the spectrum are secondary (cognitive) users and requires that they must detect and avoid the primary user. Regions of space-time-frequency that are potential opportunities for non-interfering use of spectrum, and in which a particular secondary use is possible, are called ‘spectrum holes’. Wireless systems must determine where these holes exist and reconfigure themselves to take advantage of these opportunities. Three commonly adopted methods are matched filtering, energy detection, and PU signal feature detection with the cyclo-stationary feature.

Moreover, the choice of a physical layer data transmission scheme becomes a very important design decision when implementing a cognitive radio system. Specifically, the technique must be sufficiently agile to enable unlicensed users the ability to transmit in a licensed band while not interfering with the incumbent users.

This paper develops a new wavelet approach using the Wavelet Packet Decomposition (WPD) for sensing the spectrum and also for information transmission by unlicensed users in licensed bands; the approach is justified by flexible properties of wavelets, which offer the possibility of taking into account variable channel conditions by decomposing recursively the spectrum into different subbands.

The information about the transmission opportunities offered by the spectrum could be exploited by a secondary user without causing interference to the primary one. Once transmission parameters are defined, the transmitter uses the wavelet modulation scheme to send information.

The paper is structured as follows. In section 2, we present a new method to sense the spectrum and individuate possibilities for transmission by unlicensed users, using a Wavelet Packet Decomposition Multiplexing (WPDM) system. In section 3, we describe the AC-3 system and give a scenario of application of our technique as example for highlighting the advantages of the proposed method.

2. WPDM-BASED COMMUNICATION

2.1 Spectrum Sensing

IWCMC ’09 June 21–24, 2009, Leipzig, Germany. 978-1-60558-569-7/09/06...$5.00

In this section, we propose a spectrum sensing algorithm using the discrete wavelet transform.

Wavelet analysis is one of many generalized time frequency methods which serves to describe a signal’s frequency content at a certain point in time. As opposed to Fourier analysis, however, wavelet analysis divides the time-frequency plane into non-uniform regions which are characteristic of an octave-band decomposition.

By decomposing signals into elementary building blocks that are well localized both in space and frequency, the wavelet transform can characterize the local regularity of signals.

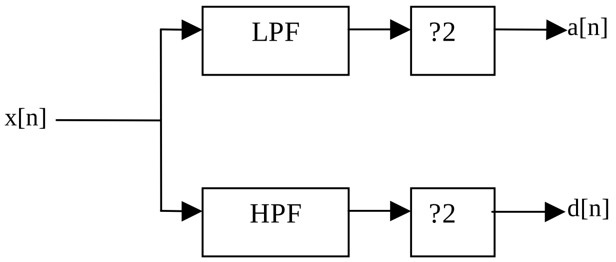

Figure 1. Wavelet filter bank.

In the proposed method the input signal *x[n]* is passed through two complementary filters, as shown in Figure 1, low-pass and high-pass decomposition quadrature mirror filters (QMFs), to obtain approximations *(a[n])*, high scale and low frequency components and details *(d[n])*, low scale and high frequency components. The outputs of these filters have frequency spectra, that are lower half and upper half of the input. A downsampling by a factor of 2, which removes every second point in the signal sequence, can be done without any loss of information. If the sampling frequency of x[n] is fs, the bandwidth of frequency for each subband at the output is given by *fs/2N*, where *N* is the total number of output sub-bands. At each decomposition stage, the number of multiplications is divided by two, due to a downsampling operation, but wavelet coefficients for each layer still contain full information of the related harmonic content.

This decomposition process using LPF and HPF is called Discrete Wavelet Packet Transform (DWPT) or Wavelet Packet Decomposition (WPD).

The sensing of spectrum is accomplished in according to the following algorithm, briefly sketched in Figure 2; its goal is to automatically define a feature set to identify spectrum opportunities or holes.

The main tasks of the sensing process are:

1) Performing a wavelet decomposition of the signal to obtain different wavelet coefficients into different subbands.
2) Computing the power of each channel.
3) For each subband, checking if the calculated power is less than a fixed power threshold.
4) Identification of white spaces.

We calculate the power of the signal according to [1], as explained in the following section.

