RF TECHNOLOGIES FOR LOW POWER WIRELESS COMMUNICATIONS

Edited by

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To my father Brigadier General Clarence C. Harvey, Jr.
Formerly of the field artillery

The caissons go rolling along . . .

JAMES HARVEY

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CONTENTS

RF TECHNOLOGIES FOR LOW POWER WIRELESS COMMUNICATIONS

INTRODUCTION

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The driving purpose of recent advances in communications technology has been to untether users, allowing them complete mobility and freedom of movement while maintaining their connection to electronic services. The wireless revolution has led to an expectation that voice, fax, and data services, and even internet access, can be available anywhere, without recourse to specific locations in a fixed infrastructure and even while moving or traveling. The last requirement tying the user to a fixed infrastructure is the requirement for power, either wall plug or battery recharging. For a commercial system, this requirement is manifested in the time between battery recharging, which is the only time the user is truly free of the fixed infrastructure. There have been very impressive advances in battery technology, resulting in longer times between battery recharges. However, battery technology is beginning to approach practical limits, still short of the real physical limits dictated by physical chemistry. Many technologists doubt that further advances in storage battery technology will produce more than a factor of 2 improvement in battery lifetime. The other end of this issue is the electronics systems that consume the power. If electronics systems can be designed to consume less power to accomplish the same functionality, then batteries will last longer without recharge. For military systems the situation is more complicated. Military operators of most manpacked and man portable electronic systems are accustomed to the use of disposable batteries in order to avoid the requirement for recharging during a combat operation. However,

transport of the batteries required for missions of more than a day become a significant load on the soldier, particularly as new concepts such as the Land Warrior and future soldier systems add significant electronic functionality to the individual soldier. A major concern is the weight in both the electronic equipment and batteries that the soldier must carry in combat. In addition, there are huge logistics requirements generated throughout the supply chain by the need to supply batteries in large quantities to front line troops. This issue is a major concern affecting plans for strategic airlift, strategic mobility, and the ability to project military force throughout the world. It affects transportation requirements, adds administrative effort just to keep track of the batteries through the system, and is a large procurement expense. There are also battery issues for unpiloted aerial vehicles (UAVs) and loitering missiles with mission times exceeding a few minutes. Battery requirements must trade off against the aerial vehicle payload or against its range and maximum mission time. Even in helicopters, with a large capacity power source from the engines, there are concerns. The greater the power usage in the electronics equipment, the heavier the equipment becomes. Also the power conditioning equipment for the electronics systems adds weight in proportion to the power required. For helicopters, weight trades off against lift, which can be critical in combat, or against the other payload.

Several years ago, a program in low power electronics was initiated by the Army Research Office. This program was focused on addressing the issue of RF and microwave systems with a major concern for the prime power required for wireless transmitters. At about the same time DARPA (Defense Advanced Research Programs Agency) initiated a program to address the reduction of power in digital and computing systems. The DARPA program was directed toward techniques to reduce processing power in CMOS-based electronics. One thrust was to reduce the bias voltage of CMOS transitors. Adiabatic switching techniques were also explored. As a complement to these programs, five years ago the Office of the Secretary of Defense (OSD) initiated a multidisciplinary university research initiative (MURI) program to augment the Army program in RF and microwave systems. This program ran for five years and involved researchers in four universities: the University of California Los Angeles (UCLA), the University of California San Diego (UCSD), the University of Michigan, and the University of Colorado at Boulder. The office of Deputy Undersecretary of Defense for Science and Technology provided the funding and program oversight for the MURI, while the day-to-day technical management was exercised by the Army Research Laboratory's Army Research Office (ARO). The principal investigators from that MURI are the authors of this book, which presents the results of the sponsored research. The presentation is coherent, placing the advances made during the program in perspective for a reader with a general electrical engineering background. The material in the book is presented to the design community in order to take advantage of the research in reducing power consumption in RF systems. The MURI effort focused primarily on communications systems. However, most of the research concepts can be applied to other RF systems, such as radar or target seekers in missiles. Currently most of the wireless market is in the high megahertz to low gigahertz frequency range, although satellite, wireless local area network (WLAN), and local multipoint distribution service (LMDS)

systems utilize higher frequencies, up to 60 GHz. New concepts have been proposed, such as high altitude, long operation (HALO) platform communications in the 48 GHz range. Hunger for bandwidth and spectrum availability will drive both commercial and military communications systems to higher wireless frequencies. For this reason the research was not limited to the traditional cell phone/PCS frequencies. It was not possible in this book to go into as much technical detail in each topical area as is contained in the many technical publications resulting from the research. The book attempts to present the concepts and conclusions in an understandable manner and to allow the reader to reference the detailed publications for more in-depth information as required.

