Accepted in 2014 IEEE International Workshop on Cognitive Cellular Systems, Rhine River, Germany, Sept. 2-14, 2014.

Low Complexity Spectrum Sensing using Variable Digital Filters for Cognitive Radio based Air-Ground Communication

Abhishek Ambede[#], Smitha K. G.[+] and A. P. Vinod[++]
School of Computer Engineering,
Nanyang Technological University,
Nanyang Avenue, Singapore 639798.
E-mail: abhishek7[#]@e.ntu.edu.sg, {smitha[+], asvinod[++]}@ntu.edu.sg

***Abstract*—Cognitive radios (CRs) enable efficient usage of the radio frequency spectrum by sensing their operating environments and adapting their transceiver characteristics accordingly. This ability of CRs makes them a feasible choice to achieve green radio networks. CRs perform spectrum sensing, wherein presence and/or absence of licensed users' signals is detected in the wideband input frequency range in order to allow opportunistic access of the vacant frequency bands to unlicensed users. Variable digital filters (VDFs) which can provide frequency responses with variable cutoff frequencies are widely used for spectrum sensing in CRs. In this paper, we propose an energy detector based spectrum sensing scheme which employs such VDFs based on first order all pass transformation and the modified coefficient decimation method. With the help of design example of an air-ground communication scenario, we show that VDFs employed in the proposed scheme are low complexity alternatives to the other relevant VDFs in literature. The proposed spectrum sensing scheme can be useful not only for solving the anticipated spectrum scarcity caused by the existing static spectrum allocation scheme in current air-ground communication systems, but also in achieving energy efficient green communications.**

Keywords*—Cognitive radio; spectrum sensing; variable digital filters; modified coefficient decimation method; all pass transformation.

I. INTRODUCTION

The cognitive radio (CR) has been proposed as a solution to target the opportunistic usage of the radio frequency spectrum [1]. CRs have the ability to sense the current spectrum utilization, and change their behavioral and transmission characteristics dynamically so as to achieve efficient spectrum usage [2]. Recent research proposes CR as an enabling technology for achieving green radio networks [3-5]. The CRs can provide energy efficiency coupled with efficient spectrum usage thus supporting the fundamental requirements of green radio communications [4]. It is observed that dynamic spectrum management using CRs can offer up to 50% energy savings in radio networks [5]. Such significant energy savings coupled with the ability to perform dynamic spectrum management makes CRs highly feasible for use in applications such as air-ground communication systems [6, 7]. The current system of air-ground communication follows static spectrum allocation, which is a bottleneck for effective usage of the limited licensed spectrum allotted for air-ground communication. With respect to green radio communications, the use of CRs for air-ground communication will not only help in solving the static spectrum allocation problem but also in achieving energy efficiency (in terms of transmitted power) in the battery operated radio terminals. An important function in CRs is spectrum sensing, wherein the presence or (and) absence of signals of licensed users is to be detected in the wideband input frequency range in order to allow opportunistic access of the vacant frequency bands to unlicensed users (called CR users) [8]. The vacant frequency bands are termed as spectrum holes. Out of the various techniques used for spectrum sensing in CRs, the energy detector based spectrum sensing is the least complex to implement [8]. It employs variable digital filters (VDFs) to detect spectrum holes by comparing signal energy in the corresponding frequency bands with a threshold value. VDFs that can provide frequency responses with variable cutoff frequencies over the entire Nyquist frequency range are ideally desired to detect spectrum holes of varying bandwidths (BWs) and locations. Table I presents a summary of different VDFs in literature [9-20] which can be used to realize energy detector based spectrum sensing schemes. From Table I, it can be noted that all pass transformation (APT) based VDFs are feasible candidates to realize low complexity spectrum sensing schemes with ability to detect spectrum holes of varying BWs and locations over the entire Nyquist frequency range.

