Signals and Communication Technology

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Cognitive Radio and Networking for Heterogeneous Wireless Networks

Recent Advances and Visions for the Future

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Foreword

COST Action IC0902 "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks" proposed coordinated research in the field of cognitive radio and networks; research activities were carried out within COST Action IC0902 between December 2009 and December 2013. Research directions were set at the beginning of the Action, and proved to have a scope and vision as wide as a 4-year research program would require.

The main objective of the Action was to integrate the cognitive concept across all layers of communication systems, with the aim of defining a European platform for cognitive radio and networks. The cognitive concept was applied to coexistence between heterogeneous wireless networks sharing the electromagnetic spectrum for maximum efficiency in resource management. The Action promoted coordinated research in the field of cognitive radio and networks in order to synergize the several trends that were in place in European research centers and consortia, consisting in introducing cognitive mechanisms at different layers of the communications protocol stack.

This Action went beyond the above trends by integrating the cognitive concept across all layers of system architecture, in view of joint optimization of link adaptation based on spectrum sensing, resource allocation, and selection between multiple networks, including underlay technologies. The cross-layer approach provided a new perspective in the design of cognitive systems, based on a global optimization process that integrated existing cognitive radio projects, thanks to the merge of a wide-range of expertise, from hardware to applications, provided by over 30 academic and industrial partner institutions. The final result was the definition of a European platform for cognitive radio and networks; algorithms and protocols for all layers of the communications stack were designed, as well as a set of standard interfaces.

Beyond scientific achievements, COST Action IC0902 had a strong impact on the scientific community under two aspects: formation of young researchers and interaction with industrial consortia. In terms of spin-off of new projects, about 20 new EU and national RTD programs were generated. An inter-disciplinary approach was pursued and networking with experts coming from research areas such as probabilistic models, mathematics and economics was incentivized.

Action IC0902 involved 17 COST countries and 7 institutions from 6 non-COST countries, and more than 200 researchers, with over 50 % of Early Stage Researchers. Early Stage Researchers played a central role in the Action; four training schools attended by more than 350 young researchers, as well as four yearly workshops, where Early Stage Researchers presented over 160 technical contributions, and two mini-workshops focusing on platforms and learning techniques, were organized.

This book is targeted to academic researchers, designers and graduate students wishing to enhance their understanding of cognitive radio and networks; the book includes and illustrates the most salient research results of COST Action IC0902's 4-year collective efforts, and forms a scientific selected outcome of the Action.

It is a great pleasure to introduce this book and to have hereby the chance to thank and congratulate all IC0902 participants, especially the authors of the different chapters of the book, as well as, in particular, Andrea Fabio Cattoni for making this book possible.

Rome, Italy
February 2014

Maria-Gabriella Di Benedetto
Chair of the COST Action IC0902

Preface

The aim of this book is to present, in a tutorial perspective, the visions and trends for future wireless networks and technologies based, inspired, and learned from Cognitive Radio (CR) investigations that have been carried out within the framework of the COST Action IC0902 "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks" (http://newyork.ing.uniroma1.it/IC0902/). COST (European Cooperation in Science and Technology) is one of the longest-running European programs supporting cooperation, sharing, and dissemination among scientists and researchers across Europe.

This book has been written by leading researchers, that are first-hand experts in a wide range of fields and disciplines, from both Academia and industrial players. The main purpose of the manuscript is to provide scientists, researchers, wireless communication network engineers and professionals, and graduate students with a widely comprehensive tutorial tool for understanding and developing cognitive radio network (CRN) technology components, based on the latest state of the art in the field.

The book will allow the reader to access both fundamental and advanced knowledge spanning from the design of CRN air interfaces to network architectures and algorithms, following a bottom-up approach. Furthermore, the book includes practical help in setting up essential investigation tools such as simulators and experimental test beds, in the form of direct step-by-step how-to.

