Sung-Moon Michael Yang

Modern Digital Radio Communication Signals and Systems

Springer

Modern Digital Radio Communication Signals and Systems

Sung-Moon Michael Yang

Modern Digital Radio Communication Signals and Systems

Springer

Sung-Moon Michael Yang
BaycoreWireless.com
Irvine, CA, USA

ISBN 978-3-319-71567-4   ISBN 978-3-319-71568-1 (eBook)
https://doi.org/10.1007/978-3-319-71568-1

Library of Congress Control Number: 2017961121

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This book is written for practitioners of wireless digital communication systems – engineers, technical leaders, and managers for product and technology development – and for digital communication systems in general.

My goal is for this book to serve as an easily accessible reference, allowing the reader to learn and refresh a particular topic quickly. To this end, a number of figures, tables, examples, and exercises are included. A topic is described with a simple but nontrivial example, and then its variations and sophistications are presented. I believe it is the fastest and most effective to learn and refresh. This does not mean only a collection of recipes. On the contrary, we emphasize that the fundamentals, when understood properly, are powerful in practice. For example, the performance of binary transmission system under additive Gaussian noise channel is fundamental and also useful both in higher-order modulations and in fading channels. A shaping pulse, matched and intersymbol interference-free, is basic and applicable everywhere, e.g., it is insightful and practically useful, in orthogonal frequency division multiplex signal, to recognize its underlying pulse being rectangular. Thus this book emphasizes both practical problem solving and a thorough understanding of fundamentals and therefore should also be useful to newcomers to the area like graduate students, serious undergraduate students, and others.

This book is the outgrowth of my involvement in telecommunication systems industry as a research and development engineer. The starting point of my career, in the early 1980s, was also when the digitalization of the industry was at the starting point of its full swing. All of the topics in this book are, in one way another, related to my hands-on experience. Part of the book material was used in UCI and UCLA extension courses and at other universities.

I am indebted to the whole community of the technologies of communication systems, but in particular to the companies that gave me opportunities to work on the topics of this book. Technologies evolve continuously and incrementally through the work of many like biological evolution. And this author hopes this book to be a small thread in this continuing evolution, in addition to be useful to its intended audience, practitioners of digital communication systems. Thus it helps to push forward the field one small increment further.

Yorba Linda, CA, USA Sung-Moon Michael Yang

Contents

About the Author

Sung-Moon Michael Yang is a practicing communication systems engineer with emphasis on wireless communication systems. While in his career he worked mostly full-time for the communication industry in Silicon Valley and more recently in Southern California, for design and development of wireless system products as well as integrated circuit components, he also taught wireless communication systems and digital signal processing part-time at various universities. He received his BS from Seoul National University, Seoul, Korea, and MS and PhD from UCLA, all in electrical engineering.

Chapter 1
Overview of Radio Communication Signals and Systems

Abstract This chapter introduces the intent of the book briefly and then overviews the content of it in a nontrivial manner thus a bit lengthy as an introduction. But, it is hoped that it stimulate a reader to the topics of the book. A new comer might find it a bit challenging for the first reading as an introduction, but one can move on since the topics will be elaborated later in detail.

List of sections in Chap. 1:

Key Innovative Terms None

General Terms AWGN · Channel coding · Channel estimation · Complex envelope · Constellations · CW signals · Demodulation · Digital modulations · DS spread spectrum · DSP · FH · Layered approach · Low-noise amplifier · OFDM · Path loss · PCM · Power amplifier · Pulse-shaping filters · Quadrature modulations · Radio propagation channel · Signals and systems · Software-defined radio · Synchronization

List of abbreviations

1G, 2G, 3G	First generation, second generation, third generation
AM	Amplitude modulation
ADC	Analog digital converter
ASK	Amplitude shift keying
AWGN	Additive white Gaussian noise
BPSK	Binary phase shift keying
BCH	Bose, Chaudhuri, Hocquenghem (names)
BCJR	Bahl, Cocke, Jelinek, Raviv (names)

S. -M. M. Yang, *Modern Digital Radio Communication Signals and Systems*,
https://doi.org/10.1007/978-3-319-71568-1_1

BSC	Binary symmetric channel
CDMA	Code division multiple access
CFSK	Continuous frequency shift keying
CP	Cyclic prefix
CW	Continuous wave
DAC	Digital analog converter
DC	Direct current
DFT	Discrete Fourier transform
DMC	Discrete memoryless channel
DMT	Digital multitone
DS	Direct sequence
DSB	Double sideband
DSL	Digital subscriber loop
DSP	Digital signal processing
FDM	Frequency division multiplex
FEC	Forward error correction
FH	Frequency hopping
FSK	Frequency shift keying
FM	Frequency modulation
Gbps	Giga bit per second
GHz	Giga Hertz (10E9 Hz)
GPS	Global positioning system
GSM	Global system for mobile communications
HD	Hard decision
IDFT	Inverse discrete Fourier transform
IEEE	Institute of Electrical Electronics Engineers
LAN	Local area network
LDPC	Low-density parity-check code
LED	Light-emitting diode
LHS	Left-hand side
LNA	Low-noise amplifier
LOS	Line of sight
LTE	Long-term evolution
MELP	Mixed excitation linear predictive vocoder
MIMO	Multiple input multiple output (antenna system)
MPEG	Motion picture expert group
MP3	MPEG-1 or 2 Audio Layer III
MSK	Minimum shift keying
OFDM	Orthogonal frequency division multiplex
OOK	On-off keying
OSI	Open system interconnect
PA	Power amplifier
PAN	Personal area network
PCM	Pulse coded modulation
PCB	Printed circuit board
QAM	Quadrature amplitude modulation

QPSK	Quad phase shift keying
RA	Repeat accumulator
RF	Radio frequency
RHS	Right-hand side
RS	Reed, Solomon
SDR	Software-defined radio
SD	Soft decision
SERDES	Serial, de-serial (parallel)
SNR	Signal to noise ratio
SSB	Single sideband
TDD	Time division duplex
VSB	Vestigial sideband
WDM	Wave division multiplex
Wi-Fi	Wireless Fidelity
WiMAX	Wireless microwave access

The title of this book is *Modern Digital Radio Communication Signals and Systems*. We explain it first.

