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A Power-efficient Spectrum Sensing Scheme using One-bit Quantizer and Modified Filter Banks

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Abstract—Spectrum sensing is an efficient way to determine spectrum availabilities over the frequency range of interest, aiding in improving the spectrum utilization in Cognitive Radio (CR) systems. Conventional Nyquist multiband sensing entails higher computational capability for sampling, quantization, and subsequent processing, lending the approach infeasible for applications with limited power budgets. In this paper, a power-efficient spectrum sensing technique is proposed that explores an accuracy-complexity tradeoff. The presented spectrum sensing architecture is based on one-bit quantization at the CR receiver, and implements it in hardware by a resource- and power-efficient approach, using a Finite Impulse Response (FIR) filter bank channelizer. The proposed scheme allows complex operators like multipliers and quantizers to be replaced by inverter logic and high-speed comparators, reducing the hardware complexity and power consumption. We validate the proposed scheme on an FPGA emulator for an aeronautical LDACS application, and our results show that the proposed scheme achieves substantial resource reduction with at most 5% degradation in detection accuracy in this case.

Index Terms—Cognitive radio, Spectrum sensing, one-bit quantization.

I. INTRODUCTION

COGNITIVE Radio (CR) [1] is a key technology that can enable improved spectrum utilization in future communication networks with the opportunistic access of the spectrum in a dynamic fashion. In CR networks, the unlicensed or secondary users (SUs) dynamically detect unused spectrum (called spectrum holes) within the licensed band, using various spectrum sensing methods [2]. The SUs should relinquish the spectrum immediately once the licensed user (primary users (PUs)) start transmission to ensure minimal disruption for PUs. Spectrum sensing can be classified into narrowband and multiband sensing schemes based on the number of frequency channels that are sensed in parallel. In case of narrowband sensing, the detector finds the occupancy of a single frequency channel at a time, while multiband sensing aims at simultaneously detecting multiple spectrum holes within a band of interest, which could be channels of equal or unequal bandwidths.

Different approaches are discussed in the literature to simultaneously scan/sense multiple frequency channels. Sub-Nyquist approaches [3] had been shown to reduce the long sensing duration and computational complexity induced by

Nyquist rate implementations. These approaches can be realized through compressive sensing [3], in which the features of the signals are represented using fewer number of signal samples by exploiting the sparse nature of the signal in some domain. However, compressive sensing requires hardware support in the form of a new analog to digital converters (ADC) with dynamically varying sampling speed. Also, a non-optimum number of samples leads to the improper representation of the PU signal, leading to erroneous detection. In Nyquist rate systems, the spectrum sensing is composed of several narrowband sensing [2] where filterbank can be used to divide the spectrum into equal or unequal individual parts.

Though conventional Nyquist rate spectrum sensing schemes use different ways to balance the trade-off between the complexity and the accuracy, they demand high-resolution ADCs with very high sampling rates to get the desired detection accuracy. The high sampling rate and resolution (bit-width) also result in considerable power overhead for base-band processing. In [4], it is shown that a low-resolution quantizer can operate at higher sampling rates consuming less power compared to a high-resolution quantizer operating at the same sampling frequency. The power consumption of a one-bit ADC with higher sampling rates is much less than that of a higher resolution ADC with the same sampling frequency. Also, one-bit ADC is hardware efficient as it can be easily implemented with a high-speed comparator. Two different approaches of one-bit quantizer based spectrum sensing are discussed in the literature. The first approach utilizes a conventional fast Fourier transform (FFT)-based wideband spectrum sensing that is modified by introducing one-bit quantizer followed by the sampling circuit [5]. Here, a sign change logic replaces the initial layer of multipliers in the butterfly implementation, resulting in a significant reduction in computational complexity; however, limitations imposed by the butterfly structure and FFT depth affect the frequency resolution of this scheme. The second approach discussed in [6] uses a combination of windowed autocorrelation and Fourier transform to estimate the power spectral density of the signal [6]. This approach also faces limitations similar to the FFT-based scheme discussed above. Moreover, both of these schemes only deal with equal width channels, which only caters to a subset of multi-standard radio applications.