Topics covered by the book include filter bank multicarrier systems that try to incorporate coexistence properties starting from the design of the CR air interface. Furthermore, recent advances in signal processing are presented in the context of interference mitigation. The reader will also get access to insights on how to design the link layer of CR, including specific highlights on essential features such as spectrum sensing and dynamic spectrum access. Climbing up in the traditional layered architecture, the book will also provide trending visions on how to evolve the internet architecture and protocols in dynamically adaptive, cognitive-oriented ones. An interesting chapter will provide also regulatory perspectives on the possible usage of the spectrum by CRN players, including economical and market reflections. Finally the book will dive into the practical aspects that a researcher or an engineer can face on the everyday job: how to simulate or develop CRN systems. Three chapters cover the most hot topics in the field, using open-source widely available tools, such as software simulations, software defined radio tools and developments, and embedded systems.

A brief description of each chapter is as follows.

In Chap. 1 by Medjahdi et al. the authors provide a tutorial overview on multicarrier techniques, which are offering flexible access to possible new spectrum opportunities. Indeed, OFDM, which is the most commonly used multicarrier technique, has been adopted in IEEE 802.22 standard for unlicensed wireless regional area network (WRAN) considering cognitive communications on the unused TV bands. Unfortunately, OFDM presents some weaknesses. In fact, the redundancy, caused by the insertion of the cyclic prefix mandatory part of the transmitted OFDM symbol, reduces the useful data rate. Furthermore, the poor spectral localization of the OFDM subcarriers due to the large sidelobes induces not only an additional spectral loss but also interference problems with unsynchronized signals. These shortcomings have stimulated the research of an alternative scheme that can overcome these problems. An enhanced physical layer based on the filter bank processing called filter bank-based multicarrier (FBMC) technique has been proposed in various works. A major improvement in spectrum efficiency and better flexibility for system coexistence can be achieved by FBMC thanks to the use of spectrally well-localized waveforms. The advantages and the drawbacks of the classical OFDM are first discussed in the chapter. Next, the authors will introduce the different schemes of FBMC systems: Filtered multitone (FMT), cosine modulated multitone (CMT) and staggered multitone (SMT, also called FBMC-OQAM). After introducing a theoretical background of the FBMC transmission, the polyphase implementation of the filter bank transceiver and the prototype filter design are reviewed. Finally, the chapter highlights the interest of FBMC spectrum sharing and investigate coexistence issues.

Interference alignment (IA) has been widely recognized as a promising interference mitigation technique since it can achieve the optimal degrees of freedom in certain interference limited channels. This topic is then addressed by Sharma et al. in Chap. 2. IA allows in fact the coexistence of two heterogeneous wireless systems in an underlay cognitive mode. The main concept behind this technique is the alignment of the interference on a signal subspace in such a way that it can be filtered out at the non-intended receiver by sacrificing some signal dimensions. This chapter starts with an overview of the IA principles, the degree of freedom (DoF) concept, and the classification of existing IA techniques. Furthermore, this chapter includes a discussion about IA applications in CR networks. Moreover, a generic system model is presented for allowing the coexistence of two heterogeneous networks using IA approach while relevant precoding and filtering processes are described. In addition, two important practical applications of the IA technique are presented along with the numerical results for underlay spectral coexistence of (i) femtocell-macrocell systems, and (ii) monobeam-multibeam satellite systems. More specifically, an uplink IA scheme is investigated in order to mitigate the interference of femtocell user terminals (UTs) towards the macrocell base station (BS) in the spatial domain and the interference of multibeam satellite terminals towards the monobeam satellite in the frequency domain.

Chapter 3 by Yilmaz et al. will provide a detailed technical insight into latest key aspects of cooperative spectrum sensing. The authors focus on fusion strategies, quantization enhancements, effect of imperfect reporting channel, cooperative spectrum sensing scheduling, and utilizing cooperatively sensed data via radio environment map (REM). The sharing of local observations between the secondary users and the fusion center is one of the most crucial factors that determines the performance of cooperative sensing. The detection performance is determined by the quality of local observations and the quality of the information received by the fusion center. Therefore, the number of quantization bins, the number of bits sent for sensing reports, the global decision logic, the imperfections in the reporting channel, and the erroneous reports due to malfunctioning or malicious secondary devices affect the system performance. Furthermore, there are many channels to sense while the cooperating nodes are few, therefore coordinating the sensing nodes for detecting high quality channels is necessary. Cooperative sensing scheduling concentrates on the scheduling of cooperative nodes and the channels to be sensed. This chapter also focuses on the energy consumption problem that becomes more severe if the users are mobile. The components of energy consumption dedicated to cooperative sensing are analyzed and optimal and sub-optimal (but efficient) sensing scheduling mechanisms are discussed in order to reduce the sensing energy consumption of the network. Once the spectrum has been sensed cooperatively, the outcomes can be utilized via REM, which can be considered as a crucial part of the cognitive engine located at the network. The sensed information may also play a crucial role in the generation of REM. Hence, this chapter also focuses on how the sensing measurements could be utilized for REM construction.