Modern is related with actual implementation of a system. Most systems take advantage of computational power being cheap to do ever more sophisticated discrete-time signal processing, often called digital signal processing (DSP), and thus achieve system performance close to theoretically possible optimum. Other than antennas, power amplifier (PA), low-noise amplifier (LNA), mixers, and oscillators, most digital radio systems are implemented by using DSP, i.e., numerical computations with digital hardware or with computer processors. The idealization of such implementations is sometimes called software-defined radio (SDR). We do not follow its particular style in this book. See Fig. 1.2 wireless system block diagram.

Digital is related with the user messages. It means that a system will carry digital information. The simplest representation of it is to use binary number {0, 1}. The user message is in the form of digital representation such as files, packet, or continuous stream of binary bits. Analog message signals such as picture, voice, and movie are converted to digital format, say using one of standard conversion formats like MPEG (motion picture expert group), MP3 (MPEG-1 or 2 Audio Layer III), and MELP (mixed excitation linear predictive) voice coder.

Radio is related with communication channels. It may be called wireless, but "radio" seems more specific than "wireless." Here we use "wireless" exchangeable with "radio." One of the most ubiquitous wireless systems is cellular phone networks. In addition there are many wireless systems: Wi-Fi wireless LAN (local area network), WiMAX, satellite communication systems, deep space communication systems, and line of sight microwave radios and short distance systems such as Bluetooth and digital cordless phones. A long list is necessary to enumerate most of them. The communication channels have a large impact to the communication signal design, along with the user need and the performance requirement. For example, DSL (digital subscriber loop) and voiceband modem, it is common practice to measure a channel response during the call setup and adjust the transmission rate accordingly. On the other hand, in radio systems, it is not possible since the channels are time-varying due to the radio media (e.g., diffraction) or due to the mobility of the radios. Fading, fast and slow, is due to mobility and is present for most of the time.

Communication signals and systems means here two-way communications, unlike broadcasting which is one way. Radar is two way but it receives its own signal after delay and distortion. Because of digital signal processing implementations, a signal representation can be implemented numerically. For testing and simulation purpose, radio channels can be represented as a signal or system representation such as an impulse response or frequency response. In this situation, signals and systems are interchangeable. Historically some ingenious circuits were very useful at the time of invention for simplicity of implementations but are no longer the case since most of implementations are "numerical." They are not our focus here; rather the ideas or their mathematical representations behind the circuits may be utilized for "numerical" implementations. Thus the fundamentals represented mathematically are important and should be mastered. After that the circuit ingenuity may be appreciated as interesting examples.

Modern Digital Radio Communication Signals and Systems is written mainly for practicing communication system design engineers and managers. This book intends to be used as a reference book in practice as well as for quickly learning and refreshing. For this purpose we include examples, figures, and tables that are useful in practice so that they can be understood and remembered at a glance. Our approach is practical and pragmatic while we realize that the solid foundation in fundamentals is powerful in practice. This book helps to realize this complementary relationship between practice and theory. In this way it is also be useful to graduate students and even to senior undergraduate students in communication systems. In fact, part of this book material has been used for postgraduate extension courses and for senior level undergraduate courses in communication systems. As said before, communication systems are heavily influenced by communication channels and user performance requirements. However, even though this book emphasizes radio channels, fundamentals of carrier modulation signals (CW signals) that are covered here will also be useful to wireline channels – DSL (twisted pair), SERDES (backplane trace), coax, power lines, and optical fibers.

1.1 Examples of Wireless Communication Systems

Cellular network systems are by far the largest digital radio communication system in use today, and the fourth generation is here and next generation (5G) is brewing. Its user device was started as a mobile phone equipped for car in the trunk and is now evolved into smartphones way beyond the initially envisioned phone service. They are not only phones but perform multiple functions, especially any time Internet access without a call setup. Additional functions are camera, video, calendar, and associated personal digital assistant functions. But the most useful functions come from the fact that a smartphone can access a larger number of applications on Internet with digital connectivity. This connectivity between Internet and a user device is accomplished by digital radio communication signals, through cellular

Fig. 1.1 Examples of cellular base station antennas are shown. LHS is a closeup view of antennas, and RHS is another example where antennas are blended as part of tree in an attempt to be less visible to the environment. Antennas are most visible part of the whole cellular infrastructure equipment

phone networks. In order to support the user applications, the physical layer link utilizes radio propagation channels with appropriate communication signals and systems, which will be studied intensely and extensively in this book.