The goal of this research program was to develop techniques to accomplish the RF functions at the lowest expenditure of energy. Certain RF functions require a disproportionate fraction of the system power. One such example is the power amplifier stage of a radio transmitter. Here the focus of the research was directed toward reduction of the power losses, rather than the power itself. A primary goal was determination of an optimal solution within system constraints. However, the intent of the research was not to address circuit optimization in isolation, but to consider an RF system as an interacting network of subsystems that could be optimized both on the subsystem level and on a global basis. The resulting comprehensive approach requires a highly interdisciplinary effort involving device and semiconductor materials science, circuit engineering, electromagnetics, antenna engineering, and communications systems engineering. As this introduction is being written, even a good cell phone is limited by very low efficiency in transmit mode. We believe that the concepts described in this book can open the door to efficiencies approaching 20%. Although the power consumed by a cell phone peaks in the transmit mode, the receive or standby mode is also very important because it is typically used for long periods of time, resulting in significant power drain. Receive mode issues are also addressed in this book.

Chapter 1 addresses low power RF issues from a system architecture point of view. It examines the power and energy usage implications of modulation (including spread spectrum) and coding techniques, including such trade-offs as bandwidth versus efficiency and bandwidth versus energy. It discusses frequency hopping, direct sequence, and multicarrier direct sequence spread spectrum techniques and examines the effects of amplifier nonlinearities on the power requirements for multicarrier transmitters and on receiver architectures. In order to achieve the linearity needed for low error rate modulation and low noise receiver operation, it is necessary to operate amplifiers with a narrower range of voltage or current swings. This results in lower efficiencies. The trade-offs between efficiency, linearity, bit error rate, and the modulation and coding schemes are complex, and these issues are introduced in this chapter.

Chapters 2–5 focus on issues of device physics, materials science, fabrication processes, and circuit issues for the active device building blocks for RF components. Although CMOS technology has made impressive advances in RF capability, this area was not included in the MURI research program because there was already significant effort being made in commercial industry. These four

chapters deal with GaAs, InP, SiGe, and GaN technologies, respectively. GaAs HBTs are currently in widespread use in commercial wireless systems because of their attractive performance, circuit integration, and fabrication characteristics. GaAs devices also represent a relatively mature technology. Chapter 2 examines the issues of emitter design and collector design on GaAs HBT performance and reliability. A unique on-ledge Schottky diode potentiometer is presented that is capable of direct, quantitative, in-place monitoring of the emitter ledge passivation. An analytic model is discussed to explain the physics of the potentiometer and to relate its measurements to the HBT performance. The effect of the ledge passivation on performance, noise characteristics, and failure mechanisms is explored. The effect of collector design on performance and reliability is also examined in Chapter 2. The DHBT (double heterojunction bipolar transistor) structure with a GaInP collector is shown to have significant potential advantages over single heterojunction designs, including better breakdown voltages, lower offset voltages, and lower knee voltage. Innovative designs are proposed to mitigate some of the disadvantages of the DHBT design. In Chapter 3, InP devices and circuits are discussed. InP devices will operate at higher frequencies than GaAs-based devices. HEMTs made in this technology generally have better noise performance, while HBTs demonstrate higher gain and better scaling features due to lower surface recombination, better process control due to etching selectivity, and better heat dissipation for power devices due to higher thermal conductivity. Moreover, the offset voltage and lower contact and sheet resistances of the emitter cap and collector layers of InP-based HBTs lead to smaller knee voltage. The smaller knee and turn-on voltages allow the use of low voltage batteries and increase the amplifier efficiency. However, the InP technology is newer and the available substrates are smaller (4 in. vs. 6 in.) and more expensive. Most InP HBT research has focused on NPN devices, that is, device structures doped N-type in the emitter and collector layers and P-type in the base, because of their speed. The MURI research focused on developing a complementary PNP InP HBT technology, in order to facilitate efficient, linear Class B power amplifier or output buffer circuits. To place the technology issues in perspective, the physics of NPN and PNP InP HBTs is also discussed and comparisons are made to GaAs technology. Finally, push–pull operation of complementary NPN and PNP InP HBT circuits is demonstrated. Chapter 4 is a discussion of Si/SiGe HBT technology. In general, SiGe technology has greater limitations in frequency range and breakdown voltage (restricting its power applications) than GaAs or InP technology, but it is compatible with silicon planar technology. It has the desirable characteristics of providing greater frequency and gain performance, and higher power efficiency than silicon BJT devices. Si/SiGe HBTs perform quite well in the low gigahertz frequency region, which is the high market volume personal communications application region. This technology offers the potential for low cost systems integrating analog and digital functions on a single die for lower frequency wireless applications. The specific contribution of the MURI research is in analyzing the device physics and in formulating the design rules for power amplifier circuits, although this chapter contains substantial additional perspective of the SiGe technology. Research into GaN devices has been conducted under a number of governmental programs because they promise the generation of

