Reconfigurable NC-OFDM Processor for 5G Communications

Mário Lopes Ferreira
INESC TEC
and
Faculty of Engineering,
University of Porto
Rua Dr. Roberto Frias
4200-465 Porto, Portugal
Email: mlf@inescporto.pt

João Canas Ferreira
INESC TEC
and
Faculty of Engineering,
University of Porto
Rua Dr. Roberto Frias
4200-465 Porto, Portugal
Email: jcf@fe.up.pt

***Abstract*—The proliferation of new wireless communication technologies and services led to a boost in the number of different available communication standards and spectrum usage. As the electromagnetic spectrum is a finite resource, concerns about its efficient management became an important aspect. Given this scenario, Cognitive Radio emerged as a solution for future wireless communication devices, by supporting multiple standards and improving spectrum utilization through opportunistic wireless access. The purpose of this research is to study and design a reconfigurable FPGA-based NC-OFDM baseband processor meeting the requirements of next generation Cognitive Radio devices in terms of multi-carrier, multi-standard communications and spectral agility in changing environments. The processor will be the core of a flexible NC-OFDM transceiver for future 5G communications with support for spectrum aggregation and run-time selection of modulation schemes and active sub-carriers. The goal is to achieve higher levels of system adaptability, upgradeability and efficiency, by employing dynamic partial reconfiguration of FPGAs.**

Keywords*—*Cognitive Radio, NC-OFDM, Dynamic Spectrum Aggregation, FPGA, Dynamic Partial Reconfiguration (DPR)

I. Introduction

The wireless communications technology field is constantly experiencing developments leading to the creation of new modes of operation and services for mobile devices. The ever increasing number of different applications provided drove the development of different standards and protocols for Wireless Communication systems. It is not expected that the emergence of new standards will stop soon, and organizations such as the IEEE or the ITU have played a major role in standardizing wireless access systems. Consequently, it is important that communication devices are able to handle such a wide variety of the existing wireless communication standards.

On the other hand, wireless technologies make use of the electromagnetic spectrum, which is a natural, finite resource and whose utilization is supervised and licensed by national governments. The proliferation of new wireless communication technologies and services caused a boost in spectrum usage, creating concerns about the management of this precious resource. Nevertheless, spectrum access is quite often a more significant problem than spectrum scarcity. Some portions of spectrum assigned to licensed users are underutilized and cannot be accessed by other potential users due to strict regulation [1]. These underutilized spectrum portions are commonly known as *white spaces*. Thus, allowing a secondary user (that is, a user without an assigned band of frequencies) to access white spaces at the right location and time would improve spectrum utilization - *opportunistic wireless access*.

From this analysis, two challenges in wireless communications were identified: to support multiple standards and to efficiently use the spectrum. Formulated by Mitola, Software Defined Radio (SDR) appeared as a solution for handling the broad variety of available services and protocols, by extending *"the evolution of programmable hardware, increasing flexibility via increased programmability"* [2]. Typically, in an SDR, operations are controlled by software, but performed by programmable and reconfigurable hardware. Building upon the SDR concept, Cognitive Radio (CR) [3] is currently viewed as a natural approach to face the problem of spectrum utilization. A CR is an intelligent wireless device able to sense the surrounding environment, detect temporarily unused spectrum portions and adapt its internal operation, in order to opportunistically use those spectrum portions, without interfering with other users. In [4], Haykin emphasizes six concepts which must be considered in any CR implementation: *awareness*, *intelligence*, *learning*, *adaptivity*, *reliability* and *efficiency*. Considering the need to rapidly change operating parameters in real time due to changing environments (e.g. vehicle-to-vehicle communications - V2V), CR must also exhibit a high degree of *reconfigurability*. This latter feature is directly inherited from SDRs.