A major innovation for a high-capacity cellular network (1G) is the spatial reuse of the same frequency over and over again. A base station is located in each cell of hexagonal geometric shape and thus is called cellular networks. Next innovation (2G) is to use digital transmission using CDMA and GSM, which increase the network capacity by nearly a factor of 10. Then the 3G system is designed for Internet access in mind. The fourth generation is based on LTE (long-term evolution) – OFDM (orthogonal frequency division multiplex) signaling format and on multiple antennas for even higher throughput. In Fig. 1.1, examples of cellular base station antennas are shown. LHS is a closeup view of antennas, and RHS is an example with camouflage as part of tree to be less visible to the environment.

The next most ubiquitous wireless system is Wi-Fi wireless LAN (local area network). One key innovation was to use unlicensed RF frequencies (2GHz, 5GHz). It is served as effective in-house wiring system connecting computers and network access for Internet. In the airport and at hotels, it is one prevalent way of providing Internet access, with least cost, without wiring up a whole building.

Related with wireless LAN, Bluetooth is a short wire replacement between earphones to smartphones, between earphones to mobile phone inside car. It is to replace a short wire within device. There are various similar devices called PAN (personal area network) such as ZigBee.

The cordless phones use the same unlicensed frequency as Wi-Fi. One can move around the house with a cordless phone. A telephone cord is replaced by a radio (mostly digitally these days) communication system.

LOS (line of sight) microwave systems were used extensively to carry long-distance telephone traffics before the advent of optical fiber systems. It was designed to be very reliable and highly bandwidth-efficient systems (5–10 bps/Hz). This means that, as an example, a system with 10 bps/Hz bandwidth efficiency can transport 1Gbps with 100 MHz bandwidth. LOS microwave systems are still used extensively for backhaul connections of cellular base stations. Now it is declined substantially compared to its peak time, but they are useful where there is no optical fiber infrastructure.

Most of TV broadcasting uses digital communication signals. Satellite-based system uses digital communication signals, which may be used for TV and for two-way communications. GPS (global positioning system) uses digital communication signals, but it is one way from sky to the earth. Garage door opener uses a simple form of digital communication signals. Many sensor network devices use digital communication signals, where one important constraint may be the battery power. They are expected to proliferate with the spread of IoT perhaps with hundreds of thousands sensors which must be connected.

1.2 Overview of Wireless Communication Systems

Based on Fig. 1.2 wireless communication system block diagram, we overview the whole system. To someone new to this wireless system area, the figure may look complicated, but it is a generic block diagram and contains only blocks of high-level view. As we go through this book, the diagram will increasingly appear to be simple. The figure is drawn somewhat unconventionally yet intentionally. Typically it is drawn horizontally that the receiver is on the right-hand side with the transmitter on the left-hand side and the channel in the middle. The intention of it will be clear as we go along; a brief justification follows.

In Fig. 1.2, if one works on a pair of blocks, for example, channel coding and decoding blocks, its right side can be considered as a channel (or resources to be utilized), and its left side is the user information to carry (or users to serve). On the

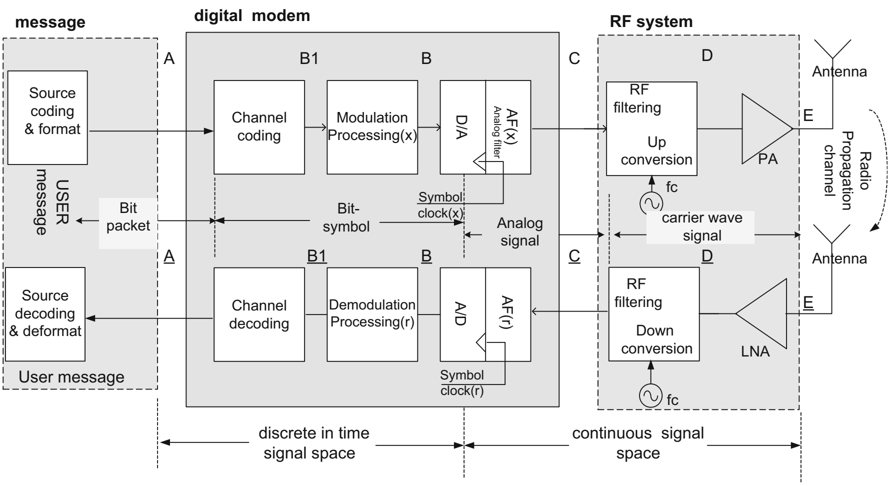
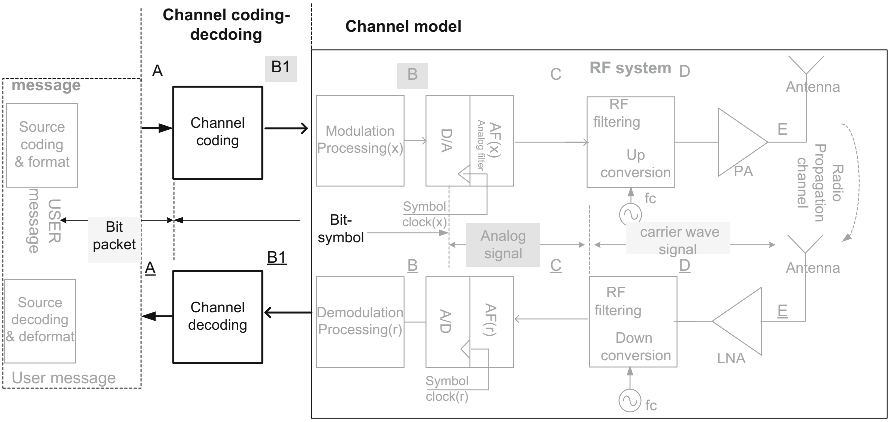
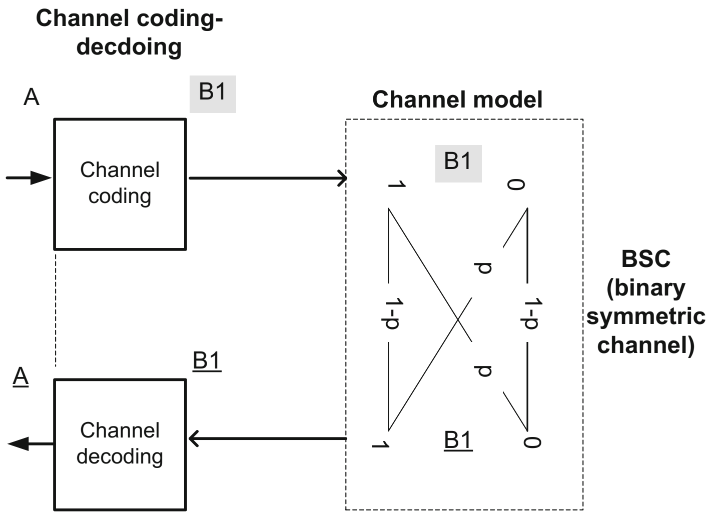


