1

Introduction

Abstract

The main goal of modern wireless communications is reliable transmission over an imperfect channel with the data rate to approach the channel capacity as much as possible. A physical channel often introduces additive white Gaussian noise, interference of various natures, and probably also multipath fading. The latter two impairments are often the sources that eventually limit the performance of a wireless system. Efforts of combating interference and multipath fading constitute an important part of the history of communications. The mathematical nature of interference is the collision between multiple symbols or multiple users in a *low-dimensional* space. Today, the paradigm of orthogonality has become a basic thought for combating different types of interference, while multi-antenna technology is a powerful means to exploit the inherent capacity of multipath fading channels.

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James Clerk Maxwell's electromagnetic theory, established in 1864, uncovered the field nature of electromagnetic waves, marking a transition in our understanding of electromagnetism from phenomenology to physical theory. It is a prelude to the two far-reaching and revolutionary events in contemporary sciences: quantum physics and Einstein's theory of relativity. In engineering aspect, Maxwell's electromagnetic theory essentially becomes a physical foundation for telecommunications, stimulating the invention of the radio by Guglielmo Marconi in 1901, the invention of television broadcasting by Philo Farnsworth in 1928, and the invention of frequency modulation by Edwin Armstrong in 1933. These inventions and their practical applications, in turn, spurred the revolutionary advances in electronic devices, as exemplified by the invention of the vacuum tube in 1904 by John Fleming, transistors in 1948 by Walter Brattain, John Bardeen, and William Stockley at Bell Labs, and digital computers in 1946 by a team led by von Neumann. Further development of telecommunications required various key technologies for transmission, among which we can list the most representatives as follows:

- Nyquist's sampling theorem in 1928 by Harry Nyquist;
- Pulse-code modulation (PCM) in 1937 by Alec Reeves;
- Matched filters in 1943 by D.O. North.

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Indeed, the electromagnetic theory and the emergence of various electronic devices had prepared the physical stage for communications. However, communication is of a different nature and is aimed at transporting information over an impaired channel; it is a process always associated with uncertainty and randomness. Clearly, we need a rigorous theory to fully reveal the nature of communications before the possibility to implement it reliably. Such a theory occurred in 1948 when Claude Shannon published his celebrated paper entitled "A mathematical theory of communication." Shannon proved, for the first time, that the maximum data rate achievable by a communication system was upper-bounded by the channel capacity and that error-free communication was possible as long as the transmission rate did not exceed the Shannon limit. It is fair to say that, while Maxwell's electromagnetic theory laid the physical foundation for communications, Shannon's theory provided it with a rigorous information-theoretic framework. Although various communication experiments had been conducted well before Shannon published his seminal papers, it was Shannon who made communication a rigorous science, casting dawn light on the horizon of modern communications.

With the advances in theories and technology, cellular mobile communications gradually developed as an industry. The idea of mobile communications dated back to 1946, when the Federal Communications Commission (FCC) granted a license for the first frequency-modulation (FM)-based land-mobile telephone operating at 150 MHz. But, a successful improved mobile-telephone service (IMTS) did not become a reality until the early 1960s when semiconductors became a matured technology. The flourishing of mobile phones, however, relied on frequency reuse over different geographical areas. That was the concept of cellular systems initiated by the Bell Laboratories in late 1940s as it requested the frequency band 470–890 MHz from the FCC for cellular telephony. Unfortunately, the request was declined twice due to other spectrum arrangements. The conflict between the industry and the FCC continued for many years. Ultimately, in 1981, the FCC finalized a bandwidth of 50 MHz from 800 to 900 MHz for cellular mobile communications, giving birth to the first-generation (1G) cellular mobile systems.

Since its first deployment in the early 1980s, cellular mobile communication technology evolved, shortly in two decades, from its first generation to the second employing digital voice transmission in 1985–1988, as represented by the GSM and IS-95, to meet the ever-increasing global market. It then evolved into its third generation (3G), which employed the wide-band CDMA technology and offered multimedia services. All the 3G standards were developed and released by an international organization called the Third Generation Partnership Project (3GPP). On the way to the fourth-generation (4G) cellular technology, the 3GPP took the strategy of long-term evolution (LTE) and released its LTE-8 standard in 2008. The standard LTE-8 and the subsequently released LTE-9 represent the transition from 3G to 4G. The true 4G is defined by the standard LTE-Advanced, which was released on December 6, 2010. 4G cellular technology can support data rate up to 1 Gb/s, and allows for variable bandwidth assignments to meet the requirements of different users.