In this paper, a filter bank (FB) based one-bit quantizer multiband sensing architecture is proposed. Similar to the one-bit sensing schemes discussed in [5], [6], the autocorrelation property induced by the high sampling of a low baud rate signal provides the spectrum occupancy information for the sensing logic. The proposed architecture replaces the multiplier in each filter tap by a selective sign inversion logic which

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Fig. 1: (a). Filterbank assisted multiband spectrum sensing scheme. (b). Transposed direct form FIR filter structure.

can be implemented using a 2's complement circuit and a 2:1 multiplexer. This optimization reduces the computational complexity, allowing multiple sensing paths to be integrated simultaneously without significant resource/power overheads. Furthermore, as the detection logic uses energy as the feature for decision making, this technique can be applied in a generic multi-standard communication system irrespective of the modulation standard and channel widths used by individual systems [2]. We evaluate the architecture using an L-band digital aeronautical communication system (LDACS) [7] as a case study in Section II-D. The approach can be efficiently applied to determine equal-width bands (as in the case of LDACS) or unequal channel widths (multi-standard CR [8]) by tuning the filter coefficients.

II. PROPOSED SENSING SCHEME

A. Conventional Filter Bank based Spectrum Sensing

Conventional filterbank (FB) based spectrum sensing scheme is illustrated in Fig. 1(a). As shown in the figure, in FB assisted spectrum sensing, the frequency band is split to narrowbands of equal or unequal bandwidths using a bank of filters. The decision algorithm is then applied individually on each channel. The transposed direct form realization of an finite impulse response (FIR) filter is shown in Fig. 1(b). As shown in the figure, the realization requires a large number of multipliers, which increases the implementation complexity. Various reconfigurable filter architectures available in literature such as coefficient decimation [8], and interpolation and masking [9], can be used to reduce the number of multipliers and hence the implementation complexity by using a fewer number of multipliers. Though all these techniques are computationally effective compared to the conventional per channel approach and modulated filterbanks, they still require a considerable number of multipliers to extract the different frequency responses in parallel. This makes them less suited for power-constrained implementations.

B. Architecture of the proposed sensing scheme

The block diagram representation of the proposed one-bit quantizer based spectrum sensing scheme is shown in Fig. 2(a). At the secondary receiver, the incoming signals are processed in the RF domain to increase signal gain and to reduce noise levels and are then down-converted to baseband for further processing/decoding [6]. The incoming signal is sampled using a high-speed sample and hold circuit;

Fig. 2: Overview of the proposed low power spectrum sensing scheme using one-bit quantizer.

Fig. 3: Illustration of the effect of one-bit quantization on the power spectral density.

then the signal samples are quantized through a high-speed comparator that considers the sign of the input signal. This results the quantized output signal a member of the set $\{1 + j, 1 - j, -1 + j, -1 - j\}$. The output of the quantizer is connected to the inputs of the FB with M FIR filters which are implemented in parallel. The Multiplier-less FIR filter design is schematically shown in Fig. 2(b). The effect of the quantization in the representation of the power spectral density is shown in Fig. 3, the power spectral densities are plotted for the received noisy signal at SNR=0 dB. It can be observed from the figure that there is a power leakage due to the quantization. However, the spectral holes are still evident in the quantized version. As shown in [4], at low SNR regimes, the effect of low-resolution ADC towards spectral leakage is very less.

The received energy over time from each narrowband is estimated using an autocorrelation-based energy estimator. The soft energy measurements are given as inputs to a decision algorithm to classify the narrowbands into vacant and occupied ones. In this design, the filter structure is same as a transpose of direct form filter where the multiplication operation at each tap is replaced by a 2:1 multiplexer and a 2's complement circuit that selects one among its two inputs $\{h_i, -h_i\}$ based on the input signal sign.