Fig. 1.2 Digital radio communication system block diagram will be used throughout the book

channel side, from channel coding point of view, it can be abstracted from complicated transmission chain from B_1, B, C, D, E, antenna, and radio channels back to <u>E</u>, <u>D</u>, <u>C</u>, <u>B</u>, and $\underline{B}_1$ (note underlines) as shown below.





This abstraction, a digital channel, is often represented to have a probability of bit error (p). This abstraction as shown above is very useful and often used in practice, and thus a specialist in coding can work without knowing many details on radio channel (coding is applicable to other channels like optical fibers and even for storage systems like magnetic tape and optical disks). The input A is a stream of bits and so is the output <u>A</u>. This channel model may be called binary symmetric channel (BSC). Different channel models (not shown here) are possible – discrete memoryless channel (DMC), erasure channel, and AWGN channel.

Back to Fig. 1.2, there are four large blocks in the figure: (1) user message, (2) digital modem, (3) RF subsystem, and (4) antennas and radio propagation channel (in the figure no block is drawn for radio channel). In this book our focus will be on the digital modem subsystem. However, it is critically influenced by other blocks, particularly by radio propagation channels. The right side of the digital modem may be considered as a "transmission channel" (C, D, E, and radio channel, then back to $\underline{E}$, $\underline{D}$, and $\underline{C}$). Its left side is the user message, which can be a continuous stream of bits or frames/packets which consist of bits (A). At the receiver side ($\underline{A}$), the recovered message should be delivered to the other user in the far end. It is not a loop which appears to be so in the figure.

Note also that signals are divided into two categories: discrete-time signals and continuous-time signals. Its boundary is between B and C at the transmitter side (DAC and transmit analog filter) and between $\underline{C}$ and $\underline{B}$ at the receiver side (receive analog filter and ADC). The function of a digital modem is to convert discrete-time signal to continuous-time signal and vice versa. At C and $\underline{C}$, the signals are analog baseband and continuous-time (also called baseband complex envelope), and the signal at D/E and $\underline{D}$/$\underline{E}$ is called CW (continuous wave) signals, i.e., carrier modulated sinusoidal waves. CW is real, not complex, in time domain. The bandwidth of analog baseband signals is limited and typically much smaller than a carrier frequency, f_c. We explain it in more detail below starting from CW signals.

1.2.1 Continuous Wave (CW) Signals

A signal at D, after up conversion with a carrier frequency, f_c, can be represented as a cosine wave being modulated by a baseband signal at C with its amplitude (A) and phase (θ). It is given by,

$$s_x(t) = A\cos\left(2\pi f_c t + \theta\right) \tag{1.1}$$

Note that the CW itself, without modulation, is given by $1.0 * \cos(2\pi f_c t)$, which is generated by a carrier frequency oscillator. A baseband signal is represented by the amplitude ($A(t)$) and phase ($\theta(t)$), which is a function of time, carrying the information. The carrier itself does not carry the information. In order to increase the power of CW, additional amplifier such as PA (power amplifier) will be used, but here we set aside the issue and the gain is set to be unity; $A(t)$ and $\theta(t)$represent entirely baseband information carrying signals.

Historically CW modulation was a major innovation in communication signals in the early twentieth century. It was applied to AM broadcasting. $A(t) = 1.0 + k * a(t)$ where k is a constant called modulation index and $a(t)$ is the modulating, analog baseband signal, i.e., voice. The phase $\theta(t)$ is not critical since it can be recovered non-coherently (i.e., without knowing the carrier phase of a signal). FM broadcasting followed, where the information is carried by frequency change, or $d\theta/dt$, while $A =$ constant. More sophisticated carrier modulations were developed in the context of TV and telephony with FDM: DSB, VSB, and SSB with suppressed carrier. In particular, SSB is the most efficient system for analog voice telephony and was used until digital hierarchy systems, such as T1, were developed. If you are not familiar with these concepts, do not worry since all of these analog modulations will be explained briefly below and later in detail. A key point is that CW modulation is still essential part of digital radio signals. And we emphasize the universality of CW represented by (1.1) and that it is real, not complex, in time. The bandwidth of analog baseband signals is limited and typically much smaller than a carrier frequency, f_c. Thus from this point of view $A(t)$ and $\theta(t)$ may be slow compared to the carrier and thus sometimes treated them as nearly constant.

