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To Stella, Maria and Dimitra and to the memory of my father

Preface

Radio communications is a field touching upon various scientific and engineering disciplines. From cellular radio, wireless networking and broadband indoor and outdoor radio to electronic surveillance, deep space communications and electronic warfare. All these applications are based on radio electronic systems designed to meet a variety of requirements concerning reliable communication of information such as voice, data and multimedia. Furthermore, the continuous demand for quality of communication and increased efficiency imposes the use of digital modulation techniques in radio transmission systems and has made it the dominant approach in system design. Consequently, the complete system consists of a radio transmitter and receiver (front-end) and a digital modulator and demodulator (modem).

This book aims to introduce the reader to the basic principles of radio systems by elaborating on the design of front-end subsystems and circuits as well as digital transmitter and receiver sections.

To be able to handle the complete transceiver, the electronics engineer must be familiar with diverse electrical engineering fields like digital communications and RF electronics. The main feature of this book is that it tries to accomplish such a demanding task by introducing the reader to both digital modem principles and RF front-end subsystem and circuit design. Furthermore, for effective system design it is necessary to understand concepts and factors that mainly characterize and impact radio transmission and reception such as the radio channel, noise and distortion. Although the book tackles such diverse fields, it treats them in sufficient depth to allow the designer to have a solid understanding and make use of related issues for design purposes.

Recent advancements in digital processing technology made the application of advanced schemes (like turbo coding) and transmission techniques like diversity, orthogonal frequency division multiplexing and spread spectrum very attractive to apply in modern receiver systems.

Apart from understanding the areas of digital communications and radio electronics, the designer must also be able to evaluate the impact of the characteristics and limitations of the specific radio circuits and subsystems on the overall RF front-end system performance. In addition, the designer must match a link budget analysis to specific digital modulation/transmission techniques and RF front-end performance while at the same time taking into account aspects that interrelate the performance of the digital modem with the characteristics of the RF front-end. Such aspects include implementation losses imposed by transmitter–receiver nonidealities (like phase noise, power amplifier nonlinearities, quadrature mixer imbalances) and the requirements and restrictions on receiver synchronization subsystems.

This book is intended for engineers working on radio system design who must account for every factor in system and circuit design to produce a detailed high-level design of the required system. For this reason, the designer must have an overall and in-depth understanding of a variety of concepts from radio channel characteristics and digital modem principles to silicon technology and RF circuit configuration for low noise and low distortion design. In addition, the book is well suited for graduate students who study transmitter/receiver system design as it presents much information involving the complete transceiver chain in adequate depth that can be very useful to connect the diverse fields of digital communications and RF electronics in a unified system concept.

To complete this book several people have helped in various ways. First of all I am indebted to my colleagues Dimitrios Toumpakaris and Konstantinos Efstathiou for reading in detail parts of the manuscript and providing me with valuable suggestions which helped me improve it on various levels.

Further valuable help came from my graduate and ex-graduate students Athanasios Doukas, Christos Thomos and Dr Fotis Plessas, who helped me greatly with the figures. Special thanks belong to Christos Thomos, who has helped me substantially during the last crucial months on many levels (proof-reading, figure corrections, table of contents, index preparation etc.).

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Radio Communications: System Concepts, Propagation and Noise

A critical point for the development of radio communications and related applications was the invention of the 'super-heterodyne' receiver by Armstrong in 1917. This system was used to receive and demodulate radio signals by down-converting them in a lower intermediate frequency (IF). The demodulator followed the IF amplification and filtering stages and was used to extract the transmitted voice signal from a weak signal impaired by additive noise. The super-heterodyne receiver was quickly improved to demodulate satisfactorily very weak signals buried in noise (high sensitivity) and, at the same time, to be able to distinguish the useful signals from others residing in neighbouring frequencies (good selectivity). These two properties made possible the development of low-cost radio transceivers for a variety of applications. AM and FM radio were among the first popular applications of radio communications. In a few decades packet radios and networks targeting military communications gained increasing interest. Satellite and deep-space communications gave the opportunity to develop very sophisticated radio equipment during the 1960s and 1970s. In the early 1990s, cellular communications and wireless networking motivated a very rapid development of low-cost, low-power radios which initiated the enormous growth of wireless communications.