Today, cellular phones, the Internet, and information exchange are ubiquitous, bringing us into the era of a knowledge explosion. In the short span of the past five decades, wireless communication has evolved from its inception to 4G, and is now moving to 5G, leaving a variety of dazzling achievements behind. We may give a long list of various events and activities that have had far-reaching impacts upon the human society and technological evolution, but it is impossible and unnecessary. What we really need is the fundamentals as well as the thoughts and philosophy behind them. Knowledge can be easily found by a google search. Only thoughts and philosophy that dictate the development of modern wireless communication can inspire us to further create novel knowledge and technology for the future. Indeed, as stated by Will Durant, "Every science begins as philosophy and ends as arts." Searching for the trajectory of thoughts, methodology, and philosophy from the history of wireless communications is interesting and challenging, and it is the direction of this book to endeavor.

We need to comb through the aforementioned dazzling events to uncover the underlying philosophy behind them. We identify four key issues, namely Shannon's theory and channel coding, the principle of orthogonality, diversity, and the turbo principle.

1.1 Resources for wireless communications

A typical communication system consists of transmitters, receivers and physical channels. By a physical channel we mean a medium connecting the transmitter to the receiver, which can be an optical fiber, a cable, twisted lines, or open air as encountered in wireless communications. Transmitters and receivers can be configured as a point-to-point communication link, a point-to-multipoint broadcast system, or a communication network. Communication networks are not in the scope of this book. A physical channel is usually imperfect, introducing noise, distortion, and interference. The objective of communication is the reliable transmission of information-bearing messages from the transmitter to the destination.

The three basic resources available for wireless communication are frequency resource, energy resource, and spatial resource. The first is usually called *frequency bandwidth*, the second is called *the transmit power*, and the third takes the form of *random fields* created when a wireless signal propagates through a spatial channel with a multitude of scatterers in random motion relative to the transceiver. The central issue to modern wireless communications is to fully exploit these resources to implement reliable communication between transmitters and receivers to satisfy a certain optimal criterion in terms of, for instance, spectral efficiency, energy efficiency, or error performance.

1.2 Shannon's theory

A fundamental challenge to communications is to look for a rigorous theoretical answer to the question of what is the maximum data rate that can be reliably supported by a given physical channel. Shannon answered this question by establishing three theorems, from the information-theoretic point of view. In his celebrated paper published in 1948 [1], Shannon showed that when a Gaussian random signal of power P watts is transmitted over an additive white Gaussian noise (AWGN) channel of one-sided power spectral density N_0 W/Hz and frequency bandwidth B Hz, the reliable communication data rate is upper-bounded by the channel capacity

$$C = B\log_2(1+\rho) \ \text{bits/s}, \tag{1.1}$$

where $\rho = P/\sigma_n^2$ is the signal-to-noise ratio (SNR) and $\sigma_n^2 = N_0 B$ is the noise power. Channel capacity is an inherent feature of a physical channel. We use a white Gaussian signal to test it, in much the same way as a delta function is used to test the impulse response of a linear system. This theorem clarifies that the resources of system bandwidth and signal power are convertible to reliable transmission data rate which, however, has a ceiling.

Shannon further asserted in his second theorem that error-free communication at a capacity-approaching rate was possible through coding. To this end, coding should be made as random and as long as possible. Before Shannon, a plausible belief was that the transmission reliability decreased with increased data rate. Shannon laid a solid foundation for information theory, igniting the dawn of modern communications.