Abbreviations used in this section are DSB (double sideband), VSB (vestigial sideband) and SSB (single sideband), and FDM (frequency division multiplex).

1.2.2 Complex Envelope and Quadrature Modulation

An equivalent but different representation called complex envelope is useful, particularly in the context of digital radio communication signals. Equation (1.1) is represented as

$$s_x(t) = Re\left\{ \left[A_I + jA_Q\right] e^{j2\pi f_c t} \right\} \tag{1.2}$$

where $A_I = A\cos(\theta)$ and $A_Q = A\sin(\theta)$.

The Eq. (1.2) can be written as

$$s_x(t) = A_I \cos(2\pi f_c t) - A_Q \sin(2\pi f_c t) \tag{1.3}$$

using the relationship of $e^{j2\pi f_c t} = \cos(2\pi f_c t) + j\sin(2\pi f_c t)$.

It is important to see that (1.1), (1.2), and (1.3) are different representations of the same CW signal.

The complex envelope, $C = A_I + jA_Q$, can be considered as a phasor representation as in Fig. 1.3 (LHS). However, this phasor is not static, but dynamically changing, depending on the baseband signal. For example, in FM, the rotation of a

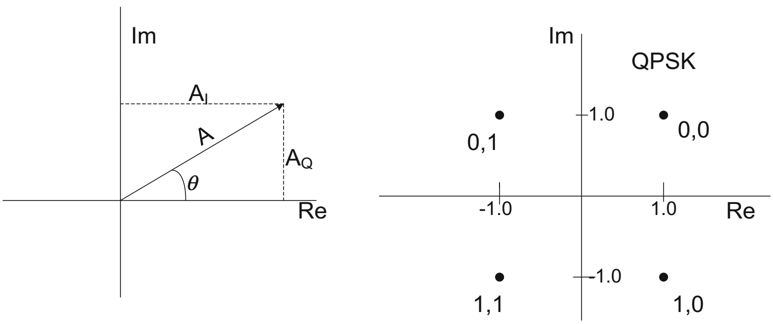


Fig. 1.3 Phasor diagram (LHS) and QPSK constellation (RHS)

phasor and its angular speed (frequency) represent the information. For DSB, VSB, and SSB, (A_I, A_Q) are related. In SSB, A_Q = Hilbert transform (A_I). In DSB, A_I=A and A_Q= 0 (null). In VSB, (A_I, A_Q) are not independent but related even though it is not possible to state it simply. Here we emphasize again the universality of complex envelope and quadrature modulation represented equivalently by (1.1), (1.2), and (1.3); it can represent all different analog modulations. In particular, (1.2) or (1.3) is more often used in digital transmission. We cannot overemphasize its universality for any kind of analog and digital modulations.

1.2.3 *Digital Modulations*

CW modulation (or quadrature modulation) with the complex envelope representation of a baseband signal in the form of (1.2) is general enough so that it is extended to digital transmission. For digital transmission it requires to generate a complex envelope $C = A_I + jA_Q$ (continuous signal) from discrete-time bit stream. There are many ways that can be done: QAM, QPSK, MSK, FSK, OOK, ASK, and so on. This will be a major topic of this book. Abbreviations used here are QAM (quadrature amplitude modulation), QPSK (quad phase shift keying), MSK (minimum shift keying), FSK (frequency shift keying), OOK (on-off keying), and ASK (amplitude shift keying); it is interesting to note that "shift keying" is originated from early telegraph system, which is a form of baseband digital communication systems.

For actual signal generation, the Eq. (1.3) is often used, and it is called quadrature modulation, since two channels, in-phase (cosine) and quadrature phase (sine), are used, and due to their 90° phase (quadrature) difference, they are orthogonal. In digital transmission, rather than using SSB, two in-phase and quadrature phase channels are used to carry two independent data stream. This is equivalent to SSB in terms of bandwidth efficiency.

The symbols (discrete in time) to transmit can be represented by points on the complex plane. For example, see Fig. 1.3 right-hand side for QPSK (RHS). A pair of bits are mapped into symbols as (0, 0) $\rightarrow\{1 + \mathrm{j}\}$, (0, 1) $\rightarrow\{-1 + \mathrm{j}\}$, (1, 1) $\rightarrow\{-1-\mathrm{j}\}$, and (1, 0) $\rightarrow\{1-\mathrm{j}\}$. This bit assignment to symbol is called bit to symbol mapping. With Gray coding, adjacent symbol has one bit difference. In Fig. 1.2, this bit to symbol mapping happens in modulation processing block (B1–B in the figure). A sequence of digital modulation symbols is generated in this way.

Then from B to C digital modulation symbols are converted to continuous signal, $A_I + jA_Q$, called complex envelope, which is up converted to CW using (1.2). This process of generating RF signals is summarized in Fig. 1.4.