If a received signal, *s(t)* is periodic signal with period T, then the power of this signal is computed by

$$P = \frac{1}{T}\int_0^T s^2(t)dt \tag{1}$$

After wavelet decomposition we can represent the signal *s(t)* as

$$s(t) = \sum_k \mathrm{a}_{j_0,k}\phi_{j_0,k}(\mathrm{t}) + \sum_{j>j_0}\sum_{\mathrm{k}} \mathrm{d}_{j,k}\psi_{j,k}(\mathrm{t}) \tag{2}$$

where a_{j0},k and $d_{j,k}$ are scaling coefficients and wavelet coefficients respectively. As a result, we can simply compute the power of the signal according to the following equation using orthonormal wavelet and scaling function properties.

$$\begin{aligned} P &= \frac{1}{T}\int_0^T s^2(t)dt \\ &= \frac{1}{T}\int_0^T \left\{ \sum_k \mathrm{a}_{j_0,k}\phi_{j_0,k}(\mathrm{t}) + \sum_{j>j_0}\sum_{\mathrm{k}} \mathrm{d}_{j,k}\psi_{j,k}(\mathrm{t}) \right\}^2 dt = \\ &= \frac{1}{T}\left[\sum_k \mathrm{a}_{j_0,k}{}^2 + \sum_{j>j_0}\sum_{\mathrm{k}} \mathrm{d}_{j,k}{}^2 \right] \end{aligned} \tag{3}$$

This formula shows that we can calculate the power of each subband using the scaling and wavelet coefficients.

The decomposition level is chosen according to the nature of the signal or on certain criteria.

We show that an estimation of spectrum opportunities can be

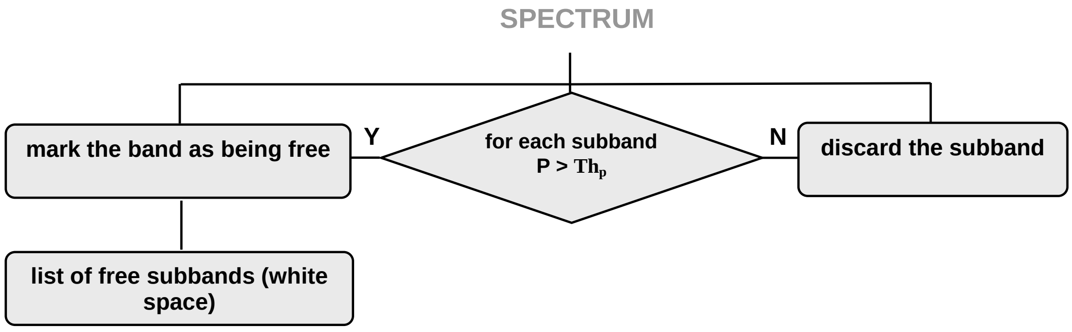

Figure 2. Algorithm for identifying spectrum holes.

obtained after successive wavelet decompositions of the input sequence into approximation and details bands.

2.2 WPDM algorithm for transmitting

Our method uses a common architecture based on WPDM for transmitting and receiving signals. WPDM is a multiple signal transmission technique in which the message signals are waveform coded onto wavelet packet basis functions for transmission. To define the wavelet packet basis functions we refer to wavelet multiresolution analysis (MRA), the details of which can be found in a number of textbooks [10]–[11] and tutorial articles [12]–[13].

Let $g_0[n]$ be a unit-energy real causal FIR filter of length N which is orthogonal to its even translates; i.e., $\sum_n g_0[n]g_0[n-2m]=\delta[m]$, where $\delta[m]$ is the Knoneker delta, and let $g_1[n]$ be the (conjugate) quadrature mirror filter (QMF), $g_1[n]=(-1)^n g_0[N-1-n]$. If $g_0[n]$ satisfies some mild technical conditions [10], [13], we can use an iterative algorithm to find the function $\phi_{01}(t)=\sqrt{2}\sum_n g_0[n]\phi_{01}(2t-nT_0)$ for an arbitrary interval T_0. Subsequently, we can define the family of functions ϕ_{lm}, $l\geq 0$, $1\leq m\leq 2^l$ in the following (binary) tree-structured manner:

$$\begin{cases}\phi_{l+1,2m-1}(t)=\sum_n g_0[n]\phi_{lm}(t-nT_l)\\ \phi_{l+1,2m}(t)=\sum_n g_1[n]\phi_{lm}(t-nT_l)\end{cases} \tag{4}$$

where $T_l=2^l T_0$. For any given tree structure, the function at the *leafs* of the tree form a *wavelet packet*. They have a finite duration, $(N-1)T_l$, and are self- and mutually-orthogonal at integer multiples of dyadic intervals, and hence they are a natural choice for scalable multiplexing applications [9], [10].