The biggest development effort was the cellular telephone network. Since the early 1960s there had been a considerable research effort by the AT&T Bell Laboratories to develop a cellular communication system. By the end of the 1970s the system had been tested in the field and at the beginning of the 1980s the first commercial cellular systems appeared. The increasing demand for higher capacity, low cost, performance and efficiency led to the second generation of cellular communication systems in the 1990s. To fulfill the need for high-quality bandwidth-demanding applications like data transmission, Internet, web browsing and video transmission, 2.5G and 3G systems appeared 10 years later.

Along with digital cellular systems, wireless networking and wireless local area networks (WLAN) technology emerged. The need to achieve improved performance in a harsh propagation environment like the radio channel led to improved transmission technologies like spread spectrum and orthogonal frequency division multiplexing (OFDM). These technologies were

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put to practice in 3G systems like wideband code-division multiple access (WCDMA) as well as in high-speed WLAN like IEEE 802.11a/b/g.

Different types of digital radio system have been developed during the last decade that are finding application in wireless personal area networks (WPANs). These are Bluetooth and Zigbee, which are used to realize wireless connectivity of personal devices and home appliances like cellular devices and PCs. Additionally, they are also suitable for implementing wireless sensor networks (WSNs) that organize in an ad-hoc fashion. In all these, the emphasis is mainly on short ranges, low transmission rates and low power consumption.

Finally, satellite systems are being constantly developed to deliver high-quality digital video and audio to subscribers all over the world.

The aims of this chapter are twofold. The first is to introduce the variety of digital radio systems and their applications along with fundamental concepts and challenges of the basic radio transceiver blocks (the radio frequency, RF, front-end and baseband parts). The second is to introduce the reader to the technical background necessary to address the main objective of the book, which is the design of RF and baseband transmitters and receivers. For this purpose we present the basic concepts of linear systems, stochastic processes, radio propagation and channel models. Along with these we present in some detail the basic limitations of radio electronic systems and circuits, noise and nonlinearities. Finally, we introduce one of the most frequently used blocks of radio systems, the phase-locked loop (PLL), which finds applications in a variety of subsystems in a transmitter/receiver chain, such as the local oscillator, the carrier recovery and synchronization, and coherent detection.

1.1 Digital Radio Systems and Wireless Applications

The existence of a large number of wireless systems for multiple applications considerably complicates the allocation of frequency bands to specific standards and applications across the electromagnetic spectrum. In addition, a number of radio systems (WLAN, WPAN, etc.) operating in unlicensed portions of the spectrum demand careful assignment of frequency bands and permitted levels of transmitted power in order to minimize interference and permit the coexistence of more than one radio system in overlapping or neighbouring frequency bands in the same geographical area.

Below we present briefly most of the existing radio communication systems, giving some information on the architectures, frequency bands, main characteristics and applications of each one of them.

1.1.1 Cellular Radio Systems

A cellular system is organized in hexagonal cells in order to provide sufficient radio coverage to mobile users moving across the cell. A base station (BS) is usually placed at the centre of the cell for that purpose. Depending on the environment (rural or urban), the areas of the cells differ. Base stations are interconnected through a high-speed wired communications infrastructure. Mobile users can have an uninterrupted session while moving through different cells. This is achieved by the MTSOs acting as network controllers of allocated radio resources (physical channels and bandwidth) to mobile users through the BS. In addition, MTSOs are responsible for routing all calls associated with mobile users in their area.

Second-generation (2G) mobile communications employed digital technology to reduce cost and increase performance. Global system for mobile communications (GSM) is a very successful 2G system that was developed and deployed in Europe. It employs Gaussian minimum shift keying (MSK) modulation, which is a form of continuous-phase phase shift keying (PSK). The access technique is based on time-division multiple access (TDMA) combined with slow frequency hopping (FH). The channel bandwidth is 200 kHz to allow for voice and data transmission.

IS-95 (Interim standard-95) is a popular digital cellular standard deployed in the USA using CDMA access technology and binary phase-shift keying (BPSK) modulation with 1.25 MHz channel bandwidth. In addition, IS-136 (North American Digital Cellular, NADC) is another standard deployed in North America. It utilizes 30 kHz channels and TDMA access technology.

