1 Introduction

1.1 Background

The advancements in the field of digital wireless communication have led to many exciting applications like mobile internet access, healthcare and medical monitoring services, smart homes, combat radios, disaster management, automated highways and factories. With each passing day novel and advanced services are being launched, while existing ones continue to flourish. While traditionally only voice and data communication were possible, wireless services have now found applicability in other sectors too including healthcare, transportation, security, logistics, education and finance. For example, telemedicine can render emergent and easy-to-access healthcare at distance. Through rural connectivity, people living in remote places in developing/underdeveloped nations can be given access to good-quality education via long-distance learning programs. In the era of open course ware (OCW), this can prove to be a boundary breaker in spreading top quality educational content to students who hitherto might not have access to them. Demand for wireless services is thus expected to grow in the foreseeable future.

However, with increasing popularity of the wireless services the requirements on prime resources like battery power and radio spectrum are put under severe pressure. For example, currently most spectrum have been allocated, and it is becoming increasingly difficult to find frequency bands that can be made available either for new services or to expand existing ones. Even as the available frequency spectrum appears to be fully occupied, a survey [1] conducted by the American regulatory body Federal Communications Commission (FCC) in 2002 revealed that much of the available spectrum is underused most of the time. The study [1] showed that only 20% or less of the spectrum is used and that spectrum congestions are more due to the sub-optimal use of spectrum than to the lack of free spectrum.

Studies have also shown that the volume of data is increasing by a factor of 18 in five years [2]. For example, the global mobile data was 0.6 exabytes per month in 2011 and more than doubled in 2012 (1.3 exabytes/month), [2]. This number is expected to grow to 4.2 exabytes in 2014 and about 10.8 exabytes/month in 2016 (see Figure 1.1). The 18-fold increase in data volume in five years corresponds to an increase of the associated energy consumption by more than 20% annually. In fact, the current world-wide energy requirements of information and communication technology (ICT) systems contribute nearly 2% of the CO_2 emissions, a figure comparable with the total emissions due to global air travel or about one quarter of the emissions due to cars and trucks.

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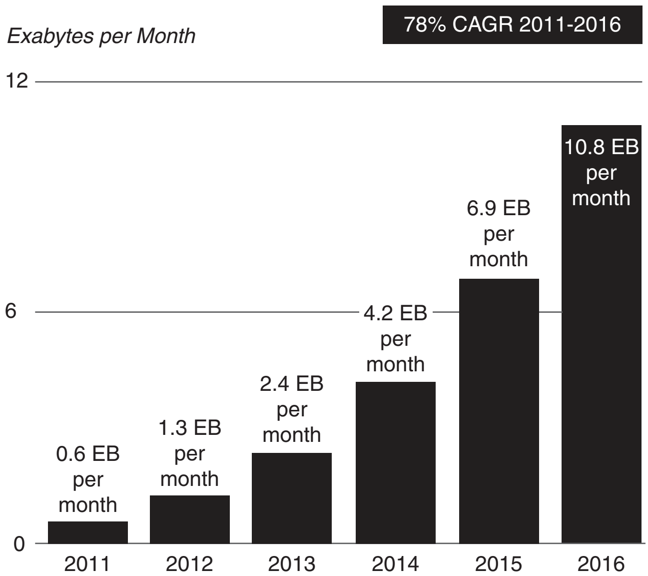

Figure 1.1 Global mobile data traffic growth (mobile traffic will grow by 18 times from 2011 to 2016). Notation in the figure: EB: exabytes (10^{18} bytes), after [2].

Another emerging trend is the demand for higher data rates as exemplified in Figure 1.2, where the growth of home bandwidth since the 1970s has been shown [3]. Today, the Universal Mobile Telecommunications Systems (UMTS) is one of the fastest solutions on the market that can operate in dispersive environments at a rate of 3.84×10^6 chips, but the rapid progress of telecommunication market has created a need for newer techniques that can accommodate data rates even higher than this.

1.1.1 The need

Thus, in a wireless environment the system requirements, network capacities and device capabilities have enormous variations giving rise to significant design challenges. There is therefore an emergent need for developing energy efficient, green technologies that optimize premium radio resources, such as power and spectrum, even while guaranteeing a desirable quality of service. Of signal interest is the development of a capable radio/PHY layer platform that facilitates optimum utilization of energy in addition to guaranteeing spectral efficiency, adequate coverage and good quality of service (QoS). Spatially, temporally and spectrally localized transmission strategies that minimize the energy spent to transmit information-bearing symbols will be crucial towards achieving high energy efficiency. Moreover, wireless systems operate under dynamic conditions with frequent changes in the propagation environment and user requirements. All these trends point to an untapped niche available for flexible, reconfigurable systems that can adapt to its radio neighbourhood.