In this paper, we propose an energy detector based spectrum sensing scheme which employs novel VDFs based on the combination of first order APT and the modified coefficient decimation method (MCDM). We show that VDFs used in the proposed scheme are low complexity alternatives to the other relevant VDFs in literature. The rest of the paper is organized as follows: Section II presents a brief literature review of APT based VDFs and the MCDM. The proposed spectrum sensing scheme is presented in Section III. A block diagram of the proposed scheme, hardware realization architecture for the VDFs employed, and a design procedure with mathematical formulation are presented in Section III. A design example to compare VDFs in the proposed scheme with other relevant VDFs is also presented. Section IV presents our conclusions.

TABLE I. COMPARISON OF VDFS

Type of VDFs	Phase response	Group delay	Complexity	Cutoff frequency/ BW control over the Nyquist frequency range
Frequency response masking (FRM) based [9]	linear	very high	very low	discrete control over entire range
Coefficient decimation method (CDM)/ Modified coefficient decimation method (MCDM) based [10, 11]	linear	low	low	discrete control over entire range
Improved coefficient decimation method (ICDM) based [12]	linear	low	low	discrete control over entire range, higher resolution than CDM/ MCDM
Frequency transformation based [13, 14]	linear	high	high	continuous control over limited section of Nyquist range
Spectral parameter approximation (SPA) based [15-17]	linear	very low	very high	continuous control over entire range, but used for limited section due to very high complexity
All pass transformation (APT) based [18-21]	non-linear	NA	high	continuous control over entire range

II. BRIEF LITERATURE REVIEW

A. *APT based VDFs*

In APT based VDFs, the delay elements in a filter structure are replaced by an all pass filter structure of appropriate order [18-20]. The resultant VDF can provide different types of frequency responses with variable cutoff frequencies.

If first order all pass filter structures are used along with a lowpass prototype filter, lowpass frequency responses with variable cutoff frequencies can be obtained. Let *H(z)* be the z-domain representation of a prototype filter and *A(z)* be the z-domain representation of a first order all pass filter. If *G(z)* denotes the warped version of *H(z)*, it is represented as [18]

$$G(z) = H(A(z)) \tag{1}$$

where $A(z) = \left[\dfrac{z^{-1} - \alpha}{1 - \alpha . z^{-1}} \right]$, $|\alpha| < 1$ and is real.

α is termed as the warping coefficient. The value of α can be varied to achieve different cutoff frequencies in the warped frequency responses. In first order APT based VDFs, if $-1 < \alpha < 0$, the resultant cutoff frequencies are higher than the original cutoff frequency. For $0 < \alpha < 1$, the resultant cutoff frequencies are lower than the original cutoff frequency whereas for $\alpha=0$, the original frequency response of the prototype filter itself is obtained.

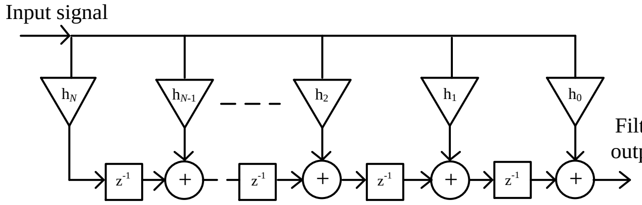

Fig. 1(a). Transposed direct form FIR filter structure.

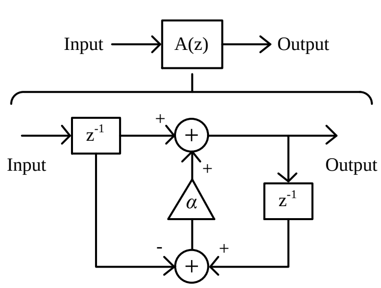

Fig. 1(b). Single multiplier implementation structure for A(z).

Fig. 1(a) shows the transposed direct form FIR filter structure which is commonly used for filter implementations [22]. If it is used to implement symmetric FIR filters, only half of the filter coefficients need to be implemented; thus offering significant savings in terms of coefficient multiplications. Fig. 1(b) shows a first order all pass filter structure that can be used to replace delay elements in Fig. 1(a) when first order APT is to be performed [19]. The single multiplier architecture in Fig. 1(b) can help to minimize the total number of multipliers required for implementing APT in the desired VDFs. Since multiplication is the most resource consuming operation in filter implementations, the combination of structures in figures 1(a) and 1(b) can help in achieving significant savings in resource consumptions in the desired APT based VDFs.