significantly higher power levels at high microwave or millimeter wave frequencies than single GaAs or InP devices. At higher frequencies, solid state sources of moderate power must use some kind of spatial or corporate combining structure, which inevitably introduces losses. By reducing the degree of combining required for a given power level, GaN RF power sources can be much more efficient than comparable sources based on other semiconductor technologies. One of the main barriers to the use of GaN in communications systems is its relative noisiness. The MURI research focused on this noise issue, and the results are reported in Chapter 5.

Chapters 6 and 7 focus on the power amplifier stage, where signal power is raised to a highest RF level in the transmitter. The efficiency of this stage is the upper bound for the efficiency of the overall system, and considerable attention has been paid to improving efficiency in the power amplifier. Amplifiers are generally much more efficient when operated in their power saturation region. This results in a trade-off of efficiency and linearity, with the high linearity requirements of modern communications systems pushing conventional amplifier circuits into an inefficient mode of operation. Chapter 6 presents several unconventional approaches to efficient power amplifier concepts. The use of a dc–dc converter to provide a continuously optimized supply voltage is discussed. The use of Class E and F switching amplifiers in microwave systems is presented, and the trade-off with linearity is examined. Techniques to preserve efficiency and linearity simultaneously, the LINC amplifier (linear amplification with nonlinear components) and Class S amplifiers, are also considered. And a novel approach to the self-consistent design of the amplifier and the antenna structure is applied to eliminate the conventional matching network, and its losses, between these transmitter stages. The possibility of using antennas for harmonic filters, in addition to radiation, is presented for increasing the amplifier efficiency. Chapter 7 presents an analysis of the nonlinearities in a power amplifier and new analytical tools to quantitatively address the complex nonlinear effects on the wide band of frequencies inherent in digital signals.

Passive components can be major sources of loss and inefficiency in planar RF circuits. Particularly at higher frequencies, interconnects can be very lossy, with losses to the substrate and to radiation, as well as ohmic losses in the metal. Planar antennas can have major losses to substrate modes, which can also seriously degrade the antenna patterns of arrays, effectively further reducing the efficiency of the antenna as well as complicating interfering antenna problems by radiating in unwanted directions and reception through sidelobes. The control of unwanted frequencies and spectral regrowth presents a special problem for truly planar fabricated or wafer scale integrated circuits. On-wafer approaches to the reduction in interference and frequency problems result in more complicated circuitry, with associated additional power consumption.

Chapter 8 presents two concepts that have the potential for a significant effect on these components. The SIMPOL technique provides very low loss interconnects for the integration of high performance microwave RF components with CMOS digital circuits. This technique opens the door to system-on-a-chip concepts, which have many system advantages in addition to reduced connection losses. The second concept is based on the so-called photonic bandgap structures (or electromagnetic bandgap structures). Periodic passive structures can provide planar approaches to

harmonic tuning of high efficiency microwave amplifiers, reduced transmission line leakage, low loss slow wave structures, improved planar filters, the elimination of antenna substrate modes, and a perfect magnetic impedance surface, which affords flexibility in the design of high efficiency antennas.

Chapter 9 reviews planar antenna approaches, including some innovative applications of the older concept of the quasi-Yagi antenna, and discusses the design of active integrated antennas. Active integrated antennas are active semiconductor devices or circuits integrated directly within the planar antenna structure. This type of integrated antenna circuit presents the opportunity to reduce losses between the power amplifier and the antenna due to impedance matching circuits. It also enables the design of an antenna array consisting of essentially nonlinear, nonreciprocal antenna elements, for application, for example, in phase conjugating, retroreflective arrays.