C. Detection Algorithm

While designing the detection algorithm, it is assumed that all subbands of interests are of equal bandwidth. Practical constraints such as limited sensing window are accounted for,

to improve spectrum efficiency and throughput, and a real-time noise floor estimation is performed, assuming that not all channels are occupied simultaneously at any given time. In FB based sensing, the frequency channels of interest are filtered using precomputed/predetermined filter coefficients. The decision-making algorithm for one-bit quantizer based spectrum sensing is given in Algorithm 1. Once the energy estimates $E(m)$ are computed for all M sub-channels, the decision algorithm evaluates the estimates to determine the ones with the lowest energy (E_{min}), which is assumed to be an unoccupied channel. The total noise variance is estimated by averaging the energies of the subbands, which are in a noise uncertain region $E_{min} \leq E(m) \leq \alpha E_{min}$, where α represents the uncertainty factor. Decision threshold is then computed as a function of false alarm and the estimated noise variance. Threshold is computed as $\left(Q^{-1}(P_{fa})\sqrt{\frac{Count}{N}} + 1\right)$ times the noise variance $\hat{\sigma}_w^2$, where P_{fa} is the false alarm rate, $Count$ is the number of channels in the noise uncertain region, and N is the number of signal samples used for detection. The function is chosen to limit the false alarm to acceptable limits while providing high detection probability.

D. Design Example

To evaluate the proposed scheme, we consider a practical communication system that uses the L-band spectrum. L-band digital aeronautical communication system (LDACS) [7], [10] is identified as the mature candidate to meet potential future needs and to support aviation growth in the future. The LDACS shares the frequency spectrum with legacy distance measuring equipment (DME) channels in the frequency range 960 – 1164 MHz. Each LDACS channel is of 0.5 MHz width, and their central frequency is 0.5 MHz and 1 MHz apart from the adjacent DME and LDACS channels respectively. CR enabled dynamic spectrum allocation is proposed in LDACS to

Algorithm 1 Decision-making algorithm for one-bit quantizer based spectrum sensing

Input: Estimated energy measurements $E(m), \forall m = 1 \dots M$,
 $E(m) = \frac{1}{N} \sum_{n=0}^{N-1} |y_m(n)|^2$, where $y_m(n)$ is the signal extracted from the m^{th} band.

- 1: $E_{min} = \min\{E(m)\} \forall m = 1 \dots M$
- 2: $E_{temp} = 0, Count = 0$
- 3: **for** $i = 1$ to M **do**
- 4: **if** $(E(m) \leq \alpha E_{min})$ **then**
- 5: $E_{temp} = E_{temp} + 1; Count = Count + 1$
- 6: **end if**
- 7: **end for**
- 8: Noise variance estimate, $\hat{\sigma}_w^2 = \frac{E_{temp}}{Count}$
- 9: Decision threshold, $\lambda = \left(Q^{-1}(P_{fa})\sqrt{\frac{Count}{N}} + 1\right) \hat{\sigma}_w^2$
- 10: **for** $i = 1$ to M **do**
- 11: **if** $(E(m) \geq \lambda)$ **then**
- 12: Channel m is occupied
- 13: **else**
- 14: Channel m is vacant
- 15: **end if**
- 16: **end for**

improve the spectrum utilization efficiency [11], [12]. Spectrum sensing is deployed in this scenario to detect the spectral holes.

Unlike terrestrial systems, spectrum sensing in aeronautical domain presents unique challenges such as limited power budget and varying channel characteristics. Nyquist rate spectrum sensing is a tedious and computationally intensive task, and its high power consumption made it impractical in aeronautical systems. Though improved techniques like cross-correlator-based sensing without deploying multipliers [13], cyclostationary detection [14] and energy difference detection [15] have been proposed for spectrum sensing in LDACS, they require higher quantization rates that makes it inappropriate for parallel multiband sensing. One-bit FFT [5] and auto-correlation [6] based spectrum require the analysis of the whole spectrum to find the power spectral density of the individual frequency channels and are hence cannot be applied to the LDACS scenario. Also, these techniques are ideal for sensing the wideband of the order of GHz, while the proposed technique can be applied to a wideband of 10 MHz comprised of 10 LDACS and DME channels each. Filter bank assisted spectrum sensing is the ideal choice in this scenario since the required areas of the spectrum can be selected in the proposed approach using the desired channel responses. The filter-coefficients can be pre-computed in this case as the channel location and bandwidth are already known, and the noise variance estimation is straight forward as all the channels are of the same bandwidth.