B. *MCDM*

In MCDM [11], a lowpass prototype filter is decimated by a factor *M*, i.e., every M^{th} coefficient is retained and the sign of every alternate retained coefficient is reversed. All other coefficients are replaced by zeros. This results in a multi-band frequency response with center frequency locations of the subbands given by odd multiples of π/M, i.e., $(2k+1)\pi/M$ where *k* is an integer ranging from 0 to (M-1). If MCDM is performed by M=1, a highpass frequency response is obtained with its BW same as that of the lowpass prototype filter. In MCDM by M=1, all the filter coefficients are retained and the sign of every alternate coefficient is reversed. In hardware implementation, this can be achieved by replacing every alternate adder block in Fig. 1(a) by an adder/subtractor (add/sub) block. When the original lowpass frequency response of the prototype filter is desired, the add/sub blocks can be used in adder mode, and when the corresponding highpass filter response is desired, they can be used in the subtractor mode. Thus using the same set of filter coefficients, we can obtain lowpass as well as highpass frequency responses in MCDM.

In the proposed spectrum sensing scheme presented in Section III, we employ VDFs based on the combination of first order APT and MCDM. First order APT is used to achieve lowpass frequency responses with variable cutoff frequencies, while MCDM with M=1 is performed to obtain the corresponding highpass frequency responses.

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III. Proposed Spectrum Sensing Scheme

A. Block Diagram and Hardware Realization Architecture

Fig. 2(a) shows block diagram of the proposed spectrum sensing scheme. The major components of the proposed scheme are the two VDFs involved, VDF I and VDF II. Fig. 2(b) shows the hardware realization architecture for VDF I and VDF II. As shown in Fig. 2(b), a single prototype filter is used for realizing both VDF I and VDF II and its coefficients are implemented using the transposed direct-form filter structure (shown in Fig. 1(a)) to exploit their symmetry property. Use of a single set of filter coefficients helps to reduce the design complexity by minimizing the number of multipliers required.

The VDF I realization corresponds to the filter structure shown in Fig. 1(a), modified by replacing every delay element with the first order all pass filter structure A(z) shown in Fig. 1(b). Thus, the VDF I branch can provide lowpass frequency responses with variable cutoff frequencies at its output, by employing first order APT in its design. The hardware realization of VDF II is shown in Fig. 2(b). The lowpass/ highpass response toggle line is used to perform MCDM by M=1 when in highpass mode, thus converting resulting lowpass frequency responses after first order APT into corresponding highpass frequency responses. Based on the combination of first order APT and MCDM, the VDF II branch can thus provide lowpass and highpass frequency responses with variable cutoff frequencies at its output. α_1 and α_2 represent the frequency warping coefficients required to perform first order APT in VDF I and VDF II respectively.

The energy computation blocks shown in Fig. 2(a) are used to compute energy values of the filtered output signals of VDF I and VDF II branches, which are termed as E_1 and E_2 respectively. The 2:1 multiplexer (mux) shown in Fig. 2(a) is used to select the appropriate computed energy value, (E_2- E_1) or E_2, to be passed on to the band occupancy decision block. The band occupancy decision block is used to compare the input energy value with a threshold to determine whether the desired frequency band is vacant or occupied.

B. Design Procedure and Mathematical Formulation

A design procedure to realize the proposed spectrum sensing scheme is presented in this section. The corresponding mathematical formulae required to compute the various parameters are also provided.