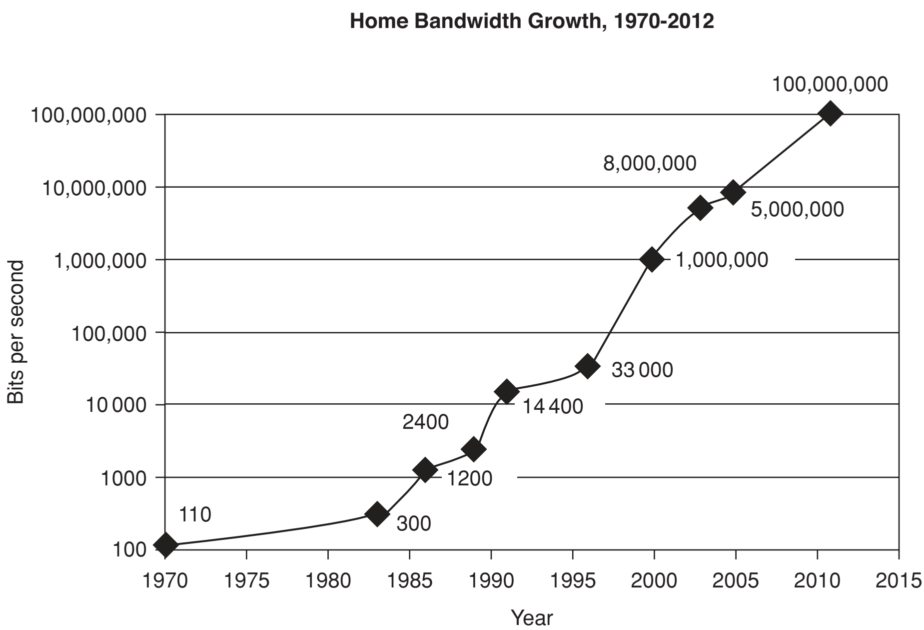

Figure 1.2 Growth of home bandwidth since the 1970s, after [3].

1.1.2 The means

Existing wireless systems and services are based on the mathematical precept of Fourier transform. In comparison to the Fourier transform, the recently formulated theory of wavelets offers many advantages for the design of wireless communications. The main property of wavelets for these applications is their ability to characterize signals with adaptive time–frequency resolution. The goal of this book is to build a generic parameterized baseband radio platform based on wavelet technology as a suitable PHY layer candidate for the design and development of communication systems that can handle large volumes of data under severe constraints of interference and resources such as power and bandwidth. By careful adaptation of the main system parameters according to the radio environment, the operation of the wavelet-based radio is optimized to save valuable energy resources. The system parameterization is realized through a generalized wavelet packet modulator (WPM) that is based on the theory of wavelets and filter banks.

1.2 Wavelet transform as a tool for wireless communications

1.2.1 Wavelets and wavelet transform

A wavelet is a waveform of limited duration. As the name suggests, wavelets are small waveforms with a set of oscillatory structures that is non-zero for a limited period of time (or space). The wavelet transform is a multi-resolution analysis mechanism where an input signal is decomposed into different frequency components with each component studied with resolutions matched to its time-scales. The Fourier transform also decomposes signals into elementary waveforms, but these basis functions are sines and cosines. Thus, when one wants to analyze the local properties of the input signal, such as edges or transients, the Fourier transform is not an efficient analysis tool. By contrast, the wavelet transforms that use irregularly shaped wavelets offer better tools to represent sharp changes and local features.

The wavelet transform is used in various applications and is finding tremendous popularity among technologists, engineers and mathematicians alike. In most of the applications, the power of the transform comes from the fact that the basis functions of the transform are localized in time (or space) and frequency, and offer different resolutions in these domains. These resolutions often correspond to the natural behaviour of the process one wants to analyze, hence the power of the transform. Such properties make wavelets and wavelet transforms natural choices in fields as diverse as image synthesis, data compression, computer graphics and animation, human vision, radar, optics, astronomy, acoustics, seismology, nuclear engineering, biomedical engineering, magnetic resonance imaging, music, fractals, turbulence and pure math.

While the wavelet transform is the *de jure* standard[1] for many signal-processing applications including the fields of image processing, speech processing and data compression, the technique has very rarely been applied to the design of communication systems. This lacuna in existing knowledge is in part a motivation for this book.