Next, let us show how to determine the maximum reliable data rate on an AWGN channel with a given SNR. In (1.1), note that the transmitted power P is related to the bit energy E_b, the bit rate R_b, and the bit duration T_b by $P = E_b/T_b = E_b R_b$. Error-free transmission requires $R_b \leq C$. Thus, on the capacity boundary defined by the Shannon theorem, we have $R_b = C$, so (1.1) becomes

$$C/B = \log_2\left(1 + \frac{E_b C}{N_0 B}\right), \tag{1.2}$$

or equivalently,

$$\frac{E_b}{N_0} = \frac{2^{C/B} - 1}{C/B}. \tag{1.3}$$

Clearly, on the Shannon bound, the SNR is a function only of the spectral efficiency. It uncovers the conversion rule between the transmitted power (through SNR) and the normalized data rate (through the spectral efficiency). We are interested in the extreme case when $C/B \to 0$. Using the L'Hopital's rule, we obtain the asymptotic minimum SNR as

$$E_b/N_0 \to \log_e 2 = 0.693 = -1.6 \text{ dB}. \tag{1.4}$$

This indicates that, if we accept a very low spectral efficiency using, for example, coding, we can implement reliable reception as long as $E_b/N_0 \geq -1.6\,\text{dB}$.

✍ **Example 1.1**

Consider a binary phase shift keying (BPSK) system operating in an AWGN channel, and use $P_b = 10^{-5}$ as the measure of reliable reception. Without coding, we need $\text{SNR} = 11.39\,\text{dB}$ to achieve $1\,\text{b/s/Hz}$ and $P_b = 10^{-5}$. As comparison, two rate-$\frac{1}{2}$ codes are used along with BPSK. One is a convolutional code with generators $G_1 = (11111)$ and $G_2 = (10001)$, alongside a 256×256 interleaver and decoding length $65,536$ bits. Another is a turbo code with two recursive systematic convolutional (RSC) coders. The results are summarized in Table 1.1.

Table 1.1 Gaps of practical systems from their Shannon limit

Scheme	Spectral efficiency (b/s/Hz)	SNR needed (dB)	Shannon SNR (dB)	Gap from Shannon (dB)
Modulation alone	1	11.39	0	11.39
Convolutional code	0.5	0.7	−0.82	1.52
Turbo	0.5	0.5	−0.82	1.32

1.3 Three challenges

Shannon's theorems uncovered the existence of good codes to approach the capacity of AWGN channels but did not provide any practical schemes for its implementation, leaving a rugged way for communications engineers to explore. Furthermore, Shannon only addressed the case of an AWGN channel. Its extension to a communication network is still unknown [2]. All these relevant issues constitute a challenge.

Other than AWGN, many practical communication systems suffer interference of different types. Even worse, it is often the interference, rather than the AWGN, that dominates the system performance. For example, inter-symbol interference (ISI) occurs when a sequence of symbols is transmitted through a bandlimited channel; inter-user interference (IUI) arises when multiple users share the same physical channel; and inter-antenna interference (IAI) happens when a number of parallel data streams share the same spatial multi-input multi-output (MIMO) channel. Regardless of their different appearances, they share a similar generating mechanism in which multiple symbols, multiple users, or multiple data streams compete for the use of the same resource. With this additional interference, the signal-to-interference plus noise-ratio (SINR) quickly deteriorates into a significant drop in the channel capacity, or equivalently, in the error performance, in accordance with (1.1). Thus, combating interference is another major challenge to the system designer.

For wireless communications, the third challenge arises from multipath propagation, which causes random fluctuation of the received signal, a phenomenon usually referred to as *multipath fading*. The consequence of multipath fading is the degradation in the system performance, and therefore multipath fading is usually considered a harmful effect. The traditional strategy is to mitigate it as much as possible. Then a philosophical question arises: is multipath fading an angel or a devil? Recent research work pioneered by Telator [3] and Foschini [4, 5] has changed our notion, uncovering that multipath fading is indeed an angel. There is huge capacity inherent in multipath random fields, which can be exploited by using multiple antennas.

Clearly, three issues central to wireless communications are coding, anti-interference, and the exploitation of spatial resource in random fields.

1.4 Digital modulation versus coding

Channel orthogonality is just like highway scheduling, aiming to eliminate or reduce IAI or IUI. Even with a dedicated channel, transmitted signals still suffer from the corruption of AWGN. Therefore at the source end, we still need to mark the "caravan" (i.e., the message sequence) with a special pattern so as to increase their recognition from the background noise. This is the job of channel coding.