Step-1: Prototype filter design –

Design the lowpass prototype filter to be employed in VDF I and VDF II (shown in figures 2(a) and 2(b)) and obtain the corresponding filter coefficients. If f_p and f_s are the chosen passband and stopband edge frequencies (normalized with respect to half of sampling frequency), δ_p and δ_s are the desired passband and stopband peak ripple specifications, then the order of the desired finite impulse response (FIR) filter (N) can be obtained using the formula [11]

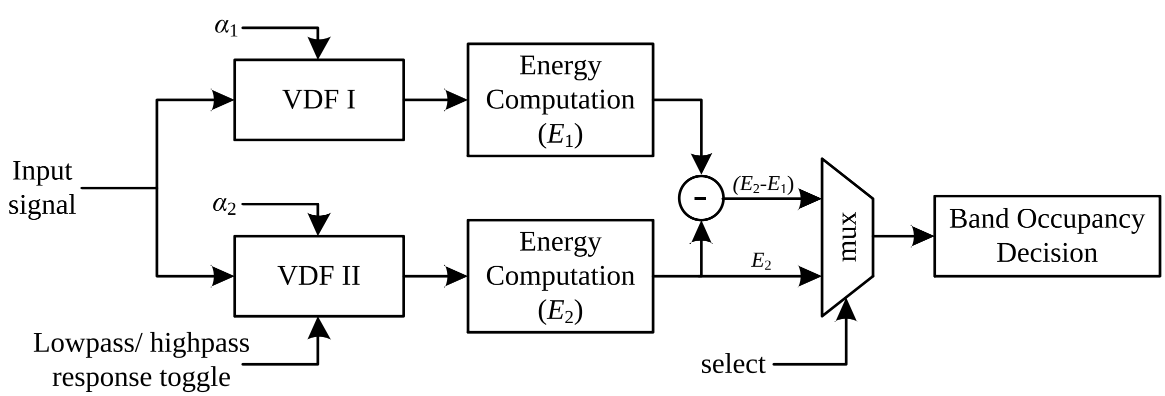

Fig. 2(a). Block diagram of proposed spectrum sensing scheme.

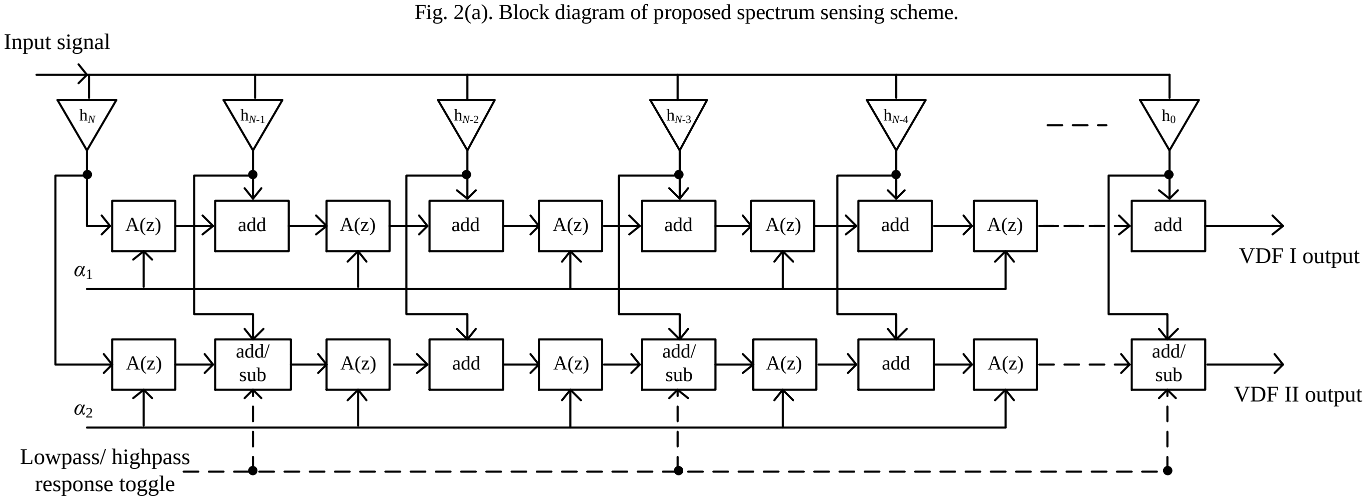

Fig. 2(b). Hardware realization architecture for VDF I and VDF II in the proposed scheme.

$$N = -\frac{4\log_{10}(10\delta_p \delta_s)}{3(f_s - f_p)} - 1 \quad (2)$$

Step-2: Implementation of proposed scheme –

Implement the proposed scheme as discussed in Section III-A, using the block diagram and hardware realization architecture shown in figures 2(a) and 2(b) respectively.