The endeavor of categorizing the existing cognitive-MAC (C-MAC) protocols requires definition of general classification frameworks or layouts that merge most of the aspects of the protocols in a single unified presentation. Chapter 4 by Gavrilovska et al. introduces the C-MAC cycle as a general classification and systematization layout for C-MAC protocols. The C-MAC cycle originates from the idea that the MAC layer in spectrally heterogeneous environments should provide support for three generic technical features: radio environmental data acquisition; spectrum sharing; and control channel management. The inclusion of these generic technical features is necessary in CRNs for improving the network performance and achieving spectrum efficiency gain while providing maximal level of protection for the primary system. This chapter will present extensive survey on the state-of-the-art advances in C-MAC protocol engineering by reviewing existing technical solutions and proposals, identifying their basic characteristics and placing them into the C-MAC cycle, with emphasis on the modularity of the C-MAC cycle. It provides an overview of a large number of technical details concerning the three generic functionalities (i.e. the radio environmental data acquisition, the spectrum sharing and the control channel management) as the main building blocks of the C-MAC cycle. Three use cases (each in different generic functional group) illustrate the capabilities of the proposed C-MAC cycle layout. In more detail, the first use case theoretically presents and practically evaluates cooperative spectrum sensing based on estimated noise power. The results illustrate the effect of estimating the noise variance on the detection capabilities of the majority voting and equal gain combining cooperative spectrum sensing strategies. The second use case presents advanced and computationally efficient horizontal spectrum sharing strategy for secondary systems based on node clustering and beamforming. Finally, the last use case presents and assesses a multiuser quorum-based multiple rendezvous strategy for control channel establishment in distributed CRNs.

In Chap. 5 by da Costa et al. the authors dive in the ever-growing demand for mobile broadband that is pushing towards the utilization of small cells, including metrocells, picocells and femtocells. In particular, the deployment of femtocells introduces significant challenges. Firstly, the massive number of expected femtocells cannot be deployed using the traditional planning and optimization techniques. This leads to uncoordinated deployment by the end-user. Secondly, the high density of femtocells, including vertical reuse, leads to very different inter-cell interference patterns than the ones traditionally considered in cellular networks. And last, but not least, the possibility of having closed-subscriber-groups aggravates the inter-cell interference problems. In order to tackle these issues the authors consider the implementation of some aspects of CR technology into femtocells, leading to the concept of cognitive femtocells (CFs). This chapter focuses on state-of-the-art techniques to manage the radio resources in order to cope with inter-cell interference in CFs. Different techniques are presented as examples of gradually increasing sophistication of the CFs, allowing for dynamic channel allocation, dynamic reuse and negotiated reuse based on information exchanged with neighbor cells.

Granelli et al. are instead moving the discussion from the wireless domain into the networking one in Chap. 6. As a matter of fact, the requirement to support an always increasing number of networking technologies and services to cope with context uncertainties in heterogeneous network scenarios leads to an increase of operational and management complexity of the Internet. Autonomous communication protocol tuning is then crucial in defining and managing the performance of the Internet. This chapter presents an evolutionary roadmap of communication protocols towards cognitive Internet in which the introduction of self-aware adaptive techniques combined with reasoning and learning mechanisms aims to tackle inefficiency and guarantee satisfactory performance even in complex and dynamic scenarios. In this chapter, the authors provide a survey and comparison between existing adaptive protocol stack solutions, reviewing the principles of cross-layer design as well as the agent-based and AI based self-configuration solutions. The fundamental principles of cognitive protocols, such as adaptation, learning, and goal optimization, are presented along with implementation examples.