The next generation of wireless communication systems (5G) aims to significantly improve data rates, energy efficiency, system capacity and spectrum usage. Due to its inherent features, CR devices will play a major role in future wireless communications and their implementation will be far more complex than that of their predecessors. System capacity and spectrum usage improvements can be achieved through *dynamic spectrum aggregation*. This technique uses possibly discontinuous frequency bands without interfering

This work was financed by the FCT - Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) within project EXCL/EEI-TEL/0067/2012 and through Ph.D. Grant PD/BD/105860/2014

978-1-4673-8299-1/15 $31.00 © 2015 IEEE
DOI 10.1109/EUC.2015.29

with primary users, such that the amount of available spectrum increases. A possible approach for spectrum aggregation is the aggregation and joint use of component carriers - *Carrier Aggregation (CA)* [5]. Regarding baseband processing, *non-contiguous multicarrier modulation* schemes have been proposed as convenient approaches. These schemes are spectrally agile versions of conventional multicarrier modulation techniques, which are able to deactivate subcarriers that would cause interference with primary wireless transmissions. In particular, *NC-OFDM (Non-Contiguous Orthogonal Frequency Division Multiplexing)* is a promising transmission technique for opportunistic wireless access [6] and dynamic spectrum aggregation [7].

The proposed research intends to study and design a reconfigurable digital hardware infrastructure for a CR transceiver baseband platform. The novelty of the approach consists in the exploration of innovative NC-OFDM hardware processing architectures, dynamic partial reconfiguration of the system and the run-time capability to select active sub-carriers and modulation schemes for each sub-band. This will allow fine grained waveform design in spectrum aggregation scenarios based on NC-OFDM approaches, while fulfilling robustness, range, throughput and adaptability requirements. Higher levels of system adaptability, upgradeability and efficiency can be achieved by means of dynamic partial reconfiguration of FPGAs, i.e., by selectively changing portions of the logic circuit implemented in the logic fabric. Due to its flexibility, the proposed approach is a good solution for the baseband processing in All-Digital transceivers, like in [8].

The remainder of this paper is organized as follows: the next section highlights some related work; Section III discusses several NC-OFDM implementations challenges; Section IV presents a general overview of the proposed approach for a reconfigurable NC-OFDM baseband processor; Section V describes the status of the current research activities; finally, Section VI presents some conclusions.

II. Related Work

The use of partial dynamic reconfiguration in embedded systems has been the object of many research efforts [9] [10]. This design methodology has the potential to increase system's flexibility and performance. Particularly, the potential of dynamic reconfiguration in CR systems has been recognized, but most work addresses specific implementation aspects, such as dynamically reconfigurable FFT [11], modulation and coding schemes. So far, little attention has been paid to dynamic and opportunistic spectrum aggregation techniques and implementations, which is the object of the current propose.

Delahaye et al. [12] showed the applicability of DPR within SDR heterogeneous platforms. In this work, DPR is applied to modules responsible for constellation mapping, convolutional encoding and FIR implementation. In [13], an extension of a NoC structure to an FPGA is proposed. A mixed platform composed of ASICs and FPGAs performs the baseband processing and communicate via a NoC. Channel coding and mapping in the receiver are implemented in the FPGA, using DPR. The code rate and constellation mapping are switched according to channel SNR. This application can be further extended to other baseband operations, such as FFT computation. In [14], modulation and demodulation blocks of a CR transceiver are dynamically reconfigured in order to choose a convenient modulation scheme according to the channel SNR. A configuration controller receives spectrum sensing information and uses this information to reconfigure the system. These works consider simple test scenarios in which the reconfiguration decision is based only on a few channel features, and focus on the application of dynamic reconfiguration in few modules, rather than presenting an integrated solution for reconfigurable flexible CR transceivers.

A proposal for the skeleton of an OFDM-based physical layer fulfilling baseband processing required by Software Defined Cognitive Radios is presented by Dutta et al. [15]. Based on that, an FPGA-based implementation is developed. The context switch required for the adaptation to changing environment is managed by a message based real-time reconfiguration method. No DPR methods are employed, and hardware blocks to handle all baseband processing cases are permanently present in the system. This requires a large amount of FPGA resources, many of which are unused for long periods (e.g.: slice utilization reaches 94%, on a Xilinx Virtex-IV FPGA).

He et al. [16] presented an architecture for baseband processing and Digital Front-End in SDR transmitters. This work focuses on efficient hardware resources utilization by identifying commonalities between several widely used wireless standards, and applying Dynamic Reconfiguration techniques in order to change functionality (Digital Modulation scheme, FFT size and cyclic prefix length) and clock frequency at run-time. None of the mentioned works supports spectrum aggregation.