Micromachining fabrication methods harness the manufacturing processes responsible for the VLSI planar IC industry for RF circuits and circuit components. These techniques can have orders-of-magnitude impact on the size, weight, and cost of RF systems and can enable a corresponding significant reduction in power dissipation. Micromachining techniques form an overarching circuit integration technology based on extremely low loss transmission lines and metallic component structures, an inexpensive self-packaging process that eliminates spurious electromagnetic packaging effects, monolithically integrated high Q filters and resonators, the wafer-scale integration of circuits based on different substrate materials, and a natural three-dimensional layered integration capability. These techniques can essentially eliminate radiation and substrate losses from transmission lines and other passive structures, reducing losses to solely ohmic losses. Thus a planar circuit structure can approach waveguide performance, although the planar structures cannot equal the waveguide performance because the waveguide structure has more metal and therefore smaller ohmic losses. Micromachining fabrication techniques also offer the opportunity for entirely new device structures, such as the combination of RF electrical and mechanical functions in a single device, the RF MEMS (micro electro mechanical systems) devices. The micromachined and MEMS devices, such as high Q filters and switches, can replace one-for-one components in existing radio or radar architectures, resulting in simple, low loss, on-chip planar circuits. Of more interest is the ability to engineer entirely new planar monolithic architectures with reduced power requirements. These micromachining and MEMS techniques are an enabling technology for such architectures as fully duplex communications, radar simultaneous transmit/receive, common aperture and common electronics, cognitive radio, and reconfigurable aperture systems. And planar high Q components can be used to increase RF circuit selectivity, thereby reducing power consumption. The high Q components also reduce the specifications for dynamic range and phase noise in the active circuit components, allowing lower-power-consuming designs of the active components. The research under the MURI program focused on some of the critical issues of this new technology, and these results are discussed in Chapters 10, 11, and 12.

Chapter 10 deals with MEMS switches for RF applications. Mechanical and electrical design considerations for fixed beam, compliant beam, and cantilever

beam switches are discussed and concepts for high isolation switching are intro-
duced. RF MEMS switches have relatively low RF insertion loss (on the order of
0.2 dB or less), virtually zero dc power consumption, small size, and are constructed
using a batch planar fabrication process. MEMS devices have switched several watts
of RF power in laboratory experiments, providing the hope that research into the
basic physical mechanical, thermal, and electrical mechanisms of operation will lead
to reliable switching of moderate power levels by single MEMS switches.
Conventional RF MEMS switches require between 40 and 80 volts to activate
reliably, which is useful for some applications. Compliant switches can activate with
as little as 5 volts, but other performance features must be traded off to achieve these
low activation voltages. These MEMS switches can be used in place of many
semiconductor switches in RF circuits that can tolerate the slower MEMS switching
times (on the order of milliseconds), for example, in phased array beam steering and
reconfigurable antenna structures. Chapter 11 describes innovative concepts in
micromachined circuits to integrate high Q filters directly with an active semicon-
ductor device to produce a planar circuit low phase noise oscillator. The MEMS
devices described in Chapter 10 are basically switches, while the micromachined
resonators and filters in Chapter 11 are nonmechanical filters based on purely
electrical resonators. In contrast, Chapter 12 describes RF MEMS devices based on
very high Q mechanical resonators, which couple to the electrical signal. The result
is a very small (on the order of 100 microns in size), very high Q (greater than 10,000
in vacuum) MEMS filter. These filters have been demonstrated at VHF and have the
potential for application at UHF. The filters are ultra low loss and require ultra small
dc activation energies. Because of their extremely small size, they provide the
potential for their massive use in entirely new RF architectures that utilize frequency
selectivity to achieve low power consumption. On the other hand, the small size and
the inherently mechanical nature of operation place a significantly increased
emphasis on packaging issues.

Individual research areas started under this MURI program continue under
various other government programs. The research on power amplifiers inspired a
workshop on this subject, which evolved into an annual IEEE Topical Workshop on
Power Amplifiers for Wireless Communications. These individual topical areas of
research continue to be of strong interest to the military and commercial RF sectors.
However, the editors strongly feel that the success of many of these areas was due to
their being conducted and managed in a university environment with a strong
multidisciplinary and interdisciplinary structure.

This book is written for graduate students and engineering professionals with
general background of electrical engineering. Although it is assumed that they are
familiar with the background subjects such as electromagnetic fields, antennas,
microwave devices, and communications systems, no detailed knowledge is expec-
ted. Although the contents are coherently organized, individual chapters can also be
read independently. Although reasonably extensive reference lists are included in
each chapter, the wealth in information in related subjects is enormous. Readers with
interest in specific subjects may refer to the latest publications such as *IEEE
Transactions*.

1

WIRELESS COMMUNICATIONS SYSTEM ARCHITECTURE AND PERFORMANCE

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1.1 INTRODUCTION

Low power consumption has recently become an important consideration in the design of commercial and military communications systems. In a commercial cellular system, low power consumption means long talk time or standby time. In a military communications system, low power is necessary to maximize a mission time or equivalently reduce the weight due to batteries that a soldier must carry. This book focuses attention on critical devices and system design for low power communications systems. Most of the remaining parts of this book consider particular devices for achieving low power design of a wireless communications system. This includes mixers, oscillators, filters, and other circuitry. In this chapter, however, we focus on some of the higher level system architecture issues for low power design of a wireless communications system. To begin we discuss some of the goals in a wireless communications system along with some of the challenges posed by a wireless medium used for communications.