1.2.2 Advantages of wavelet transform for wireless communication

The motivation for pursuing wavelet based systems primarily lies in the freedom they provide to communication systems designers [4], [5]. Unlike the Fourier bases that are static sines/cosines, wavelet bases offer flexibility and adaptation that can be tailored to satisfy an engineering demand. This feature is attributable to the fact that the wavelet transform is implemented entirely using filter bank tree structures obtainable from paraunitary filters[2]. The freedom to alter the properties of the wavelet and the filter bank tree structure gives the opportunity to fine-tune and optimize the modulated signal according to application at hand.

The benefits of wavelet-based radios for research and development of energy-efficient communication are summarized as follows:

1.2.2.1 Intelligent utilization of signal space

The wavelet-based systems are realized from tree structures obtained by cascading a fundamental quadrature mirror filter (QMF) pair of low- and high-pass filters. The construction of this tree structure can be adjusted to produce an optimum tree structure that caters to various requirements. The requirements could typically be:

[1] Examples include JPEG 2000, an image compression standard, and MPEG-4 Part 14 or MP4, a multimedia container format standard.
[2] Paraunitary filters are a class of perfect-reconstruction filters that generate orthogonal bases.

- identification and isolation of time–frequency "atoms" affected by an interfering source and communicating around the source of interference [6];
- flexibility with time–frequency tiling of the carriers that can lead to multi-rate systems which can transmit with different rates in different bands [7], a feature that can be exploited in scenarios where the channel characteristics are not uniform.

1.2.2.2 Design of wavelets to customize transceiver characteristics

By careful selection of the fundamental filters, which greatly influence the transmission characteristics, it is possible to optimize the system performance in terms of the bandwidth efficiency, localization of the transmitted signal in time and frequency, minimization of inter-symbol interference (ISI), inter-carrier interference (ICI) or peak-to-average-power ratio (PAPR), robustness towards interference from competing sources. This can also aid in opportunistic communication (e.g., cognitive radio) where unused resources can be cleverly utilized.

1.2.2.3 Flexibility with sub-carriers

The derivation of wavelets is directly related to the iterative nature of the wavelet transform. The wavelet transform allows for a configurable transform size and hence a configurable number of carriers. This facility can be used, for instance, to reconfigure a transceiver according to a given communication protocol; the transform size could be selected according to the channel impulse response characteristics, computational complexity or link quality [6].

1.2.2.4 Enhanced multi-access transmission

Wavelets offer a new dimension of diversity called the "waveform diversity" that can be exploited to enhance multiple access transmission [8]. The wavelet transform generates wavelet bases that are orthogonal to one another. By designating these bases to different users in adjacent cellular communication cells, the inter-cell interference can be minimized.

1.2.2.5 Reduced sensitivity to channel effects

The performance of communication systems is influenced by the kind of modulation scheme used. The modulation mode in turn is affected by the set of waveforms used. By cleverly altering the nature and characteristics of the waveforms used, the sensitivity of the communication system to harmful channel effects can be reduced [9].

1.2.2.6 Development of generic, multi-purpose transceivers

Furthermore, a generic and parameterized wavelet-based radio can help simplify the system architecture by doing away with multiple firmware, software, drivers that indirectly contribute to reduced power consumption and improved battery life. The radio can be designed merely by altering the parameters instead of adding/removing hardware components to the transceiver chain.

1.2.2.7 Optimization of power utilization

While there is no explicit relationship between power optimization and waveforms, the nature and characteristics of the waveform can be altered to suit a set of requirements that can indirectly contribute to a more efficient system, resulting in lower requirements of power and energy. These criteria could typically be:

- minimization of ISI, ICI or PAPR;
- greater tolerance and robustness to time/frequency/phase offset errors;
- robustness towards interference from competing sources;
- possibilities for opportunistic communication (e.g. cognitive radio) where unused resources can be cleverly utilized.

1.2.2.8 Reduced complexity of implementation

It has been proven [9] that the complexity of the wavelet systems is by and large less than OFDM systems. A lower complexity also means lower power requirements in the execution of the signal processing algorithms. The implementation of wavelet systems can be simplified even further if fast-wavelet transforms are employed.

1.2.3 Application of wavelets for wireless transmission

The wavelet transform holds promise as a possible analysis scheme for the design of sophisticated digital wireless communication systems, with advantages such as flexibility of the transform, lower sensitivity to channel distortion and interference and better utilization of spectrum. Wavelets have found beneficial applicability in various aspects of wireless communication systems design including channel modelling, design of transceivers, data representation, data compression, source and channel coding, interference mitigation, signal de-noising, energy-efficient networking. Figure 1.3 gives a graphical representation of some of the facets of wireless communications where wavelets hold promise [4].