III. NC-OFDM Implementation Challenges

Mahmoud et al. [17] discuss CR systems, as well as their physical layer requirements, and concluded that OFDM is a good candidate for the implementation of such systems. This multicarrier modulation technique is able to provide high data rates and, at the same time, has a high potential for Inter-Symbol Interference (ISI) mitigation in multipath fading channels. Additionally, OFDM can be efficiently implemented using FFT/IFFT algorithms and is the base for most recent communication standards (eg.: IEEE 802.11, IEEE 802.22, WiMAX, 3GPP-LTE). However, CR transmission environments will also require a considerable level of spectral agility, in order to opportunistically access fragmented frequency bands across the spectrum, without interfering with primary communications [6]. Classical OFDM approaches are not enough to fulfil this later requirement.

NC-OFDM has been proposed [18] as a spectral agile variant of OFDM which allows the deactivation of sub-carriers, avoiding interferences with primary users transmissions. It is still able to maintain a high data rate through carrier aggregation techniques. Considering a fast changing environment where several standards need to be supported, a set of fundamental baseband processing operations for NC-OFDM CR systems was defined in [15]:

- support for transmission/reception in any set of sub-carriers - *dynamic spectrum aggregation*;

- ability to change modulation schemes at a subcarrier level;
- ability to change FFT/IFFT size to control the number of transmission subcarriers;
- ability to change the cyclic prefix duration according to the standard operation mode;
- existence of a programmable correlator to assist in preamble based synchronization, at the receiver;
- support for channel equalization, by providing information about pilot sub-carriers location and phase to the receiver.
- ability to handle variable data rates.

Several practical implementation challenges arise from the requirements previously mentioned. Arguably, dynamic spectrum aggregation is a non-trivial concept to implement and will have a considerable impact on how baseband processing for NC-OFDM should be designed [7]. In practice, OFDM doesn't provide genuinely band-limited signals, because the subcarriers spectrum is characterized by high-level sidelobes which can cause interference with the neighbouring licensed user bands. Thus, deactivating subcarriers by simply turning them off may not be enough to mitigate narrowband interference (NBI) with coexisting communications. This will require spectrum shaping methods to suppress the side lobe power levels and reduce out-of-band (OOB) interference. In [19], an Optimized Cancellation Carriers Selection is proposed to achieve higher OOB power attenuation.

OFDM based systems are highly sensitive to incorrect symbol timing and carrier frequency offset (CFO). Although several methods for time and frequency synchronization have been proposed, it is likely that they are not suitable for NC-OFDM. In conventional OFDM systems there is a static allocation scheme where subcarriers are labeled as data, preamble or pilot subcarriers. Preamble subcarriers are used for synchronization and pilot subcarriers are used for channel equalization. For dynamic spectrum access environments, the available sub-carriers for transmission are not always the same. So, fixing frequency locations for preamble or pilot carriers could result in interferences with primary users. Several solutions have been proposed to perform synchronization without prior knowledge of preamble structure [20] or frequencies [21].

Another practical issue inherited from OFDM is the Peak-to-Average-Power-Ratio (PAPR) problem. OFDM is prone to have high values for PAPR, which is the ratio between the maximum instantaneous power and the average power of a signal. When high, PAPR provokes the signal amplitude clipping, leading to undesirable signal distortion. Several techniques have been proposed to reduce PAPR in NC-OFDM systems. In [22] and [23], interleaving and phase adjustment techniques are adaptively used depending on the PAPR level detected. Both approaches require some PAPR information to be sent to the receiver. Another approach [24] is based on tone reservation and doesn't need side information at the receiver.

A CR device should have the ability to intelligently and efficiently adapt its operating characteristics in real-time, while avoiding interference with primary users and providing a good quality of service. Cognitive tasks such as spectrum sensing or dynamic spectrum access may trigger a context switch in the device operation. If the CR device reacts too slowly, interferences with primary users can occur, provoking a negative impact in network performance. As the first wireless standard based on cognitive radio [26], IEEE 802.22$^{\text{TM}}$ defines some timing parameters to protect primary users from interferences. According to this standard [27], an IEEE 802.22 system must be able to detect a primary user signal surpassing the *incumbent detection threshold* (IDT) in less than two seconds - *channel detection time* (CDT). From the moment an IEEE 802.22 system detects a primary user signal higher than IDT, it must vacate the current channel within two seconds - *channel move time* (CMT). The aggregate duration of control transmissions by the IEEE 802.22 device during the CMT period is constrained to one hundred milliseconds - *channel closing transmission time*. CDT and CMT must accommodate both sensing time and subsequent processing time. These parameters are a good reference for the reactivity requirements that the NC-OFDM transceiver baseband processor to be designed must have.

