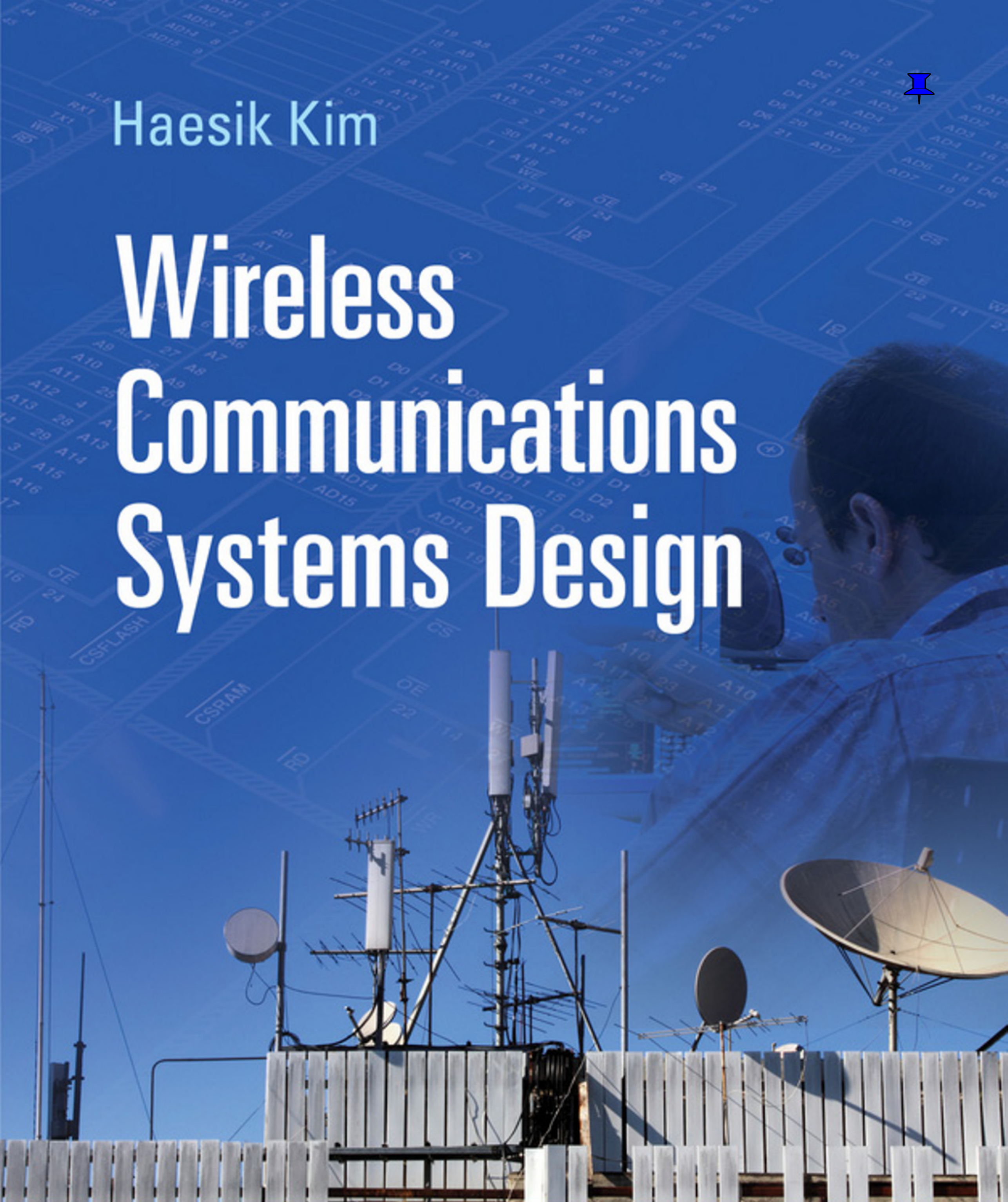
Haesik Kim

Wireless Communications Systems Design



WILEY

WIRELESS COMMUNICATIONS SYSTEMS DESIGN

WIRELESS COMMUNICATIONS SYSTEMS DESIGN

Haesik Kim
VTT Technical Research Centre of Finland

WILEY

This edition first published 2015

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN: 9781118610152

Set in 10/12pt Times by SPi Global, Pondicherry, India

1 2015

To my wife Hyeeun,
daughter Naul,
son Hanul,
and
mother Hyungsuk.