1.2.4 *Pulse-Shaping Filter*

In order to generate A_I from the real part of, and A_Q from the imaginary part of, a complex symbol, digital to analog convertor (DACs) and analog filters (one set for

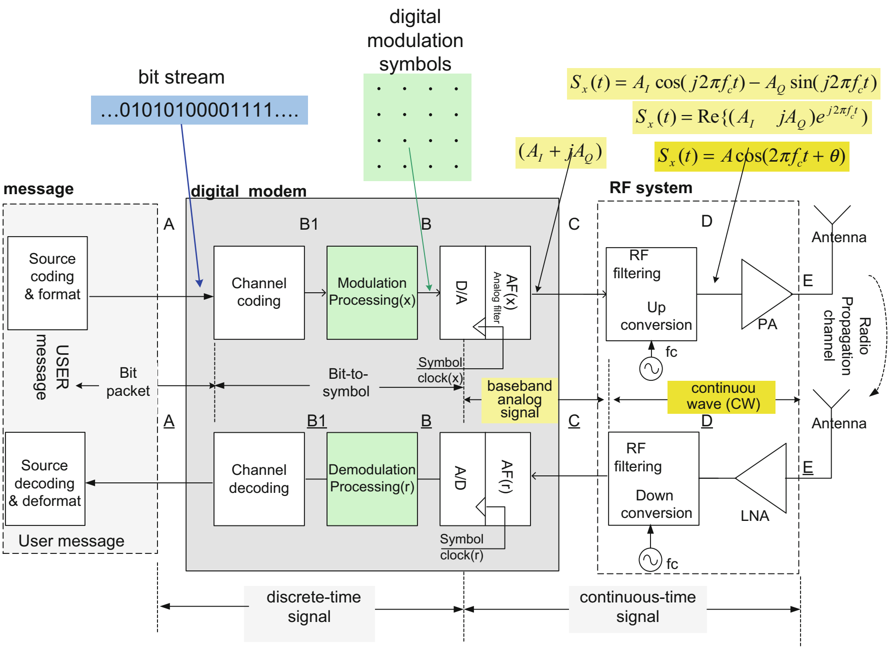


Fig. 1.4 Summary of transmit signal generation from bit stream, modulation symbols, complex envelope, and CW

the real part and the other set for imaginary part) will be used. Combined DAC and analog filter is a transmit pulse-shaping filter. A simple pulse shape is a rectangular pulse. A pulse shape is an impulse response of a pulse-shaping filter. In Fig. 1.2, only one DAC is shown for simplicity, but for complex symbols, two sets of DAC are needed, and implicit in the figure.

Thus different baseband complex envelope signals are specified by the pulse shape and constellations on the complex plane. A constellation on the complex plane is a geometric representation of a signal, i.e., digital modulation of mapping bits into discrete-time modulation symbols. The discrete-time modulation symbols are convolved in time with the impulse response of transmit filter (DAC and analog filter) to generate analog baseband signals. Another, perhaps more generic, view of this process of generating analog baseband signals is that a digital symbol is mapped to a pulse waveform with one to one correspondence. An example of BPSK is shown in Fig. 1.5. In practice, a convolution is often used, and in this book we use it exclusively otherwise stated.

1.2.5 Channel Coding

A channel coding is to add redundant bits to the information bits to be transmitted. There are infinitely many ways of how these redundant bits can be added and utilized in the receiver to correct or to detect errors. Thus the channel coding including FEC (forward error-correcting codes) is a field by itself.

A repetition code is conceptually simple and so we use it as an example. A bit to be transmitted is simply repeated. For example, $\{1\} \to \{1,1,1\}$ and $\{0\} \to \{0,0,0\}$, repeated three times. And the codewords are $\{1,1,1\}$ and $\{0,0,0\}$. All six other combinations are not codewords: $\{0,0,1\}$, $\{0,1,0\}$, $\{1,0,0\}$, $\{0,1,1\}$, $\{1,1,0\}$, and $\{1,0,1\}$. Thus at the receiver, when the received bit pattern is not from codewords, it knows that errors occurred. This repetition code can correct a single bit error by using majority rule: two or more zeros decoded as $\{0,0,0\}/\{0\}$ and two or more ones as $\{1,1,1\}/\{1\}$. This decision rule is called hard decision decoding since received BPSK symbols are decided first (hard decision), and then the majority rule is applied for bit decoding.

The hard decision decoding can be improved by soft decision decoding, where the received sample of each bit is used for decision. For example, $\{0\} \to +1$, $\{1\} \to -1$ bit to symbol mapping, as in Fig. 1.5, a received sample set is $\{+0.9, -0.2, -0.1\}$ after transmitting $\{0\}$. A hard decision will decode it incorrectly as $\{1\}$ since $\{0, 1, 1\}$ with each bit decision. With the soft decision rule, $0.9-0.2-0.1 = 0.6$, it correctly decodes it as $\{0\}$.

The soft decision rule can be obtained using a correlation metric decoding in general; the received sample $\{+0.9, -0.2, -0.1\}$ is correlated with all the codewords (two in this example), $\{0,0,0\}$, i.e.,$\{+1,+1,+1\}$, and $\{1,1,1\}$, i.e., $\{-1,-1,-1\}$, and then choose the maximum. The correlation metric with $\{-1,-1,-1\}$ will be -0.6 while with $\{+1,+1,+1\}$ it will be $+0.6$, only the sign difference. Obviously $+0.6$ > -0.6 thus it correctly decodes it as $\{0\}$.

Amazingly this correlation metric decoding works for binary linear block codes and is optimal. However, it may be quickly impractical as the size of code becomes even modest, say information bits of 20 or more. Thus it is directly usable only when the number of codewords is small. But, it may still provide conceptual frame for understanding FEC and its performance characterization. It works for AWGN channels and fading channels as well as generating branch metrics of convolution code decoding.