Step-3(a): Energy computation for a frequency band from 0 to cutoff frequency f_c ($0 < f_c < 1$, where 1 corresponds to half of sampling frequency), i.e., a lowpass frequency response –

The VDF II branch can be used alone in this case. Obtain the desired lowpass frequency response by keeping the toggle line in lowpass mode and using an appropriate value of α_2 to achieve the desired f_c. Let f_{c1} be the normalized cutoff frequency of the lowpass prototype filter and f_{c2} be the desired normalized cutoff frequency of the lowpass frequency response to be obtained. The corresponding value of α required to achieve f_{c2} can be computed using the formula [18]

$$\alpha = \frac{\sin[(f_{c1} - f_{c2})\pi/2]}{\sin[(f_{c1} + f_{c2})\pi/2]} \quad (3)$$

Compute energy E_2 for the desired frequency band achieved using VDF II and pass it on to the occupancy decision block by setting the mux select line appropriately. The energy E of a digital signal $x(n)$ of S samples can be computed using the formula [22]

$$E = \frac{1}{S}\sum_{n=0}^{S-1} |x(n)|^2 \quad (4)$$

Step-3(b): Energy computation for a frequency band from f_{cl} to f_{cu} (where f_{cl} and f_{cu} are normalized lower and upper cutoff frequencies respectively) such that $0 < f_{cl} < f_{cu} < 1$ –

In this case, obtain two distinct lowpass frequency responses by achieving f_{cl} in VDF I and f_{cu} in VDF II branches respectively, using (3). Perform energy computation for the two frequency bands (0 to f_{cl} and 0 to f_{cu}, $E_2 \geq E_1$) using (4). The difference between the computed energy values, i.e., (E_2-E_1) is the energy of the desired frequency band between f_{cl} and f_{cu} and can be passed on the occupancy decision block by setting the mux select line appropriately.

Step-3(c): Energy computation for a frequency band from f_c to 1 ($0 < f_c < 1$, where 1 corresponds to half of sampling frequency), i.e., a highpass frequency response –

Similar to the case discussed in *Step-3(a)*, the VDF II branch can be used alone in this case. Obtain the desired highpass frequency response by keeping the toggle line in highpass mode and using an appropriate value of α_2 to achieve the desired f_c. If f_{c1} is the normalized cutoff frequency of the lowpass prototype filter, and f_{c2} is the desired cutoff frequency of the highpass frequency response to be obtained, the required value of α can be computed using the formula

$$\alpha = \frac{\sin\{[(1 - f_{c1}) - f_{c2}]\pi/2\}}{\sin\{[(1 - f_{c1}) + f_{c2}]\pi/2\}} \quad (5)$$

Using (4), compute energy E_2 for the desired frequency band achieved using VDF II and pass it on to the occupancy decision block by setting the mux select line appropriately.

Step-4: Band occupancy decision –

Let E be the computed energy corresponding to the frequency band being checked to find whether the band is occupied or vacant. The occupancy decision can be taken by comparing E with a pre-determined threshold value which is selected based on the knowledge of noise variance [8]. If E is greater than or equal to the threshold, the band is occupied; else the band is vacant and can be used for the CR user's transmission. This comparison operation is performed by the band occupancy decision block shown in Fig. 2(a).

C. *Design Example: Air-Ground Communication*

In current air-ground voice communication systems, the licensed band of 108MHz to 137MHz is split into uniform sub-channels of 25kHz BW whose assignment is static and based on geographical areas and organizational structures [6]. With increasing demand for more voice channels, the 25kHz channels are further being divided in 3 sub-channels of 8.33kHz each, which is currently being practiced in Europe. Along with voice communication, transmission of data for applications such as aircraft communication addressing and reporting system (ACARS) also requires allocation of spectrum. The proposed spectrum sensing scheme can enable the identification and allocation of spectrum holes of varying BWs and locations for different communication applications. Thus by enabling CR based dynamic spectrum access, the proposed spectrum sensing scheme can help to overcome the static spectrum allocation problem in current air-ground communication systems, and achieve intelligent and efficient usage of the limited licensed spectrum.