In WPDM binary messages $x_{lm}[n]$ have polar representation (i.e., $x_{lm}[n]=\pm 1$), waveform coded by pulse amplitude modulation (PAM) of $\phi_{lm}(t-nT_l)$ and then added together to form the composite signal $s(t)$. WPDM can be implemented using a transmultiplexer and a single modulator [14]. For a two level decomposition

$$s(t)=\sum_k x_{01}[k]\phi_{01}(t-kT_0) \tag{5}$$

where $x_{01}[k]=\sum_{(l,m)\in\Gamma}\sum_n f_{lm}[k-2^l n]$, with Γ being the set of terminal index pairs and $f_{lm}[k]$ the equivalent sequence filter from the $(l,m)-th$ terminal to the root of the tree, which can be found recursively from (4). The original message can be recovered from $x_{01}[k]$ using

$$x_{lm}[n]=\sum_k f_{lm}[k-2^l n]x_{01}[k] \tag{6}$$

In Fig. 3 is shown the scheme of WPDM.

3. APPLICATION SCENARIO

The main goal of this section is to describe a possible scenario of application of our method. This sharing of the spectrum among various wireless devices that can operate in the same environment may lead to severe interference and result in significant performance degradation.

An example of application scenario is the “5+1 audio” surround systems also known as AC-3 system.

3.1 AC-3

In this section, we give a brief overview of AC-3.

AC-3 is a flexible audio coding standard from Dolby Laboratories for multichannel digital surround sound.

This standard is used in movie and home theatres and has been chosen as the audio standard for next-generation systems such as DVD, HDTV, digital broadcasts, computer audio, and DVD ROMs for video games.

"5+1 audio" is a six channels system, because there are five full-bandwidth channels with 3 Hz to 20 kHz frequency range for Front Left and Right, Centre, and Surround, plus one "Low Frequency Effects" (LFE) subwoofer channel devoted to frequencies from 3 to 120 Hz. The 0.1 channel refers to a fractional bandwidth channel intended to convey only low frequency signals.

5.1 describes the standard discrete surround-sound configuration of three full-range front channels, two full-range surround channels, and a bass-only low-frequency effects channel. The AC-3 bitstream specification permits sample rates of either 48 kHz, 44.1 kHz, or 32 kHz, and supports data rates ranging from

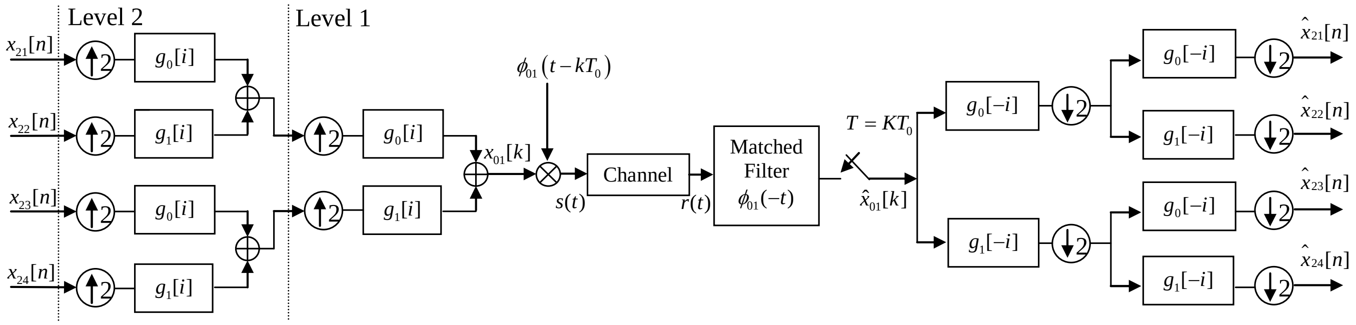

Figure 3. Transmitter and receiver for a two-level WPDM systems.