1.2   PERFORMANCE GOALS AND WIRELESS MEDIUM CHALLENGES

A system level (functional) block diagram of a wireless communications system is shown in Figure 1.1. In this figure the source of information could be a voice signal, a video signal, situation awareness information (e.g., position information of a soldier), an image, a data file, or command and control data. The source encoder processes the information and formats the information into a sequence of information bits $\in \{\pm 1\}$. The goal of the source encoder is to remove the unstructured redundancy from the source so that the rate of information bits at the output of the source encoder is as small as possible within a constraint on complexity. The channel encoder adds structured redundancy to the information bits for the purpose of protecting the data from distortion and noise in the channel. The modulator maps the sequence of coded bits into waveforms that are suitable for transmission over the channel. In some systems the modulated waveform is also spread over a bandwidth much larger than the data rate. These systems, called spread-spectrum systems, achieve a certain robustness to fading and interference not possible with narrowband systems. The channel distorts the signal in several ways. First, the signal amplitude decreases due to the distance between the transmitter and receiver. This is generally referred to as propagation loss. Second, due to obstacles the signal amplitude is attenuated. This is called shadowing. Finally, because of multiple propagation paths between the transmitter antenna and the receiver antenna, the signal waveform is distorted. Multipath fading can be either constructive, if the phases of different paths are the same, or destructive, if the phases of the different paths cause cancellation. The destructive or constructive nature of the fading depends on the carrier frequency of the signal and is thus called frequency selective fading. For a narrowband signal (signal bandwidth small relative to the inverse delay spread of the channel), multipath fading acts like a random attenuation of the signal. When the fading is constructive the bit error probability can be very small. When the fading is destructive the bit error probability becomes quite large. The average overall received amplitude value causes a significant loss in performance (on the order of 30–40 dB loss). However, with proper error control coding or diversity this loss in performance can essentially be eliminated.
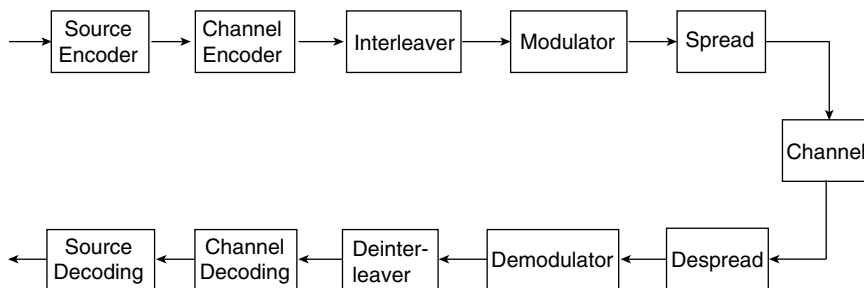

Figure 1.1. Block diagram of a digital communications system.

In addition to propagation effects, typically there is noise at the receiver that is uncorrelated with the transmitted signal. Thermal (shot) noise due to motion of the electrons in the receiver is one form of this noise. Other users occupying the same frequency band or in adjacent bands with interfering sidelobes is another source of this noise. In commercial as well as military communications systems interference from other users using the same frequency band (perhaps geographically separated) can be a dominant source of noise. In a military communications system hostile jamming is also a possibility that must be considered. Hostile jamming can easily thwart conventional communications system design and must be considered in a military communications scenario.

The receiver's goal is to reproduce at the output of the source decoder the information-bearing signal, be it a voice signal or a data file, as accurately as possible with minimal delay and minimal power consumed by the transmitter and receiver. The structure of the receiver is that of a demodulator, channel decoder, and source decoder. The demodulator maps a received waveform into a sequence of decision variables for the coded data. The channel decoder attempts to determine the information bits using the knowledge of the codebook (set of possible encoded sequences) of the encoder. The source decoder then attempts to reproduce the information.

In this chapter we limit discussion to an information source that is random data with equal probability of being 0 or 1 with no memory; that is, the bit sequence is a sequence of independent, identically distributed binary random variables. For this source there is no redundancy in the source, so no redundancy can be removed by a source encoder.