2.5G cellular communication emerged from 2G because of the need for higher transmission rates to support Internet applications, e-mail and web browsing. General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EGDE) are the two standards designed as upgrades to 2G GSM. GPRS is designed to implement packet-oriented communication and can perform network sharing for multiple users, assigning time slots and radio channels [Rappaport02]. In doing so, GPRS can support data transmission of 21.4 kb/s for each of the eight GSM time slots. One user can use all of the time slots to achieve a gross bit rate of $21.4 \times 8 = 171.2$ kb/s.

EDGE is another upgrade of the GSM standard. It is superior to GPRS in that it can operate using nine different formats in air interface [Rappaport02]. This allows the system to choose the type and quality of error control. EDGE uses 8-PSK modulation and can achieve a maximum throughput of 547.2 kb/s when all eight time slots are assigned to a single user and no redundancy is reserved for error protection. 3G cellular systems are envisaged to offer high-speed wireless connectivity to implement fast Internet access, Voice-over-Internet Protocol, interactive web connections and high-quality, real-time data transfer (for example music).

UMTS (Universal Mobile Telecommunications System) is an air interface specified in the late 1990s by ETSI (European Telecommunications Standards Institute) and employs WCDMA, considered one of the more advanced radio access technologies. Because of the nature of CDMA, the radio channel resources are not divided, but they are shared by all users. For that reason, CDMA is superior to TDMA in terms of capacity. Furthermore, each user employs a unique spreading code which is multiplied by the useful signal in order to distinguish the users and prevent interference among them. WCDMA has 5 MHz radio channels carrying data rates up to 2 Mb/s. Each 5 MHz channel can offer up to 350 voice channels [Rappaport02].

1.1.2 Short- and Medium-range Wireless Systems

The common characteristic of these systems is the range of operation, which is on the order of 100 m for indoor coverage and 150–250 m for outdoor communications. These systems are mostly consumer products and therefore the main objectives are low prices and low energy consumption.

1.1.2.1 Wireless Local Area Networks

Wireless LANs were designed to provide high-data-rate, high-performance wireless connectivity within a short range in the form of a network controlled by a number of central points (called access points or base stations). Access points are used to implement communication between two users by serving as up-link receivers and down-link transmitters. The geographical area of operation is usually confined to a few square kilometres. For example, a WLAN can be deployed in a university campus, a hospital or an airport.

The second and third generation WLANs proved to be the most successful technologies. IEEE 802.11b (second generation) operates in the 2.4 GHz ISM (Industral, Scientific and Medical) band within a spectrum of 80 MHz. It uses direct sequence spread spectrum (DSSS) transmission technology with gross bit rates of 1, 2, 5 and 11 Mb/s. The 11 Mb/s data rate was adopted in late 1998 and modulates data by using complementary code keying (CCK) to increase the previous transmission rates. The network can be formulated as a centralized network using a number of access points. However, it can also accommodate peer-to-peer connections.

The IEEE 802.11a standard was developed as the third-generation WLAN and was designed to provide even higher bit rates (up to 54 Mb/s). It uses OFDM transmission technology and operates in the 5 GHz ISM band. In the USA, the Federal Communications Commission (FCC) allocated two bands each 100 MHz wide (5.15–5.25 and 5.25–5.35 GHz), and a third one at 5.725–5.825 GHz for operation of 802.11a. In Europe, HIPERLAN 2 was specified as the standard for 2G WLAN. Its physical layer is very similar to that of IEEE 802.11a. However, it uses TDMA for radio access instead of the CSMA/CA used in 802.11a.

The next step was to introduce the 802.11g, which mostly consisted of a physical layer specification at 2.4 GHz with data rates matching those of 802.11a (up to 54 Mb/s). To achieve that, OFDM transmission was set as a compulsory requirement. 802.11g is backward-compatible to 802.11b and has an extended coverage range compared with 802.11a. To cope with issues of quality of service, 802.11e was introduced, which specifies advanced MAC techniques to achieve this.