Modern communication adopts the digital format, typically starting from digital modulation where information messages are represented in terms of discrete symbols. Each symbol is defined in a two-dimensional (2-D) Euclidean space, consistent with the fact that communication signals consist of in-phase and quadrature components. Digital modulation has a number of advantages. First, the retrieval of information messages from the received noisy data is, in essence, an estimation problem. According to statistical theory, the estimation accuracy is inversely proportional to the square-root of the available sample size. The difficulty with signal recovery in a communication system is that estimation must be done based on a single sample, implying a poor estimation accuracy even with a very large SNR. The use of discrete symbols converts the estimation problem to a decision one, in which estimation errors approach zero as the SNR tends to infinity. Second, digital modulation is a convenient way to provide the basic data rate. This data rate, obtained by digital modulation alone, shows the big gap from the Shannon's capacity bound. But it creates an easy structure to add algebraic structures (coding), usually in the Galois field, for spectral efficiency improvement. Finally, the digital format enables the exploitation of various advanced digital processing techniques to improve the system's overall performance.

Viewing the close relationship between coding and modulation, Urgerboeck asserts that "digital modulation and coding are two aspects of the same entity." Modulation provides the necessary data rate which, when used alone however, is far from the Shannon bound. The philosophy is to sacrifice part of the data rate, through adding some algebraic structure, to trade for a coding gain so that, at a lower rate than provided by modulation, the spectral efficiency approaches the Shannon bound. Stated in another way, we invest part of the symbol energy in code structures for better reliability. For example, a k-bit message is binary Hamming coded as an n-bit codeword to produce κ-bit correction capability. Suppose the message bit's energy is E_b. Then, the coded bit's energy reduces to $E_c = (k/n)E_b$, and the error performance of the coded system in AWGN with two-sided power spectral density $N_0/2$ is upper-bounded by

$$\begin{aligned} P_e &= \sum_{i=\kappa+1}^{n} \binom{n}{i} \left[Q\left(\sqrt{\frac{2(k/n)E_b}{N_0}} \right) \right]^i \left[1 - Q\left(\sqrt{\frac{2(k/n)E_b}{N_0}} \right) \right]^{n-i} \\ &= f\left(\frac{(k/n)E_b}{N_0} \right). \end{aligned} \tag{1.5}$$

The uncoded system invests all of its available energy E_b into modulation, resulting in an error performance that follows the rule of the Q-function, as shown by $P_e = Q(\sqrt{2E_b/N_0}\,)$. With coding, the system invests part of its energy, $(n-k)E_b/n$, into coding, producing a much faster dropping error probability defined above by the function $f(\cdot)$. A more powerful code can do even better than the fall-off function defined above by $f(\cdot)$.

On one hand, codes should be made as random and as long as possible, according to Shannon. Indeed, the probability of the decoding error can be made exponentially decreasing as the block size of a random-like code approaches infinity. This performance is achieved, however, at the cost of an exponential increase in decoding complexity. On the other hand, codes should have certain algebraic structures for ease of decoding. The task is therefore to seek well-structured codes with random behavior. Two classes of codes meet these requirements. They are concatenated codes and low-density parity-check (LDPC) codes. The former is constructed from two constituent encoders connected with a random interleaver, the idea originated by Dave Forney in his 1965 Ph.D. thesis. The constituent encoders are just as the usual ones, having certain algebraic structures. The random interleaver makes the synthesized code of random appearance. The LDPC codes are sparse codes with an LDPC matrix, the scheme proposed in 1960 by Robert G. Gallager in his doctoral dissertation. LDPC codes can be intuitively represented in terms of a Tanner graph, and the random behavior of the LDPC codes reflects in their random connectivity in the Tanner graph.

The use of powerful codes provides only a potential capability to approach the channel capacity, and the arrival at this goal must also rely on efficient decoding techniques. Turbo processing is one such powerful technique invented by Claude Berrou in 1993. The LDPC and Turbo codes do not eliminate codewords of small weights but make them occur with negligible probability. A turbo code consists of two constituent encoders, in series or in parallel. Its receiver correspondingly consists of two decoders forming a feedback loop with information exchange. Each decoder employs the BCJR algorithm to generate LLR soft symbol information, which is fed back to another decoder as extrinsic information to improve its detection performance. Thus, the turbo receiver can be viewed as an information-exchange learning machine.