There are important parameters when designing a communications system. These include data rate R_b (bits/s, or bps), at the input to the channel encoder, the bandwidth W (Hz), received signal power P (watts), noise power density $N_0/2$ (W/Hz), and bit error rate $P_{e,b}$. There are fundamental trade-offs between the amount of power or equivalently the signal-to-noise ratio used and the data rate possible for a given bit error probability, $P_{e,b}$. For ideal additive white Gaussian noise channels with no multipath fading and infinite delay and complexity, the relation between data rate, received power, noise power, and bandwidth for $P_{e,b}$ approaching zero was determined by Shannon as [1]

$$R_b < W \log_2\left(1 + \frac{P}{N_0 W}\right). \tag{1.1}$$

If we let $E_b = P/R_b$ represent the energy used per data bit (joules per bit), then an equivalent condition for reliable communication is

$$\frac{E_b}{N_0} > \frac{2^{R_b/W} - 1}{R_b/W}.$$

This relation determines the minimum received signal energy for reliable communications as a function of the spectral efficiency R_b/W (bps/Hz). The
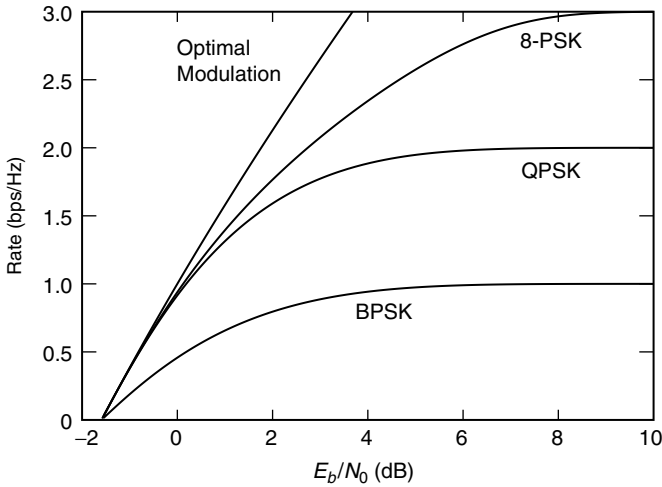
Figure 1.2. Possible data rate for a given energy efficiency.

interpretation of this condition is that for lower spectral efficiency, lower signal energy is required for reliable communications. The trade-off between bandwidth efficiency and energy efficiency is illustrated in Figure 1.2. Besides the trade-off for an optimal modulation scheme, the trade-off is also shown for three modulation techniques: binary phase shift keying (BPSK), quaternary phase shift keying (QPSK), and 8-ary phase shift keying (8PSK).

In this figure the only channel impairment is additive white Gaussian noise. Other factors in a realistic environment are multipath fading, interference from other users, and adjacent channel interference. In addition, the energy is the received signal energy and does not take into account the energy consumed by the processing circuitry. For example, power consumption of signal processing algorithms (demodulation, decoding) are not included. Inefficiencies of power amplifiers and low noise amplifiers are not included. These will be discussed in subsequent sections and chapters. These fundamental trade-offs between energy consumed for transmission and data rate were discovered more than 50 years ago by Shannon (see Cover and Thomas) [1]. It has been the goal of communications engineers to come close to achieving the upper bound on data rate (called the channel capacity) or equivalently the lower bound on the signal-to-noise ratio.

To come close to achieving the goals of minimum energy consumption, channel coding and modulation techniques as well as demodulation and decoding techniques must be carefully designed. These techniques are discussed in the next two sections.

1.3   MODULATION TECHNIQUES

In this section we describe several different modulation schemes. We begin with narrowband techniques whereby the signal bandwidth and the data rate are roughly
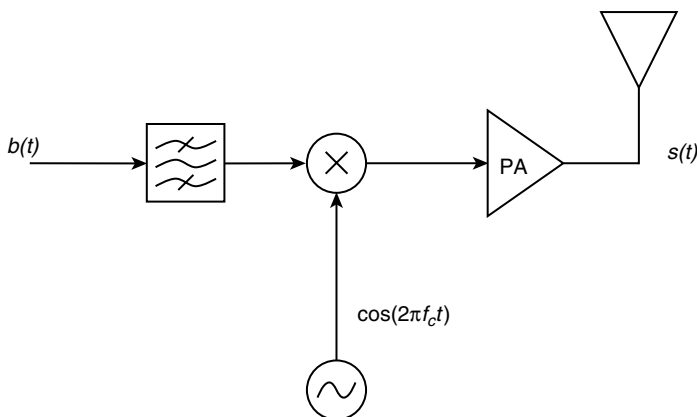
Figure 1.3. Transmitter.

equal. In wideband techniques, or spread-spectrum techniques, the signal bandwidth is much larger than the data rate. These techniques are able to exploit the frequency-selective fading of the channel. For more details see Proakis [2].