Contents

Preface

The main purpose of this book is to help senior undergraduate students, graduate students, or young engineers design wireless communications systems by themselves. The basic architecture of wireless communications has not changed much in recent decades. Especially, most of the broadband wireless communications (WiMAX, LTE, WLAN, UWB, etc.) adopt similar techniques (OFDM/OFDMA, turbo codes/LDPC, MIMO, AMC, etc.). Therefore, this book is intended to provide the basic knowledge and methodology for wireless communications systems design. This book is based on my experience in various areas (standards, research and development) of wireless communications as a researcher, developer, and consultant.

Many different interests are entangled in the wireless communications systems design. The designed wireless communication system should satisfy various interested parties such as vendors, mobile operators, regulators, and mobile users. For example, in a wireless communication system, an officer of a regulatory agency will look for efficient spectrum usage and for violation of the regulation for the frequency band. A mobile operator will look out for business opportunities, service quality, and the cost of the infrastructure. A mobile phone vendor or a network equipment vendor looks for the cost-effective design of the wireless communication system. An end user is interested in whether or not it can use a network with enough data rates and seamless connection. In order to build wireless communication systems, we consider many requirements such as spectrum, system capacity, service area, radio resource allocation, cost, and QoS. Though it is not easy to find an optimal solution, we should find a good trade-off. Wireless communication system designers require a wide range of data because one decision in one design step is closely related to another decision in the next design step. This process is very complicated and it is very difficult to find an optimal solution. Thus, they often make a decision subjectively and empirically. This book provides the reader with a big picture of wireless communications systems design in terms of a mobile device designer. It covers from fundamentals of wireless communication theory to wireless communications block implementation and system integration.

A brief design flow of wireless communications systems is as follows: Firstly, international regulator such as the International Telecommunication Union (ITU) defines the spectrum allocation for different services. The regional regulatory bodies such as European Conference of Postal and Telecommunications Administrations (CEPT) in Europe and Federal

Communications Commission (FCC) in the United States play quite an important role in decision making of ITU meetings. They are responsible for spectrum licensing and protection. After spectrum allocation for a certain service, ITU may label certain frequency allocations for a certain technology and determine the requirements for the technology. For the requirements, some standardization bodies such as the 3rd Generation Partnership Project (3GPP) and the Institute of Electrical and Electronics Engineers (IEEE) make their contributions to ITU to guarantee that their technology will meet the requirements. The actual technology is specified in the internal standardization such as 3GPP and IEEE and some standards are established at regional level. Secondly, a wireless channel is defined. Its mathematical model is developed to define the test scenario for the evaluation of the proposed technical solutions or algorithms. For example, short-range wireless channel models are different from cellular channel models. In cellular systems, we widely use empirical channel models such as ITU channel models. Thirdly, each block of the wireless communication system is selected to satisfy the requirement of the wireless communication system. This step is discussed and defined in wireless communication standards such as 3GPP and IEEE. The next steps are wireless communication system implementation. They are carried out by vendors. Fourthly, receiver algorithms under the given standard are selected and their performances are confirmed by a floating point design. Basically, standard bodies define interfaces, signaling protocol, and data structures and also give transmitter and receiver requirements. However, many freedoms of actual design and implementation are left. Fifthly, a fixed point design is performed. In this step, the architecture of a target wireless communication system is defined and the complexity can be roughly calculated. Lastly, conventional chip design processes as the remaining steps (RTL design and back-end design) are performed. This book focuses on each wireless communication algorithm design and deals with architecture design and implementation.

This book considers a broadband wireless communication system based on OFDM/OFDMA system because it is widely used in the modern wireless communication systems. The organization of the book is as follows: In Part I, the overall wireless communication theories are introduced. The basic structure of wireless communications systems is composed of a transmitter, a wireless channel, and a receiver. Their mathematical model is defined and their important theories are introduced. In addition, several physical layer techniques for mitigating wireless channel impairments are discussed. Chapter 5 "Wireless Channel Impairment Mitigation Techniques" provides a reader with fundamentals of Parts II and III. In Part II, key wireless communication blocks (FEC, MIMO, OFDM, channel estimation, equalization, and synchronization) are designed. In wireless communications systems, each block is deployed symmetrically. For example, if turbo encoder and QPSK modulator are used in a transmitter, turbo decoder and QPSK demodulator should be used in a receiver. Therefore, each block should be designed and verified pairwise. In Part III, wireless communications systems design is introduced from radio planning to system integration. Chapter 11 "Radio Planning" introduces a reader to wireless network design. In Chapter 12 "Wireless Communications System Design and Considerations," we discuss the design methodology and implementation techniques. In Chapter 13, we roughly design a 4G mobile device.