Coding may take different forms compatible with a particular operating environment. Typically, algebraic structures can be embedded in a string as a coded sequence. It can also be embedded across different subcarriers to make even the error performance along them, as encountered in OFDM, or embedded across different transmit antennas forming a 2-D pattern, as encountered in MIMO systems.

1.5 Philosophy to combat interference

Competition for a limited frequency resource often happens in wireless communications. Interference is the consequence of competitive use of an imperfect channel, despite its occurrence in different forms and diverse applications. It appears in the form of ISI when a signal is transmitted over a bandlimited channel, in the form of IAI when a parallel data streams are transmitted over a MIMO antenna channel, and in the form of multiuser interference in multi-access environments. Though they have different appearances, these interferences have a similar generating mechanism and share the same philosophy in their avoidance.

There exist two different strategies in tackling interference, each following a distinct philosophy. The first strategy has no intent to prevent the generation of interference but, rather, tries to remedy it once it happens. An example is the use of channel equalizers to suppress ISI on a temporally dispersive channel. The second strategy aims to eliminate the source of interference before its generation, representing an active philosophy. The basic tool to implement the second strategy is the paradigm of *orthogonality*, which has formed the foundation for multiple access techniques, multicarrier theory, and adjacent-cell interference suppression. It is fair to say that the paradigm of orthogonality is one of the pillars that support the architecture of modern wireless communications.

Many functional blocks we see today in a typical wireless communication systems result from the use of these two strategies for combating interference. The examples include precoder, equalizer, spreading and despreading, OFDM and its inversion, and so on. They remain in use because of their simplicity. Their basic thoughts are further demonstrated as we go through Chapters 9–13.

1.6 Evolution of processing strategy

As described above, the conventional strategy for combating interference mainly addresses the flaws of channels that are responsible for the generation of interference. Processing is done on a block-by-block basis, isolating itself from the coding and decoding process. According to Shannon, coding is an indispensable ingredient to reliable communications. It is usually done in the Galois field, thereby possessing certain good structures of finite groups or polynomial rings, which endow a communication system with the capability for noise/interference resistance. For example, Andrew Viterbi showed how to exploit the Markovian properties of convolutional codes for their efficient decoding based on a trellis diagram. The coded structure, however, is not isolated from the overall system. If we use $\mathbf{b}$ to denote the information-bearing vector, $\mathbf{C}$ to denote the linear coding operation, and the operator $\Psi(\cdot)$ to denote the overall function of the remaining blocks such as modulation, channel matrix, spreading, and despreading, then the received signal vector is expressible in the form

$$\mathbf{y} = \Psi(\mathbf{Cb}) + \mathbf{n},$$

where $\mathbf{n}$ is the additive noise component. The task of reliable communications includes two aspects: first, given the channel matrix, design the encoder $\mathbf{C}$ and the overall system function $\Psi(\cdot)$; second, once the system is designed and upon receipt of the vector $\mathbf{y}$, retrieve the message vector $\mathbf{b}$. Directly retrieving $\mathbf{b}$ is extremely involved and is, in essence, a nonlinear integer programming problem. Faced with this intractable issue, the question is: what is a feasible strategy for a practical wireless system? Three lines of thought are

1. block-by-block isolative design and processing;
2. local joint optimization; and
3. overall system design and global optimization.

The first line of thought represents the traditional philosophy of local optimization, and has been widely adopted in practice. The result is obviously a suboptimal solution. The second reflects a current trend toward joint/global processing, rooted in the following insight. Namely, an algebraic structure, once introduced into a coded sequence, belongs not only to the coding and decoding subsystem but also to the overall system. The coded structure penetrates all the functional blocks, integrating itself with the structures in modulation, OFDM, MIMO channels, ISI channels, multiuser spreading codes, or another encoder to form an even more abundant superstructure. Exploiting such a superstructure, even partly, can significantly improve the overall system performance. Such joint processing is made possible today thanks to the invention of the turbo principle by Claude Berrou [6, 7], and to the advance in the computational power of IC chips. We will revisit these important strategies in more detail in Chapter 8.