1.1.2.2 WPANs and WSNs

In contrast to wireless LANs, WPAN standardization efforts focused primarily on lower transmission rates with shorter coverage and emphasis on low power consumption. Bluetooth (IEEE 802.15.1), ZigBee (IEEE 802.15.4) and UWB (IEEE 802.15.3) represent standards designed for personal area networking. Bluetooth is an open standard designed for wireless data transfer for devices located a few metres apart. Consequently, the dominant application is the wireless interconnection of personal devices like cellular phones, PCs and their peripherals. Bluetooth operates in the 2.4 GHz ISM band and supports data and voice traffic with data rates of 780 kb/s. It uses FH as an access technique. It hops in a pseudorandom fashion, changing frequency carrier 1600 times per second (1600 hops/s). It can hop to 80 different frequency carriers located 1 MHz apart. Bluetooth devices are organized in groups of two to eight devices (one of which is a master) constituting a piconet. Each device of a piconet has an identity (device address) that must be known to all members of the piconet. The standard specifies two modes of operation: asynchronous connectionless (ACL) in one channel (used for data transfer at 723 kb/s) and synchronous connection-oriented (SCO) for voice communication (employing three channels at 64 kb/s each).

A scaled-down version of Bluetooth is ZigBee, operating on the same ISM band. Moreover, the 868/900 MHz band is used for ZigBee in Europe and North America. It supports transmission rates of up to 250 kb/s covering a range of 30 m.

During the last decade, WSNs have emerged as a new field for applications of low-power radio technology. In WSN, radio modules are interconnected, formulating ad-hoc networks.

WSN find many applications in the commercial, military and security sectors. Such applications concern home and factory automation, monitoring, surveillance, etc. In this case, emphasis is given to implementing a complete stack for ad hoc networking. An important feature in such networks is multihop routing, according to which information travels through the network by using intermediate nodes between the transmitter and the receiver to facilitate reliable communication. Both Bluetooth and ZigBee platforms are suitable for WSN implementation [Zhang05], [Wheeler07] as they combine low-power operation with network formation capability.

1.1.2.3 Cordless Telephony

Cordless telephony was developed to satisfy the needs for wireless connectivity to the public telephone network (PTN). It consists of one or more base stations communicating with one or more wireless handsets. The base stations are connected to the PTN through wireline and are able to provide coverage of approximately 100 m in their communication with the handsets. CT-2 is a second-generation cordless phone system developed in the 1990s with extended range of operation beyond the home or office premises.

On the other hand, DECT (Digital European Cordless Telecommunications) was developed such that it can support local mobility in an office building through a private branch exchange (PBX) system. In this way, hand-off is supported between the different areas covered by the base stations. The DECT standard operates in the 1900 MHz frequency band. Personal handyphone system (PHS) is a more advanced cordless phone system developed in Japan which can support both voice and data transmission.

1.1.2.4 Ultra-wideband Communications

A few years ago, a spectrum of 7.5 GHz (3.1–10.6 GHz) was given for operation of ultra-wideband (UWB) radio systems. The FCC permitted very low transmitted power, because the wide area of operation of UWB would produce interference to most commercial and even military wireless systems. There are two technology directions for UWB development. Pulsed ultra-wideband systems (P-UWB) convey information by transmitting very short pulses (of duration in the order of 1 ns). On the other hand, multiband-OFDM UWB (MB-OFDM) transmits information using the OFDM transmission technique.

P-UWB uses BPSK, pulse position modulation (PPM) and amplitude-shift keying (ASK) modulation and it needs a RAKE receiver (a special type of receiver used in Spread Spectrum systems) to combine energy from multipath in order to achieve satisfactory performance. For very high bit rates (on the order of 500 Mb/s) sophisticated RAKE receivers must be employed, increasing the complexity of the system. On the other hand, MB-UWB uses OFDM technology to eliminate intersymbol interference (ISI) created by high transmission rates and the frequency selectivity of the radio channel.

Ultra-wideband technology can cover a variety of applications ranging from low-bit-rate, low-power sensor networks to very high transmission rate (over 100 Mb/s) systems designed to wirelessly interconnect home appliances (TV, PCs and consumer electronic appliances). The low bit rate systems are suitable for WSN applications.

P-UWB is supported by the UWB Forum, which has more than 200 members and focuses on applications related to wireless video transfer within the home (multimedia, set-top boxes,