POWER OPTIMISATION FOR ADAPTIVE EMBEDDED WIDEBAND RADIOS

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Publications

Journals

J1. **T. H. Pham**, S. A. Fahmy, and I. V. McLoughlin, "Low-power correlation for IEEE 802.16 synchronisation on FPGA," *IEEE Trans. on Very Large Scale Integration (VLSI) Systems, vol. 21, no. 8, pp. 15491553, Aug. 2013.*

J2. **T. H. Pham**, I. V. McLoughlin, and S. A. Fahmy, "Robust and Efficient OFDM Synchronisation for FPGA-Based Radios," *Circuits, Systems, and Signal Processing, vol. 33, no. 8, pp. 24752493, Aug. 2014, Springer.*

Conferences

C1. **T. H. Pham**, I. V. McLoughlin, and S. A. Fahmy, "Shaping Spectral Leakage for IEEE 802.11p Vehicular Communications," in *Proceedings of the IEEE Vehicular Technology Conference (VTC Spring), Seoul, Korea, May 2014.*

C2. **T. H. Pham**, S. A. Fahmy, and I. V. McLoughlin, "Efficient Multi-Standard Cognitive Radios on FPGAs," PhD Forum Poster in *Proceedings of the International Conference on Field Programmable Logic and Applications (FPL), Munich, Germany, September 2014.*

Papers under Review

J3. **T. H. Pham**, S. A. Fahmy, and I. V. McLoughlin, "Enhanced OFDM Synchronization Through Novel Integer Frequency Offset Estimation Architecture,"

J4. **T. H. Pham**, S. A. Fahmy, and I. V. McLoughlin, "A Novel Shaping Spectral Leakage Scheme for OFDM-Based Systems,"

J5. **T. H. Pham**, S. A. Fahmy, and I. V. McLoughlin, "Efficient Multi-Standard Cognitive Radios on FPGAs,"

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Chapter 1

Research Introduction

1.1 Background

Wireless communications is advancing rapidly in terms of both the number of applications and the bandwidth requirement of applications. The increasing data rate results in the consumption of bandwidth while radio spectrum is a limited resource. Rapidly growing requirements for additional bandwidth has resulted in the possibility of spectrum scarcity. In addition, inefficient use of the spectrum is another reason which contributes to the threat of spectrum scarcity. Practical studies have shown that many licensed bands are relatively unused across time and frequency [1]. To improve the efficiency of using radio spectrum resources, the concept of unlicensed users temporarily reusing unused spectrum in licensed bands is currently being researched. This concept is known as dynamic spectrum access (DSA) [2]. Wireless communication systems for realizing DSA are required to be both reconfigurable and adaptive to improve spectrum utilization while not interfering with the communication of licensed applications and other unlicensed opportunistic users.

A cognitive radio (CR) is a node that is able to adapt its parameters to optimise performance based on interaction with the environment, as well as to perform DSA. A cognitive radio would be able to change parameters such as transmit power, coding rate, frame size, bandwidth, and centre frequency in real time to obtain suitable performance in a given, changing, environment. The radio would also be reconfigurable to be able to adjust compatibility with various useful wireless standards such as WiFi, WiMAX, GSM, WCDMA, and other defined access schemes.

Orthogonal Frequency Division Multiplexing (OFDM) has been adopted for implementation within the Cognitive Radio field, and is a prime candidate for Dynamic Spectrum Access

(DSA) networks in which the radio is required to be spectrally aware and able to dynamically access idle parts of the spectrum. OFDM is an efficient multi-carrier modulated (MCM) technique that provides robustness to frequency selective channels and the ability for employing spectrum pooling, where unlicensed users may temporarily access spectral resources during the idle periods of licensed users [3]. When transceiving signal across a given bandwidth, OFDM subcarriers that cause interference with licensed users can be selectively disabled. This technique is defined as non-contiguous orthogonal frequency multiplexing (NC-OFDM) [4].