The third philosophy, though leading to a global optimal solution, is still intractable today, due to the limited computational signal processing power. However, it represents the efforts for the future. Its implementation awaits breakthroughs in notion, methodology, and technology.

1.7 Philosophy to exploit two-dimensional random fields

As previously mentioned, random fields represent a *spatial resource* available to wireless communications. When a mobile unit moves around a complex propagation environment, random scattering from distributive

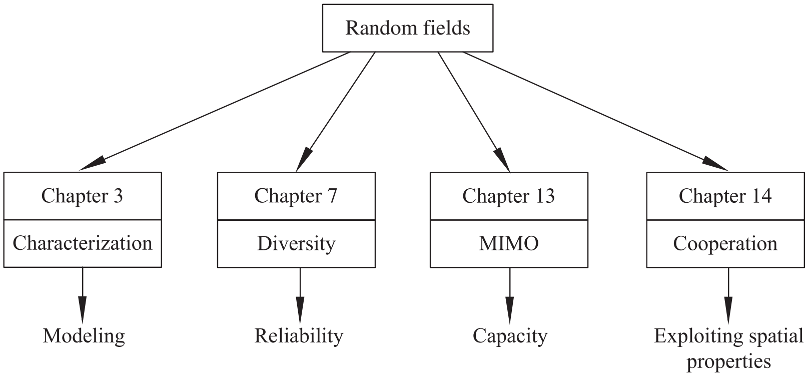

Figure 1.1 *Exploiting the spatial electromagnetic resource in random fields*

objects constitutes a random field. Random fields have many important characteristics, causing, for example, propagation loss and multipath fading of the received signals.

Multipath fading is a two-sided sword. In AWGN channels, the error probability of a coherent communications system drops exponentially with increased SNR through the relationship of a Q-function. Rayleigh fading makes the average error performance fall off much more slowly, only on the order of magnitude inversely proportional to the SNR. As such, multipath fading is traditionally treated as a harmful effect and, thus, must be suppressed as much as possible. Research in the recent two decades has changed our vision on fading, that is, random fields possess abnormal channel capacity. Exploring such capacity is increasingly important to high-data-rate wireless communications.

A powerful means to exploit fading resources is inserting multiple antennas in a 2-D random field. When placing a set of collocated antennas at a receiver, the resulting system is diversity combining, which makes the system's average error performance, in the dB scale, improve linearly with the number of antennas.

Placing an antenna array at each side of a transceiver constitutes a MIMO system, an enabling device to exploit the capacity of a random field. The average mutual information of a MIMO system is roughly proportional to the minimum number of transmit and receive antennas. A MIMO system can be configured in a multiplexing mode for high-data-rate wireless transmission or in a diversity mode for reliability enhancement. There is a tradeoff between the two. If antennas are distributively placed in a random field, they form a distributive MIMO system, which can be used, for example, for collaborative communications.

The characterization of random fields and various techniques for their exploitation are elucidated in several chapters of the present book, as outlined in Figure 1.1.

1.8 Cellular: Concept, Evolution, and 5G

The idea central to cellular systems is frequency reuse over different geographical locations, usually known as cells, so that a limited frequency bandwidth can be used to support a huge user population over a service region. A direct consequence of frequency reuse is co-channel interference caused by co-channel users at different cells, which ultimately limits the performance of a cellular system. Co-channel interference management is one of the key issues to cellular system design, and its strategy continuously evolves from 1G cellular to 5G [32–34]. The traditional technique, as widely adopted in 1G and 2G cellular, is to implement frequency reuse over well-separated cells, usually through the strategy of an N-cell reuse pattern to share