1.3.1 Narrowband Techniques

A very simple narrowband modulation scheme is binary phase shift keying (BPSK). The transmitter and receiver for BPSK are shown in Figures 1.3 and 1.4, respectively. A sequence of data bits $b_l \in \pm 1$ is mapped into a data stream and filtered. The filtered data stream is modulated onto a carrier and is amplified before being radiated by the antenna. The purpose of the filter is to confine the spectrum of the signal to the bandwidth mask for the allocated frequency. The signal is converted from baseband by the mixer to the desired center or carrier frequency (upconversion). The signal is then amplified before transmission. With ideal devices (mixers, filters, amplifiers) this is all that is needed for transmission. However, the
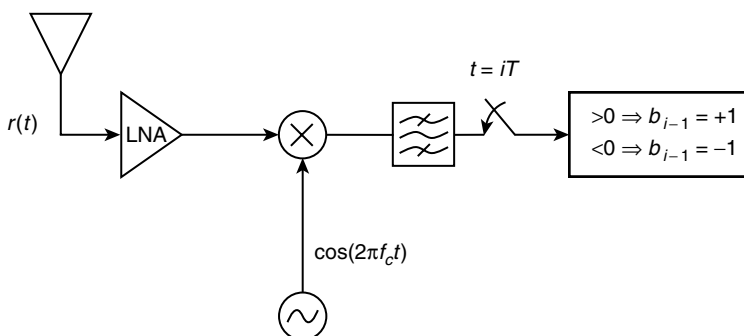

Figure 1.4. Receiver.

mixers and amplifiers typically introduce some additional problems. The amplifier, for example, may not be completely linear. The nonlinearity can cause the bandwidth of the signal to increase (spectral regrowth), as will be discussed later.

For now, assume that the filter, mixer, and amplifier are ideal devices. In this case the transmitted (radiated) signal can be written as

$$s(t) = \sqrt{2P} \sum_{l=-\infty}^{\infty} b_l h(t - lT) \cos(2\pi f_c t), \tag{1.2}$$

where P is the transmitted power, T is the duration of a data bit or the inverse of the data rate R_b, f_c is the carrier frequency, and $h(t)$ is the impulse response of the pulse-shaping filter. There are various choices for the pulse-shaping filter. A filter with impulse response being a rectangular pulse of duration T seconds results in a constant envelope signal (peak-to-mean envelope ratio of 1) but has large spectral splatter, whereas a Nyquist-type pulse has high envelope variation and no spectral splatter. The disadvantage of high envelope variation is that it will be distorted by an amplifier operating in a power efficient mode because of the amplifier's nonlinear characteristics. Thus there is a trade-off between power efficiency and bandwidth efficiency in the design of the modulation.

The simplest channel model is called the additive white Gaussian noise (AWGN) channel. In this model the received signal is the transmitted signal (appropriately attenuated) plus additive white Gaussian noise:

$$r(t) = \alpha s(t) + n(t). \tag{1.3}$$

The noise is assumed to be white with two-sided power spectral density $N_0/2$ W/Hz.

The receiver for BPSK is shown in Figure 1.4. The front end low noise amplifier sets the internal noise figure for the receiver. The mixer converts the radio frequency (RF) signal to baseband. The filter rejects out-of-band noise while passing the desired signal. The optimal filter in the presence of additive white Gaussian noise alone is the matched filter (a filter matched to the transmitter filter). This very simplified diagram ignores many problems associated with nonideal devices. For the case of ideal amplifiers and a transmit filter and receiver filter satisfying the Nyquist criteria for no intersymbol interference [2], the receiver filter output can be expressed as

$$X_l = \sqrt{\bar{E}} b_{l-1} + \eta_l,$$

where $\bar{E}$ is the received energy ($\bar{E} = \alpha^2 PT$) and η_l is a Gaussian distributed random variable with mean zero and variance $N_0/2$. The decision rule is to decide $b_{l-1} = +1$ if $X_l > 0$ and to decide $b_{l-1} = -1$ otherwise. For the simple case of an additive white Gaussian noise channel, the error probability is

$$P_{e,b} = Q\left(\sqrt{\frac{2\bar{E}}{N_0}} \right),$$

where $Q(x) = \int_x^\infty (1/\sqrt{2\pi}) \exp(-u^2/2)\, du$. This is shown in Figure 1.5.
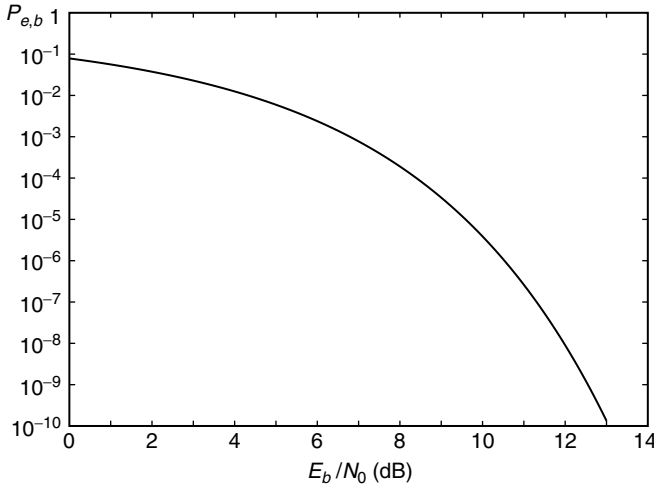
Figure 1.5. Bit error probability for BPSK in AWGN.