E. FPGA Implementation

To evaluate the reduction in computational complexity and resource consumption in hardware, we implement the proposed scheme using Verilog hardware description language and map it onto a radio platform based on the Xilinx Zynq hybrid system on chip [12]. We focus on the receive interface and integrate the proposed scheme at the output of the filterbank, which receives the downconverted signals from the RF interface logic interfacing with the analog devices radio front-end (AD-FMCOMMSS4-EBZ). The integration of the

Fig. 4: Architecture of the cognitive radio enabled LDACS radio platform with the one-bit sensing scheme.

Fig. 5: Probability of detection versus SNR: Effect of filter coefficients bit-width.

proposed spectrum sensing scheme into the receive path of our radio platform is shown in Fig. 4. More details of the radio architecture is available in [12]. A quantiser logic within the filterbank generates the one-bit input samples required by the proposed scheme, based on the sign bit of the received sample. The samples and filter coefficients are represented using two's complement notation to reduce hardware overhead.

The quantised input samples received by our logic is registered, and the output of which fed as the select line of the chain of 2-to-1 8-bit multiplexers which select respective filter coefficients based on the sign. The filter coefficients themselves are stored as a bank of registers, and are mapped as addressable locations from the ARM cores to allow these to be altered at run-time. The output at each stage is accumulated along the chain as in the case of an FIR filter; the final accumulated output over the sensing period (configured by default to 10000 samples by the programmable *sample-depth* register) is squared to generate the estimate of the energy value. The quantisation width of registers were set to 8-bits since there was no appreciable gain observed in the sensing process at higher bit-widths to justify the higher resource overhead (discussed in the results section). The bit-width of the delay pipeline was chosen to ensure that the overflows are contained within the bitwidth for the sensing period configured at design time. Multiple such sensing channels are attached to the outputs of each tap of the filterbank to perform parallel sensing. Each channel computes the energy estimate independently and uses its own register space to store the filter coefficients independent of other channels. The output of all channels are evaluated by the cognitive logic simultaneously to determine the most appropriate channel for air-to-ground transmission at that instance. When the system operates in receiver mode (i.e., receiving information from ground stations or other aircrafts), the output from the chosen channel output of the filterbank is fed into the baseband logic downstream, bypassing the quantisation and sensing logic.

III. RESULTS AND DISCUSSION

A. Simulation Results

As mentioned in Section II-D, we consider a band of 10MHz, which consists of 10 LDACS channels of bandwidth 0.5 MHz. After the one-bit quantization process, the 10

Fig. 6: Probability of detection/probability of false alarm (in red color) versus SNR under different uncertainty factors (α) in dB.

Fig. 7: Probability of detection curves for the proposed one-bit quantization scheme versus the ED [15], multiplier-less correlator [13], and one-bit autocorrelation based scheme[6].