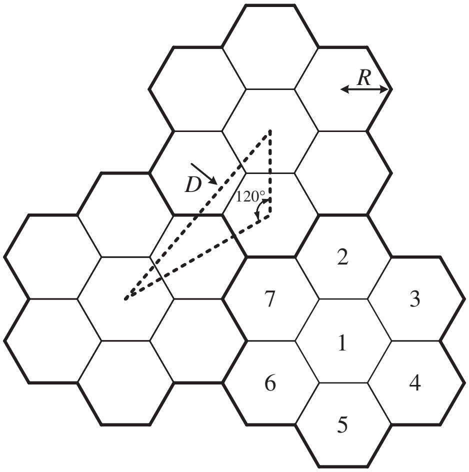

Figure 1.2 *Illustrating the seven-cell reuse pattern of hexagonal cellular*

a total of Ω frequency channels. Each cell possesses only Ω/N channels. The parameter N, known as the *cluster size*, is chosen to balance the signal to co-channel interference ratio (SIR) and the channels available in each cell. A typical N-cell reuse pattern is illustrated in Figure 1.2 where $N = 7$. A cellular system with hexagonal geometry and an N-cell reuse pattern has the following property.

$$N = i^2 + ij + j^2.$$

Let R denote the outer radius of a cellular hexagon, and let D denote the center-to-center separation between two nearest co-channel cells. The ratio $q = D/R$ is called the *reuse ratio*. For a cellular system with hexagonal geometry, the reuse ratio meets the following condition:

$$q = \frac{D}{R} = \sqrt{3N}.$$

Clearly, the idea behind the 1G and 2G systems for frequency reuse is to simply exploit the power-decay law of electromagnetic propagation with distance. This simple idea, however, fails to implement 100% frequency reuse. To further increase the user population, CDMA cellular in 2G and 3G adopts a totally different strategy for frequency reuse by separating each cell with a particular pair of short pseudo-noise (PN) sequences long scrambling code, such that interference from unintended cells is substantially blocked after decorrelation. In so doing, all the frequency channels are 100% reused over each cell. The 4G cellular employs OFDM-based access (OFDMA) schemes in which the technique based on PN sequences is no longer applicable. Thus, the suppression of adjacent-cell interference has to rely on joint frequency managements in both physical and higher layers.

Wireless communications today is on the way to its fifth generation. The 5G cellular should be a heterogeneous network, supporting cellular networks, internet of things, and others. In 5G, multiple antennas will be intensively distributed over the entire service area to fully exploit the channel capacity in a random field to support very high data rates. In the next two decades, the total global data volume of transmission is predicted to be on the order of magnitude of $E18$ with a main feature of big data and low information. The wireless capacity to be explored to meet this challenge includes efforts along three aspects. They are frequency spectrum extension, spectral efficiency improvement, and network density increase. The potential contributions of the three aspects are summarized as follows [8]:

Predicting agent	Frequency spectrum extension (times)	Spectrum efficiency improvement (times)	Network density (times)
Nokia	10	10	10
NTT	2.8	24	15
Com Mag [9]	3	5	66

Before concluding this chapter, references of relevance [16–34] are included for additional reading.

1.9 The structure of this book

Wireless communication is a still-expanding wonderland full of engineering miracles and elegant philosophy that await exploration. Some mathematical background is briefly reviewed in Chapter 2. Chapters 4–5 are dedicated to digital modulation, while Chapter 6 is devoted to channel coding. Interference is a major channel impairment that limits the error performance of wireless communications. The philosophy of combating ISI caused by temporally dispersive channels can be classified into defensive and proactive strategies, which are investigated in Chapters 9 and 10, respectively. Interference arising in multiuser channels is studied in Chapter 12. Another important issue to wireless communications is the investigation and exploitation of the spatial electromagnetic resource of a multipath channel, and these cover four chapters. Among them, Chapter 3 investigates channel modeling and characterization, Chapter 7 investigates diversity reception, Chapter 13 is devoted to MIMO wireless systems, and Chapter 14 describes cooperative wireless communications. Coding usually takes the form of an embedded algebraic structure that belongs to the entire communication system. An efficient tool towards globally exploiting such a structure is the turbo processing principle, which is studied in Chapter 11.

1.10 Repeatedly used abbreviations and math symbols

Some nomenclatures and mathematical symbols used throughout the book are tabulated below for ease of reference.