The lower priority of CR raises a challenge in term of transmission capability and quality of service. When the spectrum allowed for a CR system is fully occupied by PUs and IUs, the transmission of CRs can be blocked. Multiple Standard Cognitive Radios (MSCRs) are able to operate in multiple frequency bands with different specified standards. MSCRs are hence a more flexible generalisation of CRs as they can operate across different bands and standards to increase transmission capability and enhance the bandwidth efficiency.

1.2 Objective and Motivation

The MSCR requires the platform that provides the flexibility, the high computational throughput, and power efficiency. Most practical CRs are built using powerful general purpose processors to achieve flexibility through software but they fail to offer the computational throughput and have high power consumption. Multiple processors on chip (MPOC) architecture can enhance the throughput; however, this platform relates to intensive parallel programming and consumes significant more power because it require a large buffer to move data around parallel processes. Conversely, custom hardware designs such as application specific integrated circuits (ASICs) offer highly efficient computation, maximum throughput and possibly low power dissipation; however, they suffer from a lack of flexibility, which must also be decided at design time. In an application area with fast moving standards and support multiple standards, ASICs is a waste time and cost option for MSCR. Modern FPGAs with supporting partial reconfiguration (PR) is an attractive candidate for cognitive radios. They provide not only the high performance of a custom data-path implementation, and also offer flexibility with low power dissipation.

The feasible of MSCR implementation depends on flexibility of switching system parameters specified by from one standard to another. Multi-carrier modulation based techniques are widely investigated for state of the art and also next-generation wireless standards. These techniques divide communication channel into multi-sub-channels that allows a system to perform parallel data transmission over smaller sub-channels to combat amplitude and phase distortion, impulse noise, multipath propagation and so on. OFDM and Filter Bank Multi Carrier (FBMC) are two types of multi-carrier modulations. OFDM modulation has been the dominant technique adopted for multiple applications in high bit-rate wireless communication systems such as Wireless Local Area Networks (WLAN) standardized in IEEE 802.11 and Metropolitan Area Networks (MAN) in IEEE 802.16. It is effective to perform spectral sensing and carrier allocation for CRs. Furthermore, OFDM modulation requires a simple and low cost implementation and effectively parameterizes the system to flexibly switch from one standard to another in comparison to FBMC modulation. OFDM should be a suitable candidate for a MSCR system. The advantages of the coupling OFDM modulation and FPGA platform are investigated for the feasible of implementing the proposed low cost, low power MSCR system. The ability of PR in FPGA and effective parameterization in OFDM modulation allow the MSCR to be built for not only current OFDM-based standards such as 802.11, 802.16, and 802.22, but also be able to soft upgrade for future OFDM-based standards.

OFDM-based system has two main intrinsic disadvantages related to synchronization and spectral leakage. They become critical challenges in scenarios of OFDM-based MSCR. The state of the art synchronization of OFDM-based system can tolerate a small carrier frequency offset (CFO) that leads to high strict constraints for RF front-end design. In MSCR system, RF front-end is required an ability of switching frequency carriers in wide range according to operating standard that make the constraints of small CFO may not be feasible. A novel synchronization method that is robust to large CFO should be researched for OFDM-based MSCR system. Another challenge is that CRs normally demand small spectral leakage for both in-band and out-band of transmitted signal while OFDM signal causes spectral leakage. Pulse shaping techniques are widely studied to limit the spectral leakage of OFDM signal. But Pulse shaping techniques cannot help to effectively filter out-band spectrum in case of small frequency guard because of the present of image spectrum caused by interpolation or digital analog convertor. Fortunately, MSCR system provides flexible parameters that allow perform a frequency guard extending technique and combine with an effective Pulse shaping technique to achieve the spectral leakage requirements.

The motivation of this research is to study a low power architecture for MSCR based on coupling the PR modules and parametterised modules to minimise the adaptive time. In addition, a novel method for synchronization and an effective Pulse shaping technique are studied to be suitable for the requirements of MSCR systems.