LDACS channels are extracted using the bank of filters. The filter coefficients are estimated using the Parks-McClellan algorithm. To optimize the essential quantization level requirement for filter coefficients, we analyzed the performance using different quantization levels ($n = 6, 8, 10$ and 12) and observed that there is no appreciable gain beyond 8-bit quantization, which is demonstrated in Fig. 5. It is observed for a bit width of 8, the detector provides 100% accuracy even at -12 dB SNR. Fig. 6 shows the detection and false alarm performances of the proposed scheme for different uncertainty values (α). The curves are plotted for a wide range of SNR from -24 dB to 0 dB. As shown in the figure, the performance is analyzed for three different values of α ($\alpha = 0.1, 0.2$ and 0.3 dB). When lower values of noise uncertainty are assumed, an increased probability of detection is observed. As a trade-off, the false alarm rate is increased for low SNR regimes. For larger values of α , the detection rate is reduced along with the false alarm reductions. It is to be noted that, for $\alpha = 0.1$ dB, the false alarm rates are still within the permissible limits. In Fig 7, the detection performance of the proposed scheme is compared with the conventional spectrum sensing schemes [13], [15] and the one-bit autocorrelation [6] based schemes. For our evaluation, the received one-bit quantized signals are used as inputs to the hardware implementation (post place and route simulation performed with preloaded RAM contents). It is observed that

TABLE I: Resource consumption comparison of proposed design (for 10 narrowbands) and the competing schemes.

Design	FFs	LUTs	Slices	DSPs
Proposed design	65732	57755	–	20
Mless correlator[13]	24,000	29,895	7,806	0
Correlator with multipliers [13]	11968	6112	1528	1500
Eigenvalue detection [16]	0	5177	1892	64
Conventional ED [17]	6592	12038	6972	48
Adaptive ED [18]	6179	5220	3257	55

the hardware implementation closely followed the MATLAB model when tested with an actual LDACS frame structure. It is observed that the detection performance of the non-quantized schemes [13], [15] are slightly better than that of the proposed scheme. On the other side, the proposed scheme performs much better than that of the one-bit autocorrelation based schemes, with comparable complexity. While considering the accuracy-complexity trade-off, the proposed scheme is much efficient than that of conventional multi-bit schemes.

B. Implementation Results

To evaluate the resource overheads of the proposed sensing scheme and to estimate its power consumption, we implement the design on a Xilinx Zynq XC7Z045 FPGA board, that forms the processing logic for the radio platform. The detailed resource consumption of the design is shown in Table 1. The design achieves an operating frequency of 125 MHz on the device, and the complete design consumes only 26.4% of the resources on the Zynq design even with all 10 channels implemented in parallel, allowing the entire processing chain to be implemented on the same design without the need for advanced techniques like partial reconfiguration. For comparison, we also implemented the multiplier-less correlator (Mless correlator) scheme on the same device, and observe that the multiplier-less design consumes almost the half the resources (LUTs) for sensing one narrowband. The results of the comparison along with competing schemes are given in Table I. We also evaluate the power consumption on the device using the power analyser tool integrated into Xilinx's Vivado toolflow; to provide an accurate estimate, we simulate the post routed design feeding actual LDACS frames as inputs at a clock frequency of 100 MHz (LDACS frames generated from the code released by DLR). The tool estimate that the design consumes a mere 408 mW in operation with a static power consumption of 203 mW, which is significantly lower than the 1038 mW consumed by the multiplier-less correlator based spectrum sensing scheme in [13]. The lower power consumption, combined with the overall resource efficiency in performing parallel sensing across all channels makes this design an ideal choice for deployment in power constrained scenarios like an aircraft on-board system.

IV. CONCLUSION

In this paper, we explored a power-efficient scheme for wideband sensing in CR networks using a one-bit quantised computational pipeline. The proposed scheme uses a modified FIR pipeline aiming to reduce the computational complexity by replacing the multiplier at each tap with a multiplexer that uses the one-bit quantised signal to select between two possible filter coefficient values. We implemented the proposed architecture in hardware and evaluated the system using

a simulated LDACS scenario, using the signals generated through LDACS communication model, mimicking an actual LDACS transmission system. A detection algorithm is also proposed to utilise the output of this architecture for efficient sensing by reducing the effect of power leakage from occupied subbands. Our results show that a one-bit quantized signal can be effectively deployed to detect spectral holes in a multiband scenario, and the architecture combined with the detection scheme provides a good accuracy-complexity trade-off among competing spectrum sensing schemes.

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