From Figure 1.5 it can be seen that in order to provide error probabilities around 10^{-5} it is necessary for the received signal-to-noise ratio to $\bar{E}/N_0 = 9.6$ dB. The capacity curve for BPSK in Figure 1.2, however, indicates that if we are willing to lower the rate of transmission we can significantly save on energy. For example, it is possible to have a nearly 0 dB signal-to-noise ratio if we are willing to reduce the rate of transmission by 50%. Thus about 9.6 dB decrease in signal power is possible with a 50% reduction in transmission rate.

The above analysis is for the case of additive white Gaussian noise channels. Unfortunately, wireless channels are not accurately modeled by just additive white Gaussian noise. A reasonable model for a wireless channel with relatively small bandwidth is that of a flat Rayleigh fading channel. While there are more complex models, the Rayleigh fading channel model is a model that provides the essential effect. In the Rayleigh fading model the received signal is still given by Eq. (1.3). However, α is a Rayleigh distributed random variable that is sometimes large (constructive addition of multiple propagation paths) and sometimes small (destructive addition of multiple propagation paths). However, the small values of α cause the signal-to-noise ratio to drop and thus the error probability to increase significantly. The large values of α corresponding to constructive addition of the multiple propagation paths result in the error probability being very small. However, when the average error probability is determined there is significant loss in performance. The average error probability with Rayleigh fading and BPSK is

$$\bar{P}_{e,b} = \int_{r=0}^{\infty} f(\alpha)Q\left(\sqrt{\frac{2E\alpha}{N_0}}\right)d\alpha = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{\bar{E}/N_0}{1 + \bar{E}/N_0}}, \tag{1.4}$$
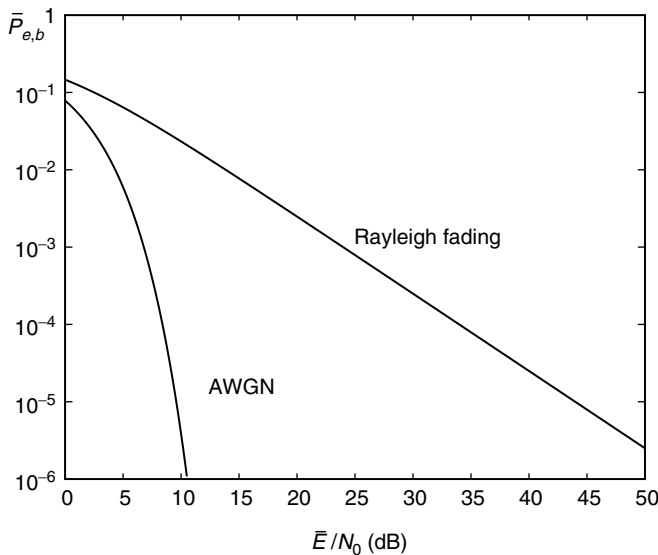
Figure 1.6. Bit error probability for BPSK with Rayleigh fading.

where $f(r)$ is the Rayleigh density and $\bar{E}$ is the average received energy. The average error probability as a function of the average received energy is shown in Figure 1.6. Included in this figure is the performance with just white Gaussian noise. As can be seen from the figure, there is a significant loss in performance with Rayleigh fading. At a bit error rate of 10^{-5} the loss in performance is about 35 dB. In early communications systems the transmitted power was boosted to compensate for fading. However, there are more energy efficient ways to compensate for fading.

For a Rayleigh fading channel the fundamental limits on performance are known as well. The equations determining the limits are significantly more complicated [3]. Nevertheless, they can be evaluated and are shown in Figure 1.7. By examining the curve for BPSK we can see that it is possible to reduce the loss in performance to about 2 dB (rather than 35 dB) if proper signal (coding) design is used. Thus by reducing the data rate by 50% with proper coding a 33 dB savings in energy is possible. One method of signaling that reduces this performance loss is by the use of wideband signals, as discussed in the next section.

1.3.2   Wideband Techniques

Wideband signals have the potential of overcoming the problem of fading [4]. This is because the fading characteristics are frequency dependent. Different frequencies fade differently because the phase relationships of different paths change as the frequency changes. In addition, wideband techniques are able to handle interference from jammers or from other users. There are several techniques that are employed for wideband communications systems. Two popular techniques are direct-sequence