IV. Proposed Approach

This research work focuses on a reconfigurable digital hardware infrastructure for CR transceiver baseband platforms. The main innovation comes from the integration of dynamic spectrum aggregation capabilities into a multi-standard platform. From an implementation perspective, the proposed architecture intends to achieve resource and energy efficiency by exploring run-time reconfiguration, hybrid HW/SW structures, flexible integration and field upgrades of the transceiver parameters.

FPGAs can be a good hardware platform to implement such baseband processing engines, since they represent a good compromise between flexibility, throughput and power consumption. Moreover, FPGAs promise high levels of adaptability and upgradeability by means of dynamic partial reconfiguration (DPR). A DPR-based reconfiguration approach has the potential for *"specialization of the computation to the near-instantaneous needs of the application"* [28], which can be translated into hardware savings and execution overhead reduction. Yet, these benefits should be balanced with additional memory space required to save extra configuration information, as well as the energy and reconfiguration time overhead.

The impact of latency introduced by DPR is an important concern in real-time systems like CR. In [29], DPR implementations were surveyed, considering different approaches and choices for the external memory, configuration port and reconfiguration controller. The measured configuration times ranged from hundreds of milliseconds to hundreds of microseconds. Based on these measurements and bearing in mind the IEEE 802.22 requirements mentioned in Section III, the application of DPR in the context considered in this PhD project is feasible. The energy consumption overhead introduced by DPR is not straightforward to evaluate [30]. It depends on the contents of the reconfigurable region and its previous configuration. However, work reported by Liu et al. [31] demonstrated the effectiveness of DPR in improving power consumption in *eMIPS*: an FPGA-based processor in which specialized instructions are added by reconfigurable logic extensions. The authors concluded that DPR can reduce either dynamic and static power, as opposed to clock gating, which reduces only dynamic power. An important condition to minimize the reconfiguration energy overhead is the maximization of the reconfiguration speeds. Also, through the research activities within this PhD project, it is intended to evaluate to what extent DPR energy overhead affects the overall system functioning. Apart from latency and energy concerns, supporting FPGA dynamic partial reconfiguration remains an architectural challenge, as parts of the circuit logic need to be modified while the rest of the device is working and processing data. This imposes physical constraints on layout and floorplaning during design flow.

An additional source of innovation consists in developing approaches to effectively mitigate or eliminate the latency introduced by the reconfiguration process. The configuration port modules (e.g.: ICAP from Xilinx) and APIs to access them are usually provided by FPGA vendors. While each device has a hard limit on the configuration ports performance, the APIs to access them can be redesigned in order to reduce reconfiguration times [32]. Other possible approaches to reduce reconfiguration latency are bitstream compression techniques and intelligent run-time reconfiguration management (like configuration pre-fetching).

Figure 1 shows the proposed architecture for a reconfigurable FPGA-based NC-OFDM transceiver baseband processor, as well as its relative position within the overall CR transceiver system. It is possible to identify two implementation domains within the FPGA: *Management Unit* and *Dynamically Reconfigurable NC-OFDM datapath*.

The Dynamically Reconfigurable NC-OFDM datapath comprises modules responsible for typical OFDM baseband processing operations, such as IFFT/FFT, (de)modulation, synchronization and channel estimation. Additional modules for spectrum aggregation and shaping are also targeted. Depending on the environment conditions and communication standard in use, the operation of some modules needs to be changed in an adaptive way. A modular approach that allows for easier upgrades, code reuse and real-time on-line adaptability must be adopted in this implementation domain. The success of DPR techniques relies on a convenient system partition and granularity level. As the focus of this research is the adoption of reconfigurable architectures for NC-OFDM baseband processors, it is important to analyse the datapath modules, identify existing algorithms for each of them, select and adapt those algorithms that are suitable for DPR-based implementation. It is also important to study baseband operation parameters and their commonalities across different standards. The interactions between different modules also require some attention. This behavioural analysis will be the base to decide which modules would benefit from DPR, and which variations on operation parameters should trigger module reconfigurations.