I am pleased to acknowledge the support of VTT Technical Research Centre of Finland and John Wiley & Sons and the valuable discussion of my colleagues and experts in Lancaster University, University of Leeds, Nokia, Samsung, NEC, NICT, Cadence, and so on. I am grateful for the support of my family and friends.

Haesik Kim
VTT Oulu, Finland

List of Abbreviations

2G	The 2nd Generation
3G	The 3rd Generation
3GPP	The 3rd Generation Partnership Project
ACS	Add-Compare-Select
ADC	Analogue to Digital Converter
AGC	Automatic Gain Control
AHB	Advanced High-performance Bus
AMBA	Advanced Microcontroller Bus Architecture
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone System
APB	Advanced Peripheral Bus
ARQ	Automatic Repeat Request
ASIC	Application-Specific Integrated Circuit
AVS	Adaptive Voltage Scaling
AWGN	Additive White Gaussian Noise
BCH	Bose-Chaudhuri-Hocquenghem
BCJR	Bahl-Cocke-Jelinek-Raviv
B-DMC	Binary Discrete Memoryless Channels
BEC	Binary Erasure Channel
BER	Bit Error Rate
BLAST	Bell LAboratories layered Space Time
BPF	Band Pass Filter
BPSK	Binary Phase Shift Keying
BS	Base Station
BSC	Binary Symmetric Channel
BTC	Block Turbo Code
CBIC	Cell-based IC
CC	Convolutional Code
CDF	Cumulative Distribution Function

CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications Administrations
CID	Connection Identifier
CINR	Carrier to Interference-plus-Noise Ratio
CIR	Channel Impulse Response
CMOS	Complementary Metal Oxide Semiconductor
CORDIC	COordinate Rotation DIgital Computer
CP	Cyclic Prefix
CPS	Common Part Sublayer
CPU	Central Processing Unit
CQI	Channel Quality Indicators
CQICH	Channel Quality Information Channel
CRC	Cyclic Redundancy Check
CS	Convergence Sublayer
CSI	Channel State Information
CTC	Convolutional Turbo Code
DAC	Digital to- analogue Converter
DC	Direct Current
DDCE	Decision-Directed Channel Estimation
DFG	Data Flow Graph
DFT	Discrete Fourier Transform
DMA	Direct Memory Access
DNS	Domain Name System
DPSK	Differential Phase Shift Keying
DRS	Demodulation Reference Signal
DS	Direct-Sequence
DSL	Digital Subscriber Line
DSP	Digital Signal Processor
DVB-T	Digital Video Broadcasting-Terrestrial
DVFS	Dynamic Voltage and Frequency Scaling
DwPTS	Downlink Pilot Time Slot
EDA	Electronic Design Automation
EGC	Equal Gain Combining
EIRP	Effective (or Equivalent) Isotropic Radiated Power
eNB/eNodeB	Evolved Node B
ESD	Energy Spectral Density
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FCH	Frame Control Head
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FEQ	Frequency Domain eQualization
FFT	Fast Fourier Transform
FIR	Finite Impulse Response

FPGA	Field Programmable Gate Array
FSD	Fixed Sphere Decoding
FSM	Finite State Machine
FTP	File Transfer Protocol
FUSC	Fully Used Subchannels
GF	Galois Field
GOS	Grade of Service
GP	Guard Period
GPIO	General-Purpose Input/Output
GSM	Global System for Mobile Communications
HDL	Hardware Description Language
HSPA	High Speed Packet Access
HTTP	Hypertext Transfer Protocol
HW	Hardware
IC	Integrated Circuit
ICI	Inter-Carrier Interference
ICMP	Internet Control Message Protocol
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IGMP	Internet Group Management Protocol
IP	Internet Protocol
ISI	Inter Symbol Interference
ISO	International Standard Organisation
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radio communications sector
JPEG	Joint Photographic Experts Group
LDPC	Low Density Parity Check
LFSR	Linear Feedback Shift Register
LLC	Logical Link Control
LLR	Log Likelihood Ratio
LMMSE	Linear MMSE
LNA	Low Noise Amplifier
LO	Local Oscillator
LPF	Low Pass Filter
LS	Least Square
LT	Luby Transform
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
LUT	Look-Up Table
MAC	Media Access Control
MAP	Maximum a Posteriori
MAPL	Maximum Allowable Path Loss
MBSFN	Multicast Broadcast Signal Frequency Network
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood

MMSE	Minimum Mean Squared Error
MPEG	Moving Picture Experts Group
MPSK	M-ary Phase Shift Keying
MPSoC	MultiProcessor System-on-Chip
MRC	Maximal Ratio Combining
MS	Mobile Station
MSE	Mean Squared Error
NMT	Nordic Mobile Telephone
NP	Nondeterministic Polynomial
NTT	Nippon Telegraph and Telephone
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PCI	Protocol Control Information
PDCCH	Physical Downlink Control Channel
PDF	Probability Density Function
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PED	Partial Euclidean Distance
PEP	Pairwise Error Probability
PHICH	Physical Hybrid ARQ Indicator Channel
PHY	PHYsical Layer
PLL	Phase Locked Loop
PMCH	Physical Multicast Channel
PN	Pseudo-Noise
PPP	Point-to-Point Protocol
PRACH	Physical Random Access Channel
PSD	Power Spectral Density
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSC	Partially Used Subchannels
PUSCH	Physical Uplink Shared Channel
QC	Quasi Cyclic
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R2MDC	Radix-2 Multi-path Delay Commutator
R2SDF	Radix-2 Single-path Delay Feedback
RACH	Random Access Channel
RB	Resource Block
RF	Radio Frequency
RM	Reed-Muller

rms	Root Mean Square
RS	Reed-Solomon
RSC	Recursive Systematic Convolutional
RSSI	Received Signal Strength Indication
RTG	Receive Transition Gap
RTL	Register-Transfer Level
SAP	Service Access Points
SC	Selection Combining
SD	Sphere Decoding
SDMA	Space-Division Multiple Access
SDR	Software Defined Radio
SDU	Service Data Unit
SFID	Service Flow Identifier
SIC	Successive Interference Cancellation
SINR	Signal to Interference plus Noise Ratio
SISO	Soft Input Soft Output
SMB	Server Message Block
SNR	Signal to Noise Ratio
SoC	System-on-Chip
SOVA	Soft Output Viterbi Algorithm
SPC	Single Parity Check
SRAM	Static Random Access Memory
SRS	Sounding Reference Signal
SS	Synchronization Signal
SSH	Secure Shell
SSL	Secure Sockets Layer
SSS	Secondary Synchronization Signal
STBC	Space Time Block Code
STC	Space Time Coding
STTC	Space Time Trellis Code
SVD	Singular Value Decomposition
SW	Software
TC	Turbo Code
TCM	Trellis Coded Modulation
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TEQ	Time Domain eQualization
TTG	Transmit Transition Gap
UART	Universal Asynchronous Receiver/Transmitter
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UpPTS	Uplink Pilot Time Slot
UWB	Ultra-WideBand
VHDL	VHSIC Hardware Description Language

VLSI	Very-Large-Scale Integration
W-CDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
ZC	Zadoff-Chu
ZF	Zero Forcing
ZP	Zero Padding

Part I

Wireless Communications Theory

1

Historical Sketch of Wireless Communications

The reason why humans have become the most advanced species is that they produce information, store it on paper or in electronic devices, and exchange it among them. Especially, the exchange and diffusion of information has changed people's lifestyle significantly. For example, let's assume a traveler is visiting a place. Before cellular phones were in use, the traveler had to plan his visit carefully. He should book the hotel and flight and collect the information about the location manually beforehand. To locate the hotel or attraction points, he should make use of a map. Some people find this difficult as they may be disorientated. After cellular phones have come into use, a traveler can book a hotel and flight on the website using his smart phone. Once he reaches the place, the phone can guide him to the attraction points and provide useful information such as about a nice restaurant or a nearby bargain sale shop. In addition, he can make use of his phone to check email or stock price anytime and at anyplace. This drastic change in lifestyle is due to high-speed wireless communication. In this chapter, we will trace back through successive stages of wireless communications development in technical and economical aspects.