1.3 Research Contributions

This thesis addresses the design of low complexity, low power wideband radios with the flexibility to support multiple standards. The contributions of the thesis, which are published or under review as listed in "Publications" section above, are elaborated below:

(i) A multipilerless cross-correlation is proposed in [J1] to perform OFDM synchronisation for a low power, low complexity systems. The conventional approach, with the availability of embedded DSP blocks on these FPGAs, is implemented using standard multiplier-based cross-corellation. However, this can consume a significant number of DSP blocks, and may not fit on low-power devices. A comparison of DSP48E1 Slice-based design and four different quantisations of multiplierless correlation is investigated in terms of resource utilisation and power consumption on Xilinx Virtex-6 and Spartan-6 FPGA devices. OFDM timing synchronisation accuracy is evaluated for each system at varying signal-to-noise ratio. This research show that even relatively coarse multiplierless coefficient quantisation can yield accurate timing synchronisation, and do so at high clock speeds. Multiplierless designs enjoy reduced power consumption over the DSP48E1 Slice-based design, and can be used where DSP Slice resources are insufficient, such as on low-power FPGA devices.

(ii) A novel OFDM synchronization method that combines robust performance with computational efficiency is proposed in [J2]. FPGA prototyping is used to investigate the trade-off between the number of computations to be performed and computation word length with respect to both synchronization performance and power consumption. Through simulation, the proposed method is proven to provide accurate fractional CFO estimation as well as STO estimation in a range of channels. In particular, it can yield excellent synchronization performance in the face of a CFO that is larger than many state-of-the-art synchronization implementations can handle. The system implementation demonstrates efficient resource usage and reduced power consumption compared to existing methods and this is explored as a fine-grained trade-off between performance and power consumption. The proposed method is robust and suitable for use in low-power radios or some multi-standard radios, enabling less precise analogue front-ends to be used.

(iii) The third contribution presented in [J3] proposes a novel approach for implemeting IFO estimation, which reduces both power and computational cost of system. Performing the IFO cross-correlation using four-fold resource sharing reduces the estimation cost. Meanwhile, adopting a multiplierless technique and carefully optimising word lengths yields significant power reduction, while maintaining sufficient accuracy to meet performance requirements. The method is studied in theoretically, using numerical simulation and with post place-and-route analysis. The novel method is shown to achieve excellent performance, similar to the theoretically achievable bound. In fact, performance is significantly better than conventional techniques, while being much more efficient. In case of applying for IEEE 802.16-2009, the proposed method saves significant power over the conventional technique on low-power FPGA devices. The method is also applicable to IEEE 802.11 and IEEE 802.22. Coupling the robust OFDM synchronisation presented in [J2] and Performing IFO estimation at baseband is importance to allow the RF front-end specification to be relaxed, thus reducing system cost. In fact, for some multi-standard radios, and applications suffering significant Doppler shift, RF constraints may be infeasible without techniques such as IFO estimation.

(iv) The forth contribution firstly published in [C1] and then extended in [J4] proposes a novel method that explores the Cognitive Radio (CR) architecture in a new filtering scheme for adaptively shaping spectral leakage of OFDM signal according to the transmitted power and Spectrum Emission Mask (SEM) requirements. OFDM presents a disadvantage in term of spectral leakage due to large side lobes in signal spectrum. In addition, some recent OFDM-based standards such as 802.11p for vehicular communication and 802.11af for reusing Television White Spaces (TVWS) demand the strict requirements on spectral leakage that raises a tough challenge for radio frequency (RF) front-end circuits. The proposed method can achieve the specification for the most stringent SEM of 802.11p.

For 802.11af, it not only meets the requirement of strict SEM but also feasibly increase the spectrum usage of 10 sub-carriers in a basic channel band without violating the SEM specification. The proposed method, performed at baseband to relax the strict constraints of the RF front-end, allows the RF front-end to be implemented using commercial off-the-shelf (COTS) RF hardware, resulting in reduced total system cost.