Consider a spectrum sensing scenario wherein spectrum holes are to be detected in a wideband frequency range of 2.5MHz from 108MHz to 110.5MHz, within the 108MHz to 137MHz air-ground communication frequency range. Fig. 3(a) shows an input signal spectrum wherein three spectrum holes (SH1 of BW 8.33KHz, SH2 and SH3 of BW 25KHz) exist at different locations as shown. Fig. 3(b) shows the three pairs of frequency responses obtained using VDF I (provides fcl) and VDF II (provides fcu) in the proposed scheme, which are used to detect the spectrum holes shown in Fig. 3(a). Thus it can be noted that VDF I and VDF II outputs can be appropriately coupled to detect spectrum holes of varying BW and location in the input frequency range. For the specifications f_p =0.4985, f_s =0.5015, δ_p=0.1dB and δ_s=-40dB, we obtain N=1328, using (2). The total number of multiplications required to implement corresponding filter coefficients and realize the VDF branches in the proposed scheme as shown in Fig. 2(b) is 3321. For a conventional design approach wherein two lowpass and one highpass prototype filter branches are implemented, the total number of multiplications required is 5314, which is 60% higher than the proposed scheme mainly due to distinct sets of filter coefficients implemented in the lowpass and highpass filter branches. For the design approach proposed in [20], the total number of multiplications required is 4649, which is 40% higher than the proposed scheme due to use of one additional multiplier per filter coefficient to perform lowpass to highpass frequency response transformation. Thus the VDFs in the proposed scheme are low complexity alternatives to the other relevant VDFs in literature.

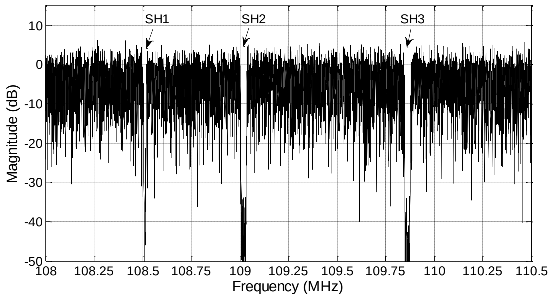

Fig. 3(a). Input signal spectrum with three spectrum holes (SH1, SH2, SH3).

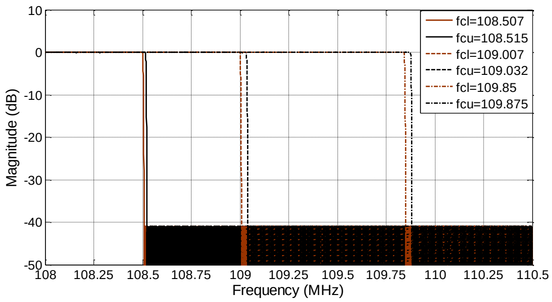

Fig. 3(b). Frequency response pairs obtained using VDF I and VDF II, which are used to detect spectrum holes in Fig. 3(a).

IV. Conclusion

In this paper, we proposed an energy detector based spectrum sensing scheme for CR based air-ground communication systems. The proposed scheme employs VDFs based on first order all pass transformation and the modified coefficient decimation method. With the help of a design example, we showed that VDFs employed in the proposed scheme are low complexity alternatives to the other relevant VDFs in literature. The proposed low complexity spectrum sensing scheme can help not only in solving the static spectrum allocation problem in current air-ground communication systems, but also in achieving energy efficient green communications (in terms of transmitted power as well as implementation complexity). It can be noted that the proposed scheme is not limited to spectrum sensing in air-ground communication applications; it can be used for spectrum sensing in multi-standard communication scenarios as well.

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