1.1 Advancement of Wireless Communications Technologies

Smoke signals used by Indian tribes are considered to be the start of wireless communication systems. Transmitting and receiving, and sending a message from one place to another place are pre-planned by them. However, the transmission range is limited to visual distance and can be carried out only in good weather. There are similar alternatives such as communication drums, signal lamps, carrier pigeons and semaphore flags. All the above have been used for thousands of years and semaphore flags are still being used in maritime communications.

The innovative paper *On Physical Lines of Force* was published by Scottish physicist and mathematician J. C. Maxwell between 1861 and 1862 [1]. This paper mathematically describes

Wireless Communications Systems Design, First Edition. Haesik Kim.

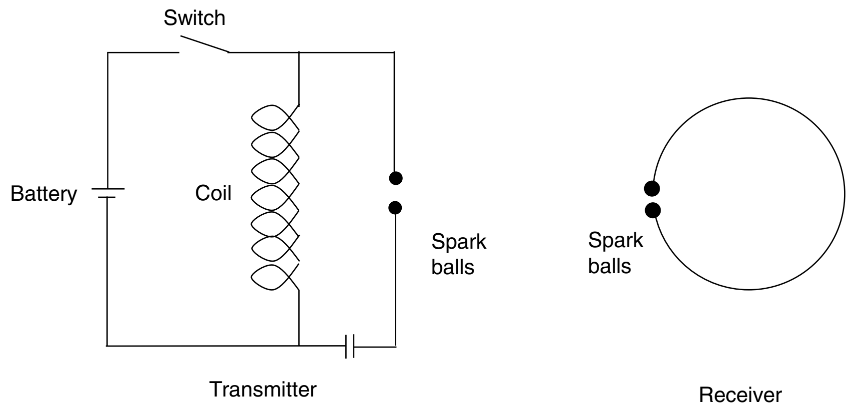


Figure 1.1 Hertz's experiment

how electromagnetic waves propagate. He predicted that the speed of electromagnetic wave is the same as that of the light waves. In 1880s, many scientists tried to prove the existence of electromagnetic waves. H. R. Hertz built an experimental apparatus to prove Maxwell's theory in 1887. The apparatus consists of simple transmitter and receiver with a small gap through which sparks could leap as shown in Figure 1.1. The transmitter can generate a spark and the receiver was placed several yards away from the transmitter. If the second spark appears in the receiver after the transmitter generates the first spark, it means the electromagnetic wave was transmitted and Maxwell's theory is correct. He published his work in the book *Electric Waves: Being Researches on the Propagation of Electric Action with Finite Velocity through Space* [2].

In the 1890s, many scientists continued Hertz's experiments. French scientist, E. Branly, invented the metal filings coherer which consists of a tube containing two electrodes. This device could detect the electromagnetic waves. Russian scientist, A. S. Popov, built a controllable electromagnetic system. On March 24, 1896, he demonstrated a radio transmission between two buildings in St. Petersburg. His paper "Apparatus for the detection and recording of electrical oscillations" [3] was published in the *Journal of the Russian Physical Chemical Society*. G. Marconi known as the father of long-distance radio transmission began his experiment in Italy contemporaneously. His experiment was nothing new but he focused on developing a practical radio system. He kept doing experiment with extending the communication distance. In 1901, he built a wireless transmission station in Cornwall, England, and successfully transmitted a radio signal to Newfoundland (it is now a part of Canada) across the Atlantic Ocean. His radio system was huge and expensive equipment with 150 m antenna, high power, and low frequency. In 1906, L. D. Forest invented a vacuum tube which made the radio system to become smaller. This radio system was used by the US government and purchased by many other countries before the Great War. After the end of the Great War, there were many efforts to find alternatives to fragile vacuum tubes. American physicist W. Shockley and chemist S. Morgan in Bell Labs established a group that worked on solid-state physics and developed a transistor. This device opened a new era of electronics. This revolution made the field of wireless communication systems to become narrower and closer to the public. A transistor radio developed in 1954 was a small portable wireless receiver and the most popular wireless communication device.