As mentioned in Section I, carrier aggregation (CA) is a technique with the potential to increase system's capacity and enhance spectrum usage. LTE-Advanced standard considers two types of CA techniques [33]: *contiguous CA* and *non-contiguous CA*. The implementation of contiguous CA does not require deep changes in the transceiver physical layer (PHY). On the other hand, for non-contiguous CA, a multidimensional PHY is needed [34]. The proposed approach intends to explore a DPR-based architecture composed of tilled PHY blocks which are turned on/off according to the communication demands. Here, the multiplicity of PHY block is constrained by FPGA available resources and power consumption requirements. Moreover, it is necessary to carefully handle the parallel execution of several PHY instantiations in real-time.

The Management Unit is responsible for controlling and adapting the baseband operation according to the communication scenario. The context awareness is built upon the information about spectrum utilization and communication characteristics provided by system upper layers. Reconfiguration may occur at different communication stages [35]. For instance, it can be at the beginning of a communication session, if the communication parameters are different from the ones used in a previous session; or it can be during a session, due to communication requirements change triggered by changes in communication. In the later case, reconfiguration times must be very short and data may need to be buffered while configuration takes place. These aspects must be considered by the Management Unit, in order to handle the datapath reconfiguration intelligently, mitigating the impact of reconfiguration latency and, thus, improving system's reactivity to environmental changes.

As the outcome of this research work, it is expected that the state of the art will be advanced in the following points: 1) Design and evaluation of reconfigurable and efficient NC-OFDM processing architectures enabling data throughputs compatible with next generation wireless communication systems; 2) Reduction of the performance impact of reconfiguration times and storage requirements, through intelligent run-time operation management of the NC-OFDM transceiver. It is worth mentioning that the focus of this research will be on the reconfigurable architecture concept rather than on the implementation details of each individual baseband processing module. The idea is to design a NC-OFDM baseband processing engine supporting spectrum aggregation schemes and able to dynamically and intelligently reconfigure its operation in response to communication demands. Obviously, this will require interventions on baseband processing datapath, where emphasis will be given to parametrized operations, such as FFT/IFFT and digital modulation/demodulation.

V. Current Status

The research activities are currently in an embrionary stage. After a literature review and state-of-the-art study, a conceptual architecture was designed (Figure 1). A preliminary analysis of the baseband processing operations and most used wireless standards (such as IEEE 802.11, WiMAX and 3GPP-LTE) indicated that IFFT/FFT is a good candidate for DPR application. FFT requirements, such as FFT size and number of streams, vary across different standards, and also across operations modes within the same standard. More general standard aspects, as sampling frequency and data throughput, also present variation and influence the performance requirements of baseband operations. Considering these requirements, FFT algorithms and architectures were studied.

The Cooley-Tukey algorithm [36] provides a good overall solution to compute the FFT, considering arithmetic and computational efficiency. Most FFT implementations for OFDM