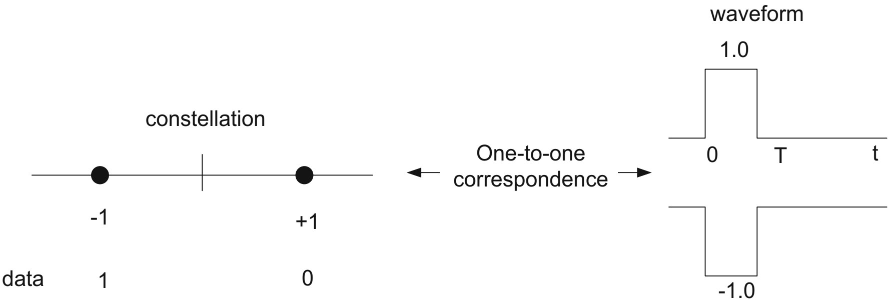


Fig. 1.5 Constellation to pulse mapping; binary phase shift keying (BPSK) to rectangular pulse. Both pulse shape and constellation are necessary

Exercise With the information bits of 20 in a code, how many codewords are there? Answer: $2^{20} = 1{,}048{,}576$ codewords. In repetition code there is only one bit of information; thus there are two codewords.

The hard decision decoding rule is obtained by applying the correlation metric decoding, left as an exercise. In this sense the difference between hard decision decoding and soft decision decoding can be understood clearly. A rule of thumb improvement of soft decision over hard decision is, in Gaussian noise channel, about 2 dB. In fading cases, it can be much larger than 2 dB.

There is no net coding gain with a repetition code. In order to see it, our argument is as follows. In order to transmit 3 bits, after coding of 1 bit, the bandwidth required will be three times. Thus in the receiver, three time more noise must be allowed. In order to have a net coding gain, a code should be more sophisticated than the repetition. First of such code is Hamming code. For example, for 4 bits of information, 3 parity bits are added to have a single error correction.

Historically, algebraic codes such as Hamming, BCH, and RS were developed first and were important for simplicity of implementation and understanding. However, here we focus on the codes which can approach the channel capacity such as Turbo, LDPC, and RA. These codes require iterative soft decoding. In wireless channels, the soft decision is important especially when FEC is used to cope with fading. Thus the channel coding is integral part of communication signal design. This will be explored in detail in Chap. 6 Channel Coding.

Abbreviations used in this section are LDPC (low-density parity-check code), RS (Reed, Solomon), BCH (Bose, Chaudhuri, Hocquenghem), and RA (repeat accumulator).

Exercise A 3 bit repetition code may be modified as $\{1\} \rightarrow \{1,1,0\}$ and $\{0\} \rightarrow \{0,0,1\}$. Is it OK? Devise decoding schemes for HD and SD. Hint: It is OK. For HD choose $\{0\ 0\ 1\}$ if a received pattern after HD is one of $\{000\}$ $\{001\}$ $\{011\}$ $\{101\}$, i.e., data '0' is received. And $\{1\ 1\ 0\}$ if a received pattern after HD is one of $\{111\}$ $\{110\}$ $\{100\}$ $\{-010\}$, i.e., data '1' is received. For SD, use the correlation decoding.

1.2.6 *Demodulation and Receiver Signal Processing*

*This section might be skimmed through quickly without losing continuity if this type of material is new since it will be covered in later chapters.

Thus far we discussed a signal generation summarized in Fig. 1.4, A–B1 (channel coding), B1–B (digital modulation), B–C (baseband complex envelope with pulse-shaping filter), and C–D (complex envelope to CW signal with RF oscillator). In channel coding, we briefly discussed channel decoding as well.

Now we will discuss the receiver signal chain from $\underline{\text{D}}$–$\underline{\text{C}}$, $\underline{\text{C}}$–$\underline{\text{B}}$, and $\underline{\text{B}}$–$\underline{\text{B}}$1 in Fig. 1.2. Essentially these are the inverse of transmission process: CW signal to complex envelope ($\underline{\text{D}}$–$\underline{\text{C}}$), analog complex envelope sampled ($\underline{\text{C}}$–$\underline{\text{B}}$), and then demodulated ($\underline{\text{B}}$–$\underline{\text{B}}$1) as shown in Fig. 1.2.

1.2.6.1 CW Signal to Complex Envelope (D–C)

We explain two ways of recovering the complex envelope of A_I and A_Q from $s_x(t)$ represented by the equations of (1.1), (1.2), and (1.3).

First we use the Eq. (1.2). We need to find the corresponding imaginary part of (1.2), denoted as $\hat{s}_x(t)$.

$$s_x(t) + j\hat{s}_x(t) = \left[A_I + jA_Q\right]e^{j2\pi f_c t} \tag{1.4}$$

The imaginary part can be obtained from the real part, $s_x(t)$, by using Hilbert transform. It is a phase shift system by 90° (or multiplying j in the frequency domain; $-j$ for positive frequency and $+j$ for negative frequency).

$$\hat{s}_x(t) = Im\left\{\left[A_I + jA_Q\right]e^{j2\pi f_c t}\right\} \tag{1.5}$$

In order to remove CW modulation, (1.4) is multiplied by $e^{-j2\pi f_c t}$, i.e., demodulated. This is shown in Fig. 1.6 (LHS). Note that the receiver should know the carrier frequency, f_c. In fact, the phase should be known as well, which may be absorbed into the complex envelope (A_I and A_Q). This carrier synchronization issue will be a major topic in later chapter.