1.2.4 Wavelet-packet-based multi-carrier modulation (WPM) system

The promise of wavelets for wireless systems design is exemplified in this research work by realizing an orthogonal multi-carrier system based on wavelet packets[3]. Orthogonally multiplexed communication is a modulation format that places independent information-carrying symbols on orthogonal signals. These orthogonal signals are typically equi-spaced sub-carriers that are modulated to occupy different centre frequencies. Hence, this signalling is also referred to as multi-carrier modulation (MCM). In traditional implementations of MCM, such as the orthogonal frequency division multiplexing or OFDM, the sub-carrier waveforms are Fourier bases or complex exponential functions. Recently, the wavelet packet transform has emerged as an important signal-processing tool. The basis functions in wavelet packet representation are obtained from a single

[3] Wavelet packets are generalized form of wavelets and will be dealt with in detail in Chapters 2 and 3.

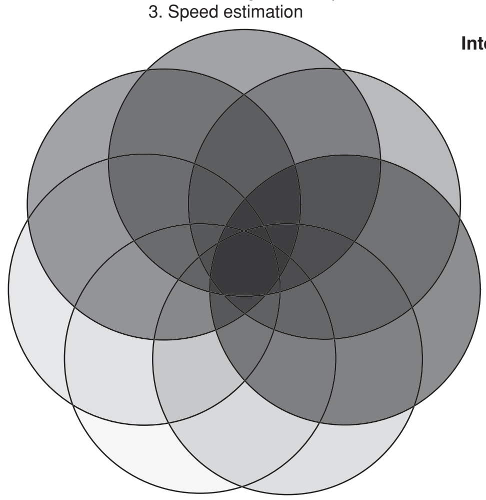

Figure 1.3 The spectrum of wavelet applications for wireless communication.

function called the mother wavelet through scaling and translations. When the scales and translations are dyadic, the resultant basis functions are orthogonal and span[4] embedded sub-spaces of $L^2(\mathbb{R})$,[5] at different resolutions yielding a multi-resolution analysis. From the perspective of communication system design, this has important and interesting implications – finite energy signals in $L^2(\mathbb{R})$ can be decomposed into orthogonal sub-spaces through a wavelet packet transform, or conversely information can be packed into mutually orthogonal wavelet packet basis functions in a way that they do not interfere with one another. Since the basis functions and sub-spaces are orthogonal, such structures can be used in developing orthogonal waveforms for a wavelet-packet-based MCM, leading to the idea of WPM.

The greatest motivation for pursuing WPM in wireless communication systems is in the flexibility and adaptability that they offer [10]–[13]. Unlike OFDM where the carriers are static sine/cosine bases, WPM uses wavelets whose features can be tailored to satisfy an engineering demand. Different wavelets result in different sub-carriers with varying temporal and spectral characteristics and different transmission properties. By careful selection of proper wavelets, it is possible to optimize WPM performance in terms of bandwidth efficiency, frequency selectivity of sub-carriers, sensitivity to synchronization errors, peak-to-average power ratio (PAPR), etc. Furthermore, the WPM

[4] The span of S may be defined as the collection of all (finite) linear combinations of the elements of S.
[5] Set of square-integrable functions in $\mathbb{R}$.

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can be efficiently implemented with filter banks obtained by cascading a fundamental quadrature mirror filter pair.

Futuristic wireless transceivers demand a great deal of flexibility and adaptability in order to operate in the crowded spectrum. These requirements correspond to the nature of WPM, making it a strong candidate for the upcoming intelligent communication systems. However, existing knowledge on wavelets for multi-carrier modulation is very limited and the literature on the topic is sparse. Moreover, a lot of key research questions remain to be addressed before WPM can become practically viable. Addressing these issues forms the basis for the efforts of this research book.

1.3 Scope of the book

The objectives stated in the previous section are too broad and ambitious to be covered in a single book. Hence, this research work will confine itself to the mathematical modelling and implementation of the wavelet packet modulator (WPM) on a simulation platform. Furthermore, some of the major technical challenges in the implementation will also be addressed. Only the radio transmission (physical layer) challenges will be considered in the following. The book is organized in eight chapters with the material categorized into three broad divisions, namely, theoretical background (Chapters 1 and 2), wavelet radio (Chapters 3, 4 and 5) and wavelet applications in cognitive radio design (Chapters 6 and 7).