Introducing cognitive mechanisms at the application layer is instead investigated by Boldrini et al. in Chap. 7 and it may lead to the possibility of an automatic selection of the wireless network that can guarantee best perceived experience by the final user. This chapter investigates this approach based on the concept of quality of experience (QoE), by introducing the use of application layer parameters, namely key performance indicators (KPIs). KPIs are defined for different traffic types based on experimental data. A model for an application layer cognitive engine is presented, whose goal is to identify and select, based on KPIs, the best wireless network among available ones. An experimentation for the VoIP case, that foresees the use of the one-way end-to-end delay (OED) and the mean opinion score (MOS) as KPIs is presented. This first implementation of the cognitive engine selects the network that, in that specific instant, offers the best QoE based on real captured data.

Another important piece of information that CRNs can use for optimizing services is the location of the CR terminal. This aspect will be clarified by Chochliouros et al. in Chap. 8. Starting from a general survey of several among the critical capabilities and/or features characterizing CRNs, in the context of actual European standardization efforts, the chapter will present an overall and harmonized technical concept for future CR systems, especially by discussing several options affecting the future evolution of radio technologies and network architectures towards more flexible and reconfigurable CR systems, as the latter are expected to increase the efficiency of the overall spectrum usage by offering new sharing opportunities and thus to provide more flexibility to applications-services.

In Chap. 9 Georgakopoulos et al. will provide a trending vision on the architectural possibilities that are offered to wireless mobile broadband networks for jointly satisfying complex context of operations as well as system requirements like QoE (quality of experience) and energy and cost efficiency. Introduction of intelligence in the Cloud-RANs will lead towards this direction by providing the necessary decisions based on the received inputs. Cloud-RANs have the capabilities to adapt their network topology and resource allocation so as to realize environmental-friendly and cost-efficient solutions by moving elements of the legacy RAN to cloud-based infrastructures. The authors will try to provide, in the chapter, an indication on the elements of the approach as well as the identification of the benefits from such a concept.

The purpose of Chap. 10 by Doyle and Forde is instead to give a regulatory perspective on CR, that can be seen as a natural part of the roadmap for advanced communication systems and from this standpoint can be dealt with within the context of normal regulations. However one of the key and unique advantages of CR is that it is an enabler of spectrum sharing in its many forms. Hence the main part of this chapter is devoted to different regulations in spectrum sharing and the implications for CR. It looks at regulations which are in existence as well as emerging regulations. The chapter also provides a generic framework in which to place different sharing regimes.

Chapter 11 by Caso et al. is leading the discussion in the practical everyday issues of researchers and engineers. In fact, a widespread methodology for performance analysis and evaluation in communication systems engineering is network simulation. It is widely used for the development of new architectures and protocols. Network simulators allow to model a system by specifying both the behavior of the network nodes and the communication channels, and CR-related research activities have been often validated and evaluated through simulation too. Following this approach, this chapter presents an ongoing effort towards the development of a CR simulation framework, to be used in the design and the evaluation of protocols and algorithms. OMNeT++, in combination with MiXiM framework functionalities, was chosen as the developing platform, thanks to its open source nature, the existing documentation on its architecture and features, and the user-friendly integrated development environment (IDE).

More and more researchers are entering the idea of research-oriented test beds. Unfortunately, it is very difficult for a wide number of research groups to start with their own set up, since the potential costs and efforts could not pay back in term of expected research results. Chapter 12 by Cattoni et al. provides a tutorial, first-hand overview on software defined radio solutions, which offer an easy way to communication researchers for the development of customized research test beds. While several hardware products are commercially available, the software is most of the times open source and ready to use for third party users. Even though the software solution developers claim complete easiness in the development of custom applications, in reality there are a number of practical hardware and software issues that research groups need to face, before they are up and running in generating results. With this chapter the authors will provide a tutorial guide, based on direct experience, on how to enter in the world of test bed-based research, providing both insight on the issues encountered in everyday development, and practical solutions. Finally, an overview on common research-oriented software products for SDR development, namely GNU radio, Iris, and ASGARD, will be provided, including how to practically start the software development of simple applications.

In Chap. 13 Šolc et al. describe their experiences with the design, deployment and experimental use of the LOG-a-TEC embedded, outdoor CR test bed, based on the VESNA sensor node platform. The authors will describe the choice of experimental low-cost reconfigurable radio frontends for LOG-a-TEC and discuss the potential capabilities of custom designs. The core part of this chapter will provide practical experiences with designing the embedded testbed infrastructure, covering topology design and performance evaluation of the management network as well as considerations in the choice of network protocols employed in the LOG-a-TEC testbed. Use cases using LOG-a-TEC test bed for performing experiments are also covered, one relevant to the investigation of coexistence of primary and secondary users in TV white spaces and the other addressing power allocation and interference control in the case of shared spectrum.