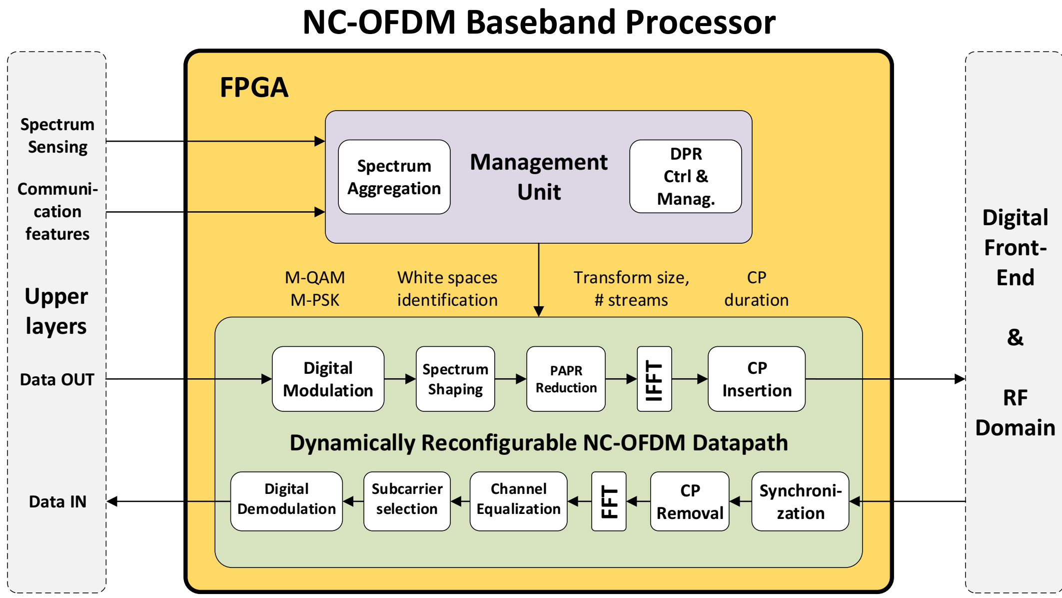

Fig. 1: NC-OFDM baseband processor proposed architecture

applications ([37], [38], [11]) only cover powers-of-two sizes. However, with the emergence of wireless communication protocols such as 3GPP LTE, non-power of two FFT sizes can also occur (e.g.: 1536-point FFT). Cooley-Tukey Mixed-Radix FFT algorithms allow the computation of FFTs with sizes combining powers of different radices.

There are two main kinds of FFT architectures: memory-based and pipelined. Pipelined architectures [39] [40] have the ability to handle continuous flows of data, and present a regular and scalable architecture. So, they are an attractive option for real-time applications where data arrives continuously and FFT requirements are prone to vary with time.

In the context of this proposal, preliminary work has addressed the implementation of FPGA-based FFT processors for the most used FFT sizes (64-2048/1536-points) in 3G/4G wireless standards, using a Mixed-Radix-$2^2/2/3$ Single-Delay Feedback approach. Resource utilization after Place and Route was quantified for every case and it was observed that, in a changing environment, the use of an FFT processor for the worst case scenario in every situation leads to resource inefficiency. The next short-term steps are the exploitation of DPR techniques to implement an efficient and reconfigurable FFT processor, power consumption evaluation and understanding of data flow interactions of the FFT module within the NC-OFDM processor. Long-term plans include extending behaviour and implementation analysis to other baseband datapath modules and the development of efficient and intelligent strategies for the Management Unit.

VI. Conclusion

An architecture for an NC-OFDM processor based on FPGA was proposed. Baseband processing operation are implemented on a dynamically reconfigurable datapath. A management unit is responsible for the control and dynamic reconfiguration of the datapath operations, according to the communication scenario. At this initial work stage, FFT operation and implementation were studied and opportunities for employing DPR were identified.

The proposed research aims to meet the requirements of next generation Cognitive Radio baseband processors, in terms of multi-carrier, multi-standard communications and spectral agility in changing environments. Towards this goal a reconfigurable FPGA-based NC-OFDM baseband processor will be studied and designed. The main novelties of the proposed approach are the introduction of dynamic spectrum aggregation capabilities, and exploitation of dynamic partial reconfiguration techniques, in order to enable the capability for designing optimized waveforms on-line, by employing custom modulations for each sub-band.

The main implementation challenge is related with the adaptation of NC-OFDM baseband operations to a reconfigurable framework whose operation management is done at run-time in an intelligent way, such that higher levels of system adaptability, upgradeability and efficiency, by employing dynamic partial reconfiguration of FPGAs are achieved.

References

[1] FCC, "Spectrum Policy Task Force," Federal Communications Commission, Tech. Rep. Rep. ET Docket no. 02-135, Nov. 2002.

[2] J. Mitola, "The software radio architecture," *IEEE Communications Magazine*, vol. 33, no. 5, pp. 26–38, May 1995.

[3] J. M. III, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," Doctor of Technology, Royal Institute of Technology (KTH), Stockholm, Sweden, 2000.

[4] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, Feb 2005.

[5] S. Parkvall, A. Furuskar, and E. Dahlman, "Evolution of LTE toward IMT-advanced," *IEEE Communications Magazine*, vol. 49, no. 2, pp. 84–91, February 2011.

[6] H. Bogucka, A. M. Wyglinski, S. Pagadarai, and A. Kliks, "Spectrally agile multicarrier waveforms for opportunistic wireless access," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 108–115, June 2011.

[7] H. Bogucka, P. Kryszkiewicz, and A. Kliks, "Dynamic spectrum aggregation for future 5G communications," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 35–43, May 2015.

[8] N. Silva, A. Oliveira, and N. Carvalho, "Design and Optimization of Flexible and Coding Efficient All-Digital RF Transmitters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 1, pp. 625–632, Jan 2013.