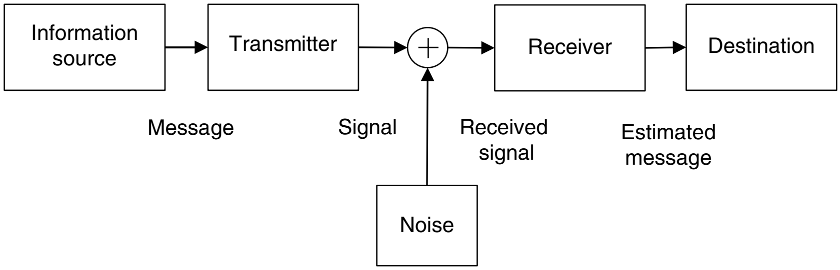


Figure 1.2 Shannon's communication architecture

Another revolution came from Bell Labs at the same time. Bell Labs scientist, C. E. Shannon, proposed information theory and published the landmark paper "A mathematical theory of communication" [4] in *Bell System Technical Journal*. Scientists at that time wanted to know how to measure information and how much information can be sent in a channel. Shannon adopted the concept of entropy to measure information, which was used in thermodynamics. Entropy of information theory means a level of the uncertainty of a random variable. He defined the channel capacity as the maximum rate of reliable communications over a noisy channel. In addition, he designed the communication architecture and is shown in Figure 1.2.

All of the current communication systems are based on Shannon's communication architecture. This architecture was innovative because a communication system designer can treat each component of the communication system separately. The time information theory was proposed became the golden age for the communication society. Many scientists developed new communication theories and implemented a new communication system. Another driving force of wireless communication systems came from the evolution of electronics. In 1958, engineer J. Kilby from Texas Instruments invented the Integrated Circuit (IC) and another engineer R. Noyce from Fairchild developed it independently a half year later. Noyce's IC chip was made of silicon while Kilby's IC chip was made of germanium. Noyce's IC chip was close to practical solutions and became an industry standard of the modern IC chips because silicon is much cheaper and easier to handle than germanium. As electronic devices evolve, wireless communication systems could be portable. The weight of the world's first mobile phone was over 30 kg. However, wireless communication systems reached greater levels due to IC technology and gradually the weights of mobile phones were significantly reduced.

A cellular system which has hexagonal cells covering a whole area without overlaps was introduced in the paper "The cellular concept" by V. H. MacDonald [5]. This paper produced another landmark concept and overcame many problems in wireless communication system such as power consumption, coverage, user capacity, spectral efficiency, and interference. The frequency reuse is one of the key concepts in the cellular network. The coverage of the cellular radio system is divided into hexagonal cells which are assigned different frequencies (F1–F4). Each cell does not have adjacent neighboring cells with same frequency as shown in Figure 1.3. Thus, cochannel interferences can be reduced, cell capacity can be increased, and cell coverage can be extended.

In each cell, it is necessary to have a multiple access scheme that enables many users to access a cellular network. Several multiple access schemes such as Frequency Division Multiple Access

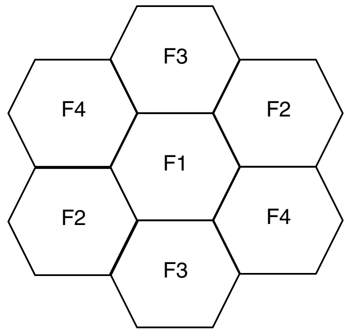


Figure 1.3 Example of frequency reuse

(FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Orthogonal Frequency Division Multiple Access (OFDMA) are widely used in cellular systems. This new concept opened another new era of wireless communications. Based on this concept, many commercial wireless communication systems were deployed. In 1979, Nippon Telegraph and Telephone (NTT) Corporation deployed the first commercial cellular network in Tokyo. Nordic Mobile Telephone (NMT) was launched in Finland, Denmark, Norway, and Sweden in 1981. Advanced Mobile Phone System (AMPS) developed by Bell Labs was deployed in Chicago, USA, on October 13, 1983, and Motorola mobile phones were used. These cellular networks were analogue-based systems. The analogue cellular phones were not popular due to high cost. After the digital Global System for Mobile Communications (GSM) called the 2nd Generation (2G) was launched in Finland in 1991, the mobile phone finally became an essential device. The huge success of GSM attracted many people to wireless communications. With wireless communication technologies advancing at a fast-growing rate, many new wireless communications were developed in not only long ranges but also short ranges. The 2G system provided voice service to users but the 3rd Generation (3G) focused on data service. The Universal Mobile Telecommunication System (UMTS) was one of the 3G systems standardized by the 3rd Generation Partnership Project (3GPP). The UMTS based on Wideband Code Division Multiple Access (W-CDMA) provided a high data rate service by including many new technologies such as turbo codes and adaptive modulation coding. High-Speed Packet Access (HSPA), Long-Term Evolution (LTE), and Long-Term Evolution-Advanced (LTE-A) kept achieving a high data rate because the volume of data service in wireless communication systems was getting bigger. In addition, the advent of smart phone brought the upheavals in wireless communication industry. The voice call is no longer the main feature of a mobile phone. Data services such as web browsing, video call, location service, internet games, and email service have become more important. Thus, the data rate has become the key metric to evaluate wireless communication systems. Table 1.1 shows us the evolution of 3GPP standards.