1.3.1 Theoretical background (Chapters 1 and 2)

The theoretical background, is presented over two chapters. The contents provided thus far constitute the first chapter. In Chapter 2, material on the theory of wavelets is provided.

1.3.2 Wavelet radio (Chapters 3, 4 and 5)

In Chapter 3 the wavelet packet modulator, which is the focus of this book, is introduced. We take up three of the issues encountered in the implementation of WPM. Each of these challenges is handled in separate chapters.

In Chapter 4 the influence of loss of synchronization (time/frequency/phase) on the performance of the WPM system is analyzed. For each of these synchronization errors a model is presented and theoretical analysis is given for both WPM and OFDM. The bit error rate (BER) performance under time offset, frequency offset and phase noise is investigated by means of simulation studies. The simulations are performed for WPM with different types of standard wavelets and compared to OFDM.

In Chapter 5 the sensitivity of WPM to PAPR is explored.

1.3.3 Wavelet applications in cognitive radio design (Chapters 6 and 7)

In the final two chapters some of the benefits of pursuing wavelet-based systems for wireless systems design are demonstrated with some examples:

In Chapter 6 a spectrum estimator based on wavelet packets for cognitive radio applications is explained. The proposed method is shown to be efficient in estimation of spectrum and the performances comparable with existing techniques. An efficient wavelet packet spectral estimator (WPSE) based on compressed sensing and with reduced number of sensing measurements is also developed.

In Chapter 7, a general, unified approach to design and develop orthogonal wavelet packet bases according to a requirement is presented. To this end, the design criterion and the wavelet constraints are first listed. The problem that is originally non-linear and non-convex in nature is then converted into a tractable convex optimization problem and finally solved using suitable semi-definite programming (SDP) tools. The proposed mechanism is demonstrated through two *toy* examples where families of wavelets that are i) maximally frequency selective and ii) have the lowest cross-correlation energy, respectively, are developed. The design procedure borrows from the studies conducted in earlier chapters. For example, the design of maximally frequency selective filters borrows from the studies of Chapter 6, while the construction of filters with low cross-correlation uses the conclusions of Chapter 4.

Finally, the book rounds off in Chapter 8 with conclusions and recommendations for future research.

References

[1] R.W. Brodersen, A. Wolisz, D. Cabric, and S.M. Mishra, "CORVUS: A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum," Berkeley Wireless Research Center (BWRC), White paper, 2004.

[2] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2011–2016, Retrieved July 2012, from http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11–520862.pdf

[3] Fiber To The Home (FTTH) Council, Fiber to the Home Advantages of Optical Access, Retrieved July 2012, from http://www.salisburync.gov/ftth/fiber_advantages.pdf

[4] M.K. Lakshmanan and H. Nikookar, "A Review of Wavelets for Digital Wireless Communication," *Wireless Personal Communications*, vol. 37, Numbers 3–4, May 2006, pp. 387–420(34), Springer.

[5] G. Wornell, "Emerging Applications of Multirate Signal Processing and Wavelets in Digital Communications," *Proceedings of IEEE*, vol. 84, no. 2.2, pp. 586–603, April 1996.

[6] A. Lindsey, "Wavelet Packet Modulation for Orthogonally Transmultiplexed Communications," *IEEE Trans. Signal Processing*, vol. 45 no. 5, pp. 1136–9, 1997.

[7] P. Vaidyanathan, *Multirate Systems and Filter Banks*, Prentice Hall, NJ, 1993.

[8] L. Ramac and P. Varshney, "A Wavelet Domain Diversity Method for Transmission of Images over Wireless Channels," *IEEE J. Select. Area. Communications*, vol. 18, no. 6, June 2000.

[9] A. Jamin and P. Mahonen, "Wavelet Packet Modulation for Wireless Communications," *Wireless Communications and Mobile Computing Journal*, vol. 5, Issue 2, pp. 123–37, John Wiley and Sons Ltd., March 2005.

[10] H. Nikookar, "Wavelet Radio: Smart, Adaptive and Reconfigurable Radio Systems Based on Wavelets," *European Conference Wireless Technology*, October 2007, Munich, Germany.

[11] H. Nikookar, "Wavelets for Wireless Communication," *10th International Symposium on Wireless Personal Multimedia Communications*, December 2007, Jaipur, India.

[12] H. Nikookar, "Wavelet based Multicarrier Communication Techniques for Cognitive Radios," *First International Conference on Wireless VITAE* 2009, Aalborg, Denmark.

[13] H. Nikookar, "An Introduction to Wavelets for Cognitive Radio," *12th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, September 2009, Sendai, Japan.