Finally, as Editors of this volume, we would like to express our gratitude to all the contributors for their help, support, and effort in making this book possible. Furthermore, we would like to thank the Springer editorial team for their continuous support along the publication process.

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Chapter 1
New Types of Air Interface Based on Filter Banks for Spectrum Sharing and Coexistence

Yahia Medjahdi, Didier Le Ruyet, Daniel Roviras, and Michel Terré

Abstract Today, we witness a continuous evolution of applications for wireless communications. In fact, there is a growing interest in the design and the development of cognitive radio technology to overcome the problem of spectrum scarcity resulting from conventional static spectrum allocation. The concept of cognitive radio is based on opportunistic access to the available frequency resources. It offers to future communication systems the ability to dynamically and locally adapt their operating spectrum by selecting it from a wide range of possible frequencies.

Multicarrier techniques are promising and potential candidates offering flexible access to these new spectrum opportunities. Indeed, OFDM, which is the most commonly used multicarrier technique, has been adopted in IEEE 802.22 standard for unlicensed wireless regional area network (WRAN) considering cognitive communications on the unused TV bands. Unfortunately, OFDM presents some weaknesses. In fact, the redundancy, caused by the insertion of the cyclic prefix mandatory part of the transmitted OFDM symbol, reduces the useful data rate. Furthermore, the poor spectral localization of the OFDM subcarriers due to the large sidelobes induces not only an additional spectral loss but also interference problems with unsynchronized signals. These shortcomings have stimulated the research of an alternative scheme that can overcome these problems. An enhanced physical layer based on the filter bank processing called filter bank-based multicarrier (FBMC) technique has been proposed in various works. In fact, a major improvement in spectrum efficiency and better flexibility for system coexistence can be achieved by FBMC thanks to the use of spectrally well-localized waveforms.

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The goal of this chapter is to present a tutorial review of the fundamental theory of FBMC techniques. First, we succinctly explain the general concept of multi-carrier transmissions. The advantages and the drawbacks of the classical OFDM are then discussed. Next, we introduce the different schemes of FBMC systems: Filtered MultiTone (FMT), Cosine modulated MultiTone (CMT) and Staggered MultiTone (SMT, also called FBMC-OQAM). Then, we develop theoretical background of the FBMC transmission. Furthermore, the polyphase implementation of the filter bank transceiver and the prototype filter design are reviewed. Finally, we highlight the interest of FBMC spectrum sharing and investigate coexistence issues.

1.1 The Concept of Multicarrier Transmission

Let us consider a single carrier transmission scheme with linear modulation (e.g. M-QAM) and a symbol duration T. Let B the frequency bandwidth which is typically of the order of the inverse of the symbol duration (T^{-1}). For a propagation channel with a delay spread τ_{ds}, we can avoid the intersymbol interference (ISI) if [24]

$$\tau_{\mathrm{ds}} \ll T \tag{1.1}$$

On the other hand for $\tau_{\mathrm{ds}} > T$, equalization at the receiver can deal with the generated ISI. However when $\tau_{\mathrm{ds}} \gg T$, equalization complexity becomes so high that multicarrier modulations (MCM) are preferred.

The key idea in multicarrier transmission to reduce the equalization complexity is to split the data stream into N parallel low-rate streams which are transmitted on N adjacent subcarriers. The bandwidth of each subcarrier is B/N, while the symbol duration T is multiplied by a factor of N. However, the choice of the number of subcarriers N must also provide the robustness of the transmission to the time incoherence of the channel which is related to the maximum Doppler frequency ν_{max}. This can be achieved by fulfilling the following condition

$$\nu_{max} T \ll 1 \tag{1.2}$$

Therefore to obtain the best possible transmission for a given propagation channel characterized by parameters (τ_{ds},ν_{max}), we have to choose the optimal symbol duration that satisfies both conditions at the same time.