1.2 Wireless Communications, Lifestyles, and Economics

Let's imagine we have to send a message (100 alphabets) across the Atlantic Ocean. Before the advent of wireless communication systems, we had to deliver it by ship and it took about three weeks. The data rate was (100 alphabets × 8bits)/(3 weeks × 7 days × 24 hours × 60

Table 1.1 Evolution of 3GPP standards

	Data rate	Key features	Release date
GSM	DL: 9.6 kbps UL: 9.6 kbps	Digital, TDMA	1991
GPRS	DL: 14.4–115.2 kbps UL: 14.4–115.2 kbps	TDMA, GMSK, convolutional coding	1999
UMTS (Release 99)	DL: 384 kbps UL: 384 kbps	WCDMA, turbo coding	March 2000
UMTS (Release 4)	DL: 384 kbps UL: 384 kbps	Higher chip rate than release 99	March 2001
HSDPA (Release 5)	DL: Up to 14 Mbps UL: 384 kbps	HARQ, fast scheduling, channel quality feedback, AMC	June 2002
HSUPA (Release 6)	DL: Up to 14 Mbps UL: Up to 5 Mbps	Multimedia broadcast multicast service (MBMS), integration with WiFi	March 2005
HSPA+ (Release 7)	DL: Up to 28 Mbps UL: Up to 11.5 Mbps	MIMO, higher order modulation, latency reduction	December 2007
LTE (Release 8 and 9)	DL: 140 Mbps (10 MHz)/300 Mbps (20 MHz) UL: 25 Mbps (10 MHz)/75 Mbps (20 MHz)	OFDMA, dual carrier HSPA, SON, femtocell	December 2008 (Release 8) December 2009 (Release 9)
LTE-A (Release 10)	DL: 1 Gbps (peak download) UL: 500 Mbps (peak upload)	Carrier aggregation (CA), coordinated multiple point transmission and reception (CoMP), relay	March 2011

minutes × 60 seconds) = 0.00044 bps. After wireless telegraph was invented, the transmission time was reduced to about 2 minutes and the data rate was reduced to (100 alphabets × 8bits)/(2 minutes × 60 seconds) = 6.67 bps. Now, let us compare these with the modern wireless communication technology such as GSM. The data rate of GSM is 9.6 kbps. Thus, it was raised by a factor of about 20 million times and about 1440 times, respectively. When comparing GSM with LTE-A, the data rate of LTE-A is 1 Gbps and LTE-A was raised by a factor of about 104,000 times. In terms of the transmission rate, we made great strides in the wireless communications technologies. It took 150 years to build the current cellular system from telegraph. Especially, it took only 20 years from GSM to LTE-A. The data rate improvement of wireless communications is summarized in Figure 1.4.

How does the improvement of wireless communication technologies affect people's life? If we consider the cost of delivery, it must be a significant impact. When we sail across the Atlantic Ocean in order to deliver a short message, we should spend for labour, fuel, ship maintenance, and so on. Besides the cost of delivery, we already have experienced the big change caused by the developments in wireless communication. The invention of a transistor radio made people listen to brand new music and the latest news in real time. Especially, when a weather centre issues a storm warning, radio is the most efficient way to distribute