(v) Cognitive radios that support multiple standards and modify operation depending on environmental conditions are becoming more important as the demand for higher bandwidth and efficient spectrum use increases. Traditional implementations in custom ASICs cannot support such flexibility, with standards changing at a faster pace, while software implementations of baseband communication fail to achieve the performance required. Hence, FPGAs offer an ideal platform bringing together flexibility, performance, and efficiency. The fifth contribution presented in [C2, J5] proposes and explores the possible techniques for designing multi-standard radios on FPGAs. This contribution presents the mathematic analysis the performance of proposed architecture for MSCR based on mixing the PR modules and parametterised modules. The calculated results based on the FPGA systhesis show that the proposed architecture achieves a significant reduction in terms of system latency compared to conventional structure. The proposed method requires a very small FIFO in comparison to conventional structure. This allows a MSCR be implemeted on FPGA platform for a low cost, low power systems.

1.4 Organization

This thesis is organized as follows: Chapter 2 presents the comprehensive background of this research. Power consumption on FPGA devices is investigated. Power estimation tool and also low power design strategies, particularly focused on implementing OFDM systems on FPGA, are studied and discussed. This chapter provides the background for OFDM in terms of mathematical representation and functionality, and then the advantages and limitations of OFDM are also discussed. Moreover, the chapter also consists of the introduction to MSCR. The related works on MSCR research are presented and discussed to show the main challenges of implementing a MSCR. The synchronisation issue of OFDM systems is deeply considered, and the related work focusing on achieving the good performance of synchronisation is discussed on its merits as well as limitations. The challenge of shaping spectral leakage is studied for the stringent SEM constraints of the state of the art wireless standards.

Chapter 3 presents the design of several correlators for timing synchronisation with preamble symbols based upon IEEE 802.16d standard. The comparison between a DSP48E1 Slice-based design to four different quantisations of multiplierless correlation is shown and discussed in terms of resource utilisation and power consumption. OFDM timing synchronisation accuracy is evaluated for each system at varying signal to-noise ratio.

Chapter 4 researches the issue of synchronisation in OFDM system receivers in terms of timing offset and frequency offset. A robust and efficient synchronisation method is proposed and discussed. The performance of the proposed method is evaluated in comparison to methods in previous works in terms of robustness to large CFO, accuracy of time synchronisation and fractional CFO estimation in both additive white Gaussian noise (AWGN) and frequency selective channels. The results shows the proposed method to achieve a more accurate fractional CFO estimation and to be robust to the large CFO while still obtaining acceptable accuracy for frame synchronisation. In addition, this chapter presents a novel approach for implemeting IFO estimation, which reduces both power and computational cost in implementation. The efficiency and hardware reduction are shown in the simulation results as well as implementation reports.

Chapter 5 studies on the novel shaping spectral leakage scheme at the baseband replied upon the cognitive radio architecture. The proposed method can meet the specification of class D, the most stringent of the four 802.11p SEMs and the stringent SEM of 802.11af. The proposed method also enhances the spectral efficiency in case of reusing the Television White Spaces in 802.11af standard.

Chapter 6 explores the feasibility of designing efficient multi-standard radios to improve bandwidth efficiency and avoid spectrum congestion. A novel MSCR architecture is proposed and investigated in term of performance and hardware reduction.

Finally, we conclude this research in Chapter 7, then give an outline and schedule of our future research plans.

Chapter 2

Background Literature

Chapter 3

Multiplierless Correlator Design for low-power systems

Chapter 4

Proposed Method for Synchronisation

Chapter 5

Proposed Method for Shaping Spectral Leakage

Chapter 6

A Novel Architecture for Multiple Standard Cognitive Radios

Chapter 7

Conclusion and Future Work

References

[1] Federal Communications Commission, "Spectrum policy task force report," Tech. Rep. No. 02135, 2002.

[2] R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, *OFDM-Based Cognitive Radios for Dynamic Spectrum Access Networks*. The University of Kansas, USA.

[3] T. A. Weiss and F. K. Jondral, "Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency," *IEEE Radio Communications*, March 2004.

[4] R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "An efficient implementation of NC-OFDM transceivers for cognitive radios," in *Proceedings of the 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, June 2006.