[9] P.-A. Hsiung, M. D. Santambrogio, and C.-H. Huang, *Reconfigurable System Design and Verification*, 1st ed. Boca Raton, FL, USA: CRC Press, Inc., 2009.

[10] M. Silva and J. Ferreira, "Exploiting dynamic reconfiguration of platform FPGAs: implementation issues," in *20th International Parallel and Distributed Processing Symposium, 2006. IPDPS 2006.*, Apr. 2006, p. 8 pp., 00004.

[11] C. Vennila, G. Lakshminarayanan, and S.-B. Ko, "Dynamic Partial Reconfigurable FFT for OFDM Based Communication Systems," *Circuits, Systems, and Signal Processing*, vol. 31, no. 3, pp. 1049–1066, 2012. [Online]. Available: http://dx.doi.org/10.1007/s00034-011-9367-9

[12] J.-P. Delahaye, J. Palicot, C. Moy, and P. Leray, "Partial Reconfiguration of FPGAs for Dynamical Reconfiguration of a Software Radio Platform," in *16th IST Mobile and Wireless Communications Summit, 2007.*, July 2007, pp. 1–5.

[13] J. Delorme, J. Martin, A. Nafkha, C. Moy, F. Clermidy, P. Leray, and J. Palicot, "A FPGA partial reconfiguration design approach for cognitive radio based on NoC architecture," in *2008 Joint 6th International IEEE Northeast Workshop on Circuits and Systems and TAISA Conference, 2008. NEWCAS-TAISA 2008.*, June 2008, pp. 355–358.

[14] C. Vennila, K. Suresh, R. Rathor, G. Lakshminarayanan, and S.-B. Ko, "Dynamic partial reconfigurable adaptive transceiver for OFDM based cognitive radio," in *26th Annual IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), 2013*, May 2013, pp. 1–4.

[15] A. Dutta, D. Saha, D. Grunwald, and D. Sicker, "An architecture for Software Defined Cognitive Radio," in *ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS), 2010*, Oct 2010, pp. 1–12.

[16] K. He, L. Crockett, and R. Stewart, "Dynamic Reconfiguration Technologies Based on FPGA in Software Defined Radio System," *Journal of Signal Processing Systems*, vol. 69, no. 1, pp. 75–85, 2012. [Online]. Available: http://dx.doi.org/10.1007/s11265-011-0646-2

[17] H. Mahmoud, T. Yucek, and H. Arslan, "OFDM for cognitive radio: merits and challenges," *IEEE Wireless Communications*, vol. 16, no. 2, pp. 6–15, April 2009.

[18] R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "An efficient implementation of NC-OFDM transceivers for cognitive radios," in *in Proc. of 1st Conf. on Cognitive Radio Oriented Wireless Networks and Commun., Mykonos*, 2006.

[19] P. Kryszkiewicz and H. Bogucka, "Out-of-Band Power Reduction in NC-OFDM with Optimized Cancellation Carriers Selection," *IEEE Communications Letters*, vol. 17, no. 10, pp. 1901–1904, October 2013.

[20] H. Abdzadeh-Ziabari and M. Shayesteh, "Robust Timing and Frequency Synchronization for OFDM Systems," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 8, pp. 3646–3656, Oct 2011.

[21] A. Dutta, D. Saha, D. Grunwald, and D. Sicker, "Practical Implementation of Blind Synchronization in NC-OFDM Based Cognitive Radio Networks," in *Proceedings of the 2010 ACM Workshop on Cognitive Radio Networks*. New York, NY, USA: ACM, 2010, pp. 1–6. [Online]. Available: http://doi.acm.org/10.1145/1859955.1859957

[22] R. Rajbanshi, A. M. Wyglinski, and G. Minden, "Adaptive-Mode Peak-to-Average Power Ratio Reduction Algorithm for OFDM-Based Cognitive Radio," in *2006 IEEE 64th Vehicular Technology Conference, 2006. VTC-2006 Fall.*, Sept 2006, pp. 1–5.

[23] Q. Han, V. Clarkson, and X. Zeng, "Joint algorithm for Peak-to-Average Power Reduction of NC-OFDM system," in *2010 3rd International Congress on Image and Signal Processing (CISP)*, vol. 9, Oct 2010, pp. 4399–4403.