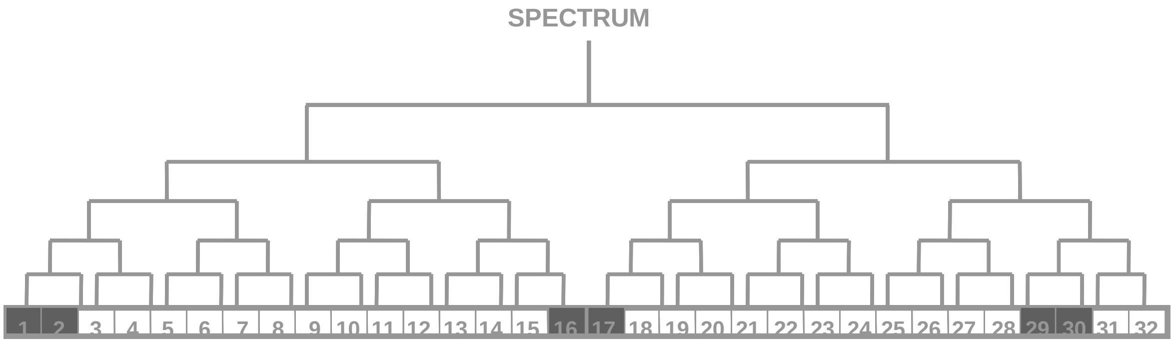

Figure 4. Spectrum sensing using WPDM with 5 levels.

32 kbps (kilobits-per-second) to 640 kbps.

The first step in the encoding process is to transform the representation of audio from a sequence of PCM time samples into a sequence of blocks of frequency coefficients. This is done in the analysis filter bank. Overlapping blocks of 512 time samples are multiplied by a time window and transformed into the frequency domain. Due to the overlapping blocks, each PCM input sample is represented in two sequential transformed blocks. The frequency domain representation may then be decimated by a factor of two so that each block contains 256 frequency coefficients. The individual frequency coefficients are represented in binary exponential notation as a binary exponent and a mantissa. The set of exponents is encoded into a coarse representation of the signal spectrum which is referred to as the spectral envelope. This spectral envelope is used by the core bit allocation routine which determines how many bits to use to encode each individual mantissa. The spectral envelope and the coarsely quantized mantissas for 6 audio blocks (1536 audio samples per channel) are formatted into an AC-3 frame. The AC-3 bit stream is a sequence of AC-3 frames.

The decoding process is basically the inverse of the encoding process. The decoder must synchronize to the encoded bit stream, check for errors, and de-format the various types of data such as the encoded spectral envelope and the quantized mantissas. The bit allocation routine is run and the results used to unpack and de-quantize the mantissas. The spectral envelope is decoded to produce the exponents. The exponents and mantissas are transformed back into the time domain to produce the decoded PCM time samples.

AC-3 encoders may use a range of bit rates to encode audio data, so it is possible to adapt network bandwidth by adjusting the encoder bit rate in real time or by having multiple copies of content encoded at different bit rates. AC3 employs a bit allocation routine that distributes bits to channels and frequencies depending on the signal content.

3.2 System Configuration

The use of a band of spectrum by one system in the vicinity of a second system's receiver (tuned to the same band) will generally degrade the performance of that second system if the total interference exceeds a critical value.

Communication architecture is based on a local coordinator which senses the environment through the proposed algorithm and broadcasts to the others channels information about free bands. The Coordinator operates as a cognitive base station that must continuously monitor the spectrum for possible usage. An overview of the system configuration with a coordinator is shown in Figure 5.

The others channels are considered as secondary users (SU) and they implement the same TX / RX WPDM-based blocks. Secondary users do not exchange spectrum occupation data among them and the communication between coordinator and SU is unidirectional (coordinator broadcasts).