Second we use the Eq. (1.3). We need cos($2\pi f_c t$) and sin ($2\pi f_c t$), and their phase is 90° apart. The Eq. (1.3) is multiplied by 2 cos ($2\pi f_c t$), and then remove the frequency component twice of the carrier by low-pass filtering. The result is A_I. The Eq. (1.3) is multiplied by 2 sin ($2\pi f_c t$), and then remove the frequency component twice of the carrier by low-pass filtering. The result is A_Q. In the figure the scale factor 2 is not shown for simplicity. In practice this is easy to accommodate by adjusting the gain of an oscillator. A single oscillator can generate cos () and sin () by 90° phase shift. This is shown in Fig. 1.6 (RHS). Again note that the receiver should know the carrier frequency, f_c, as well as carrier phase.

Both methods are used in practice. The second method was more common with analog implementations, but with the digital implementations, the first method is used since digital Hilbert transformer is not difficult to build numerically.

In practice, CW to complex envelope conversion (or quadrature demodulation) may happen at a convenient intermediate frequency (IF) after the down conversion (or frequency translation) from the carrier frequency.

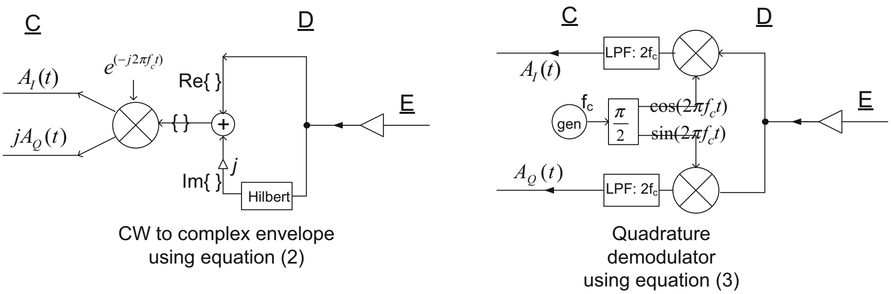


Fig. 1.6 CW signal to complex envelope; two methods are displayed using Eqs. (1.2) and (1.3), respectively

1.2.6.2 Analog Complex Envelope (A_I and A_Q) Is Sampled ($\underline{\text{C}}$–$\underline{\text{B}}$)

Here real and imaginary part of an analog complex envelope may be thought of as channels, commonly called in-phase channel and quadrature phase channels. Since the sampling process is identical, we consider only one channel (i-channel or q-channel). But it applies to both i- and q-channels.

In Fig. 1.2, assuming that radio propagation channel does not distort the signal, and that RF system, both transmission direction (up conversion and PA) and receive direction (LNA and down conversion) are perfect, C → $\underline{\text{C}}$ is like a direct connection. Thus the signal at $\underline{\text{C}}$ is the same as one at C (or nearly so). To make it concrete, we use a rectangular pulse as shown in Fig. 1.5. The only thing that a receiver will do is to sample the signal at $\underline{\text{C}}$. The use of a rectangular pulse in this way happens in practice if C to $\underline{\text{C}}$ is connected by a short wire or by a PCB trace in a circuit board.

However, in radio channels, even if all things are perfect, one still needs to consider thermal noise at the receiver front end (i.e., LNA). It is often (and accurately) modeled as noise with Gaussian distribution, called additive white Gaussian noise (AWGN). The white means that the spectrum of noise is flat in frequency domain. This channel model at C–$\underline{\text{C}}$ (toward right side in Fig. 1.2) is shown in Fig. 1.7, showing only i-channel, and the same figure is applicable to q-channel.

One needs to select a pulse-shaping filter. If the transmit pulse shape is rectangular, the receiver pulse-shaping filter must be "matched" to the transmit pulse shape. This is called a matched filter. This will maximize the signal-to-noise ratio at sampling instant. In general a matched filter pair is related as

$$g_R(t) = g_X(-t) \tag{1.6}$$

In case of a rectangular pulse shown in Fig. 1.5, the receiver pulse is identical as transmit pulse. In order to make a shaping filter causal, or realizable, one needs to introduce a delay (D), which can be given by $g_R(t) = g_X(D - t)$.

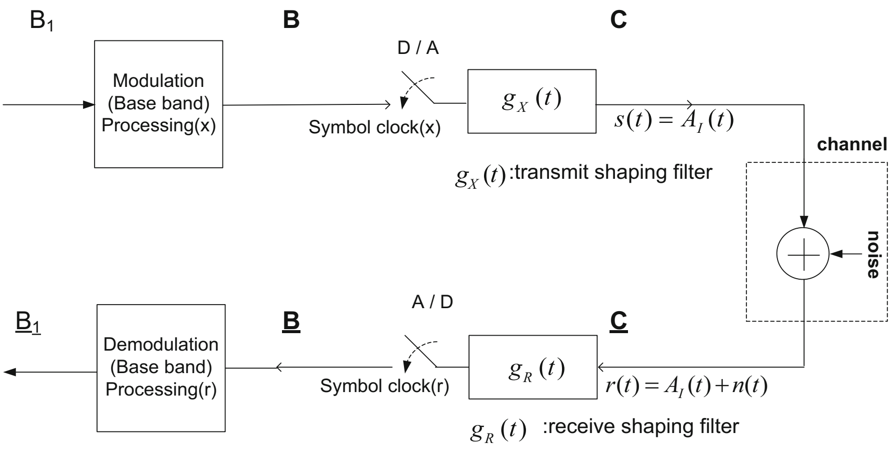


Fig. 1.7 Baseband AWGN channel model (i-channel only)