1.1.1 Gabor Analysis of Multicarrier Systems

The symbol period T and the subcarrier spacing F are the main parameters characterizing any multicarrier transmission. Theses parameters can be investigated via Gabor analysis, where the product $T \times F$ stands for the symbol density of a given multicarrier system. It determines in addition to the spectral efficiency of the transmission, the representability of the signal space and the invertibility of the transformation between information symbols and constructed multicarrier signal [46]. The modulation in frequency and the translation in time of a given prototype filter constitute what we call the modulation basis or Gabor family. This latter should be linearly independent to ensure the invertibility of the transformation allowing a perfect reconstruction of the signal. We can distinguish three classes of multicarrier systems with respect to the spectral efficiency of the systems, the linear independency and the completeness of the modulation basis [33, 51]:

1.1.1.1 Undersampled Lattice ($T \times F > 1$)

Gabor family, in this case, cannot be a complete basis since the lattice is not sufficiently sampled. However, linear independency between the basis functions is still possible. Therefore, well-localized prototype filters obtained from incomplete bases can be adapted to the communication systems.

1.1.1.2 Critically Sampled Lattice ($T \times F = 1$)

In this case, we have a complete Gabor system and orthogonal bases exist. However, according to Balian-Low theorem [22], such systems are not able to use well-localized waveforms maintaining in the mean time the orthogonality condition. Therefore, this multicarrier class is using bad localized waveforms like rectangular window filter. In [33], it has been demonstrated that the perfect reconstruction might not be possible beyond the critically sampled grid condition. Hence, the spectral efficiency is maximized for $T \times F = 1$.

1.1.1.3 Oversampled Lattice ($T \times F < 1$)

An overcomplete Gabor family is obtained in this case and it cannot be considered as a basis. However, since Gabor family is overcomplete, representation of a signal might not be unique leading to a lossy reconstruction [51].

1.1.2 Orthogonal and Biorthogonal Multicarrier Systems

A multicarrier system is orthogonal when an orthogonal modulation basis is used at both the transmitter and the receiver. In other words, the transmit filter is equal to the receive filter. This corresponds to the match filtering which maximizes the signal-to-noise ratio (SNR) in the additive white Gaussian noise (AWGN) channel.

Furthermore, perfect reconstruction is still possible by using two different orthogonal Gabor systems at the transmitter and the receiver. In that case, we have a biorthogonal system. In contrast to orthogonal systems, biorthogonal ones are more robust to the dispersiveness of the propagation channel [52].

1.2 Orthogonal Frequency Division Multiplexing (OFDM): Advantages and Drawbacks

OFDM is the most well documented MCM scheme. It has also been adopted by various practical and commercial systems such as, digital audio broadcasting (DAB) [16, 30] terrestrial digital video broadcasting (DVB-T) [17], and the IEEE 802.11a wireless local area network (WLAN) [25], etc. This success comes from a number of advantages that it offers:

- Its robustness to multipath fading effects and its ability to avoid both intersymbol and intercarrier interference (ISI and ICI) by appending a cyclic prefix (CP) that significantly reduces the complexity of the equalization to a single complex coefficient per subcarrier equalizer. This holds as long as the CP covers the maximum delay spread of the channel τ_{ds}.
- The digital implementation of both OFDM modulator and demodulator can be efficiently realized making use of fast Fourier transform (FFT).
- Closely spaced orthogonal subcarriers that divide the available bandwidth into a maximum collection of narrow subchannels.
- Adaptive modulation schemes that can be applied to maximize the spectral efficiency.

Nevertheless, in spite of these advantages, OFDM has some drawbacks:

- There is a loss in spectral efficiency due to the cyclic prefix insertion. Indeed, the cyclic prefix is a copy of part of the transmitted OFDM symbol, and this redundancy reduces the effective throughput.
- OFDM is very sensitive to residual frequency and timing offsets that can be generated by a defective synchronization as well as the Doppler effect [26, 42].
- The use of a rectangular impulse response in OFDM causes large sidelobes at each subcarrier. Hence, the subchannels at the edge of the transmission bandwidth could be a source of interference for other neighboring systems [40, 42].

1.3 Filter Bank Based Multicarrier Systems

To overcome some CP-OFDM shortcomings such as the poor spectrum localization while maintaining some of its advantages, a finite pulse shape filter (or prototype filter) different from the rectangular one with smooth edges can be used [21]. This