The Coordinator functions include:

- spectrum sensing using WPDM with e.g. 5 levels (32 resulting frequency subbands) (Fig. 4)
- compression of the resulting wavelet coefficients (RLL, Huffman, etc.)
- broadcast of the coefficients over a dedicated channel

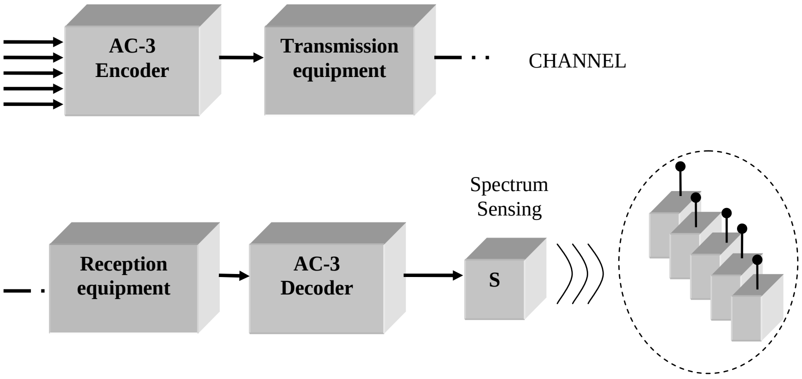

Figure 5. System configuration with coordinator.

- repeat operation after a predefined time unit

4. CONCLUSIONS

After reviewing various spectrum-sensing methods, the energy detection method was chosen to be implemented in the design of a spectrum sensing system. Instead of using the FFT for analysing the power content of the spectrum, we opted for an alternative method based on the wavelet transformation and its discrete application, the Discrete Wavelet Packet Transformation.

In this paper we introduced our cognitive method for sensing spectrum. However, we still need to add more simulations to accomplish the mentioned algorithm.

5. REFERENCES

[1] Cosovic, I., Jondral, K., Buddhikot, M., and Kohno, R. “Cognitive Radio and Dynamic Spectrum Sharing Systems”, EURASIP Journal on Wireless Communications and Networking, 2008.

[2] Murroni, M. “On the Efficient Broadcasting of Heterogeneous Services over Band-Limited channels: Unequal Power Allocation for Wavelet Packet Division Multiplexing”, Signal Processing: Image Communication. Volume 22, Issue 3, March 2007.

[3] Tian, Z. and Giannakis, G. B. “A wavelet approach to wideband spectrum sensing for cognitive radios,” in Cognitive Radio Oriented Wireless Networks and Communications, 2006. 1st International Conference on, vol. 3.

[4] Haykin, S. ”Cognitive Radio: Brain-Empowered Wireless Communications,” IEEE Journal on Selected Areas in Communications, Vol.23, No.2, pp. 201-220, February 2005.

[5] Hamid, E. Y. and Kawasaki, Z.-I. “Instrument for the quality analysis of power systems based on the wavelet packet transform,” IEEE Power Eng. Rev., vol. 22, pp. 52–54, Mar. 2002.

[6] Yoon W., and Devaney, M. J. Measurement Using the Wavelet Transform” IEEE Transactions on Instrumentation and Measurement, vol. 47, no. 5, October 1998.

[7] Lindsey, A.R. “Wavelet packet modulation for orthogonally transmultiplexed communication,” IEEE Trans. Sig. Process., vol. 45, no. 5, pp. 1336–1339, May 1997.

[8] Federal Communications Commission, “Spectrum policy task force report”, 2002.

[9] Daubechies, I. Ten Lectures on Wavelets. Philadelphia, PA: SIAM, 1992.

[10] Strang, G., and Nguyen, T. *Wavelet and Filter Banks.* Wellesley, MA: Wellesley-Cambridge Univ. Press, 1996

[11] Strang, G. “Wavelets and dilation equations: A brief introduction,” *SIAM Rev.*, vol. 31, pp. 614–627, Dec. 1989.

[12] Daubechies, I. “Orthonormal bases of compactly supported wavelets,” Common. Pure Applied Math, vol. XLI, no. 7, pp. 909–996, Oct. 1988.

[13] Wong, K. M., Wu, J., Davidson, T. N., and Jin, Q. “Wavelet packet division multiplexing and wavelet packet design under timing error effects”, IEEE Trans. Signal Processing, vol. 45, no. 12, pp- 2877-2890, December 1997.