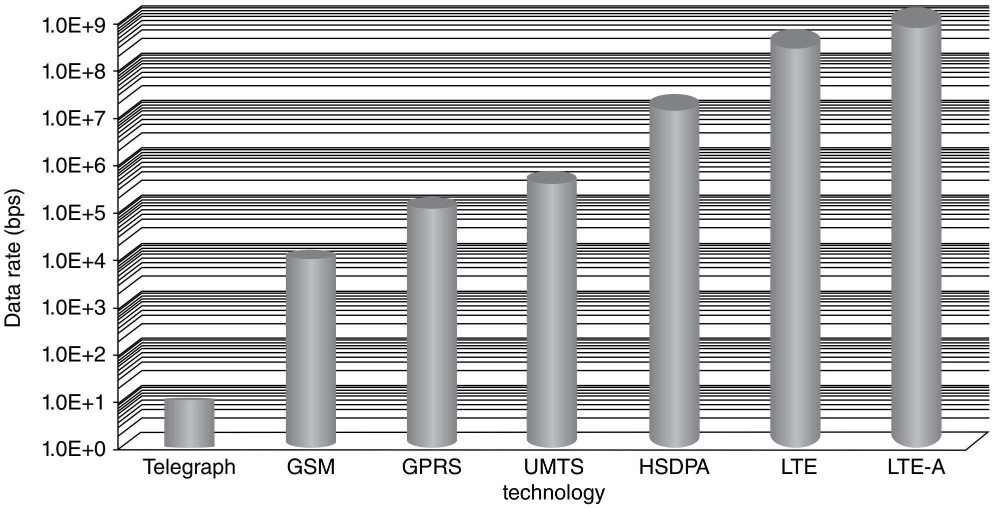


Figure 1.4 Data rates of wireless communications

information. The advent of the point-to-point communication brought another drastic change in our life. The first popular personal wireless communication device is a pager. This device can receive a short message consisting of a few digits that could be telephone numbers or some codes. After receiving the digits, people should find a landline phone to make a call. This device enables people to connect more freely. However, this device is one-way communication and does not support voice calls and relies on a landline phone. Today, the digital 2G system has become more popular and useful personal wireless communication device. The voice quality it provided is almost the same as a landline phone service. People were connected wirelessly and could work inside and outside. The 3G system made a revolution in the usage of Internet and the advent of smartphones, thereby drastically changing lifestyle. It supports broadband service and can access mobile web. Smartphone is mobile terminal supporting voice call and mobile computing. This device enables mobile users to trade stocks, browse webs, download files, exchange emails, trace locations, play video games, and so on. Regardless of time and place, people can access Internet.

Now, let's take a look at commercial usages and economics of wireless communications. When the electromagnetic waves are actively researched, many scientists didn't realize their commercial value. H. Hertz who proved the existence of electromagnetic waves was one of them. He said *It is of no use whatsoever this is just an experiment that proves Maestro Maxwell was right. We just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there* [6]. When he was questioned about their commercial importance, he said "*Nothing*." However, G. Marconi was different. He applied for a patent for his invention and was awarded famous British patent No. 7777 "Improvements in apparatus for wireless telegraphy" [7]. He established his company, Wireless Telegraph and Signal Company, in 1897, and provided telegraphic service. Until a transistor radio was invented, wireless communication systems were of limited usage because it was bulky and expensive, and therefore, it was operated among wireless stations. The invention of transistor radio made advertisers more fascinating about the device. Radio commercial is still one of the most important modes of marketing. Their interest in wireless communication systems has been sped-up since the advent of television. The wireless communication device having become a personal device, spectrum shortage problem started to occur. Therefore, the International Telecommunication Union (ITU) started coordinating the use of radio spectrums and building communication standard. The role of ITU is to allocate frequencies to some wireless communications in overall point of view, and national regulators such as the Office of Communications (Ofcom) of the United Kingdom allocates frequencies to specific uses with complying with ITU guidelines. The usage of frequencies differs across counties. For example, Britain operates frequency bands from 88 MHz to 1 GHz for TV broadcasting (40%), defence (22%), GSM (10%), and maritime communication (1%) [8]. As the number of different wireless communication systems is rapidly rising, the price of the frequency band is getting higher and there is an increased shortage of frequency band. Basically, a government sells them to telecommunication operators by spectrum auction. The Britain sold the 3G frequency bands to telecommunication operators in 2000 and the total winning bid was €38.3 billion. Thus, wireless resources have become one of the most valuable natural resources in the world.

References

[1] J. C. Maxwell, "On Physical Lines of Force," *Philosophical Magazine*, 1861.

[2] H. Hertz, *Electric Waves: Being Researches on the Propagation of Electric Action with Finite Velocity through Space*, Authorized English translation by D. E. Jones, Macmillan and Company, New York, 1893.

[3] A. S. Popov, "Apparatus for the Detection and Recording of Electrical Oscillations" (in Russian), *Zhurnal Russkag Fizicheskoi