AWGN	Additive white Gaussian noise
CDF	Cumulative distribution function
CDMA	Code-division multiple access
CHF	Characteristic function
CR	Cognitive radio
CSIR	Channel state information available at receiver
CSIT	Channel state information available at transmitter
DMT	Diversity and multiplexing tradeoff
EGC	Equal gain combining
FMDA	Frequency-division multiple access
LDPC codes	Low-density parity-check codes
MASK	M-ary amplitude shift keying
MFSK	M-ary frequency shift keying
MPSK	M-ary phase shift keying

QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
MIMO	Multiple-input multiple-output
ML	Maximum likelihood
MRC	Maximal ratio combining
MSK	Minimum shift keying
OFMDA	Orthogonal frequency-division multiple access
PDF	Probability density function
PN sequences	Pseudo-noise sequences
RSC codes	Recursive systematic convolutional codes
SC	Selection combining
SNR	Signal-to-noise ratio
TMDA	Time-division multiple access
ZFE	Zero-forcing equalization
i.i.d.	Independent and identically distributed

E_s	Symbol energy
N_0	One-sided power spectral density of AWGN in W/Hz
$N_0/2$	Two-sided power spectral density of AWGN in W/Hz
$\sim$	Distributed as
$\otimes$	Kronecker product; namely, $\mathbf{A} \otimes \mathbf{B} = [a_{ij}\mathbf{B}]$
$\mathbf{A}^\dagger$	Hermitian transpose of complex matrix $\mathbf{A}$
$\mathbf{A}^T$	Transpose of a real matrix $\mathbf{A}$
$\mathbb{E}[\cdot]$	Expectation operator
$\text{var}[x]$	Variance of random variable x
$\text{Cov}[\mathbf{x}]$	Covariance of random vector $\mathbf{x}$
$\Re(z)$	The real part of z
$\Im(z)$	The imaginary part of z
$\langle x(t), y(t) \rangle$	Inner product of two functions or two vectors
$\\|x(t)\\|$	Norm of $x(t)$; namely $\\|x(t)\\| = [\langle x(t), x(t) \rangle]^{1/2}$
$Q(x)$	Q-function; namely, $Q(x) = \int_x^\infty \frac{1}{2\pi} e^{-\xi^2/2} d\xi$
$\Pr\{A\}$ or $\Pr(A)$	Probability of event A
$\mathcal{N}(\mathbf{m}, \mathbf{R})$	Gaussian distribution with mean $\mathbf{m}$ and covariance matrix $\mathbf{R}$
$\mathcal{CN}(\mathbf{m}, \mathbf{R})$	Complex Gaussian distribution with mean $\mathbf{m}$ and covariance matrix $\mathbf{R}$ [10].
$\mathcal{CW}_m(N, \mathbf{R})$	m-Dimensional complex Wishart distribution with sample size N and covariance matrix $\mathbf{R}$ [11, 12]
$\mathcal{NK}(m, \Omega)$	Nakagami distribution with fading parameter m and power Ω
$\mathcal{LN}(\mathbf{m}, \mathbf{R})$	Joint lognormal distribution with mean $\mathbf{m}$ and covariance matrix $\mathbf{R}$
$\chi(m)$	Chi distribution with m degrees of freedom. ([13], p. 421)
$\chi^2(m)$	Chi-square distribution with m degrees of freedom [14]
$\Gamma(x)$	Gamma function
$\tilde{\Gamma}(x)$	Complex gamma function
${}_1F_1(a; b; z)$	Confluent (Kummer's) hypergeometric function. ([15], p. 504)
${}_2F_1(a, b; c; z)$	Gauss hypergeometric function. ([15], p. 556)

As a convention throughout the book, an equation referred to in the text is indicated only by its number for simplicity. For example, Equation (9.16) is simply written as (9.16). Whenever necessary, a subscript will be added to a distribution symbol to indicate the dimension of the distribution, for example, $\mathcal{CN}_m(\mathbf{v}, \mathbf{R})$ and $\mathcal{N}_m(\mathbf{v}, \mathbf{R})$. The subscript m for dimension is dropped when no ambiguity is introduced.

Problems

Problem 1.1 Name five breakthroughs you consider the most significant in communications theory in past six decades, and justify your assertions.

Problem 1.2 Enumerate five technological breakthroughs you consider the most significant in communications in past six decades, and justify your assertions.

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