[24] S. Tabassum, S. Hussain, and A. Ghafoor, "A Novel Adaptive Mode PAPR Reduction Scheme for NC-OFDM Based Cognitive Radios," in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, June 2013, pp. 1–5.

[25] C. Cordeiro, K. Challapali, D. Birru, and N. Sai Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," in *DySPAN 2005. 2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005.*, Nov 2005, pp. 328–337.

[26] *IEEE Std 802.22^{TM}-2011: Standard for Local and metropolitan area networks - Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands*, IEEE 802.22 Working Group on Wireless Regional Area Networks Std., 2011.

[27] R. Tessier, K. Pocek, and A. DeHon, "Reconfigurable Computing Architectures," *Proceedings of the IEEE*, vol. 103, no. 3, pp. 332–354, March 2015.

[28] K. Papadimitriou, A. Dollas, and S. Hauck, "Performance of Partial Reconfiguration in FPGA Systems: A Survey and a Cost Model," *ACM Trans. Reconfigurable Technol. Syst.*, vol. 4, no. 4, pp. 36:1–36:24, Dec. 2011. [Online]. Available: http://doi.acm.org/10.1145/2068716.2068722

[29] R. Bonamy, D. Chillet, S. Bilavarn, and O. Sentieys, "Power consumption model for partial and dynamic reconfiguration," in *Reconfigurable Computing and FPGAs (ReConFig), 2012 International Conference on*, Dec 2012, pp. 1–8.

[30] S. Liu, R. N. Pittman, and A. Forin, "Energy Reduction with Run-Time Partial Reconfiguration," Tech. Rep. MSR-TR-2009-2017, September 2009. [Online]. Available: http://research.microsoft.com/apps/pubs/default.aspx?id=112466

[31] L. Möller, R. Soares, E. Carvalho, I. Grehs, N. Calazans, and F. Moraes, "Infrastructure for Dynamic Reconfigurable Systems: Choices and Trade-offs," in *Proceedings of the 19th Annual Symposium on Integrated Circuits and Systems Design*. New York, NY, USA: ACM, 2006, pp. 44–49. [Online]. Available: http://doi.acm.org/10.1145/1150343.1150360

[32] "Carrier Aggregation explained," http://www.3gpp.org/technologies/keywords-acronyms/101-carrier-aggregation-explained, 2015, accessed: 31/08/2015.

[33] G. Yuan, X. Zhang, W. Wang, and Y. Yang, "Carrier aggregation for LTE-advanced mobile communication systems," *IEEE Communications Magazine*, vol. 48, no. 2, pp. 88–93, February 2010.

[34] T. Becker, W. Luk, and P. Cheung, "Parametric Design for Reconfigurable Software-Defined Radio," in *Reconfigurable Computing: Architectures, Tools and Applications*, ser. Lecture Notes in Computer Science, J. Becker, R. Woods, P. Athanas, and F. Morgan, Eds. Springer Berlin Heidelberg, 2009, vol. 5453, pp. 15–26. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-00641-8_5

[35] J. W. Cooley and J. W. Tukey, "An Algorithm for the Machine Calculation of Complex Fourier Series," *Mathematics of Computation*, vol. 19, no. 90, pp. 297–301, 1965. [Online]. Available: http://www.jstor.org/stable/2003354

[36] A. Cortés, I. Vélez, I. Zalbide, A. Irizar, and J. F. Sevillano, "An FFT Core for DVB-T/DVB-H Receivers," *VLSI Des.*, vol. 2008, no. 2, pp. 12:1–12:9, Jan. 2008. [Online]. Available: http://dx.doi.org/10.1155/2008/610420

[37] I. Cho, C.-C. Shen, Y. Tachwali, C.-J. Hsu, and S. Bhattacharyya, "Configurable, resource-optimized FFT architecture for OFDM communication," in *2013 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, May 2013, pp. 2746–2750.

[38] S. He and M. Torkelson, "A new approach to pipeline FFT processor," in *Proceedings of IPPS '96, The 10th International Parallel Processing Symposium, 1996.*, Apr 1996, pp. 766–770.

[39] M. Garrido, J. Grajal, M. Sanchez, and O. Gustafsson, "Pipelined Radix-2^k Feedforward FFT Architectures," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 21, no. 1, pp. 23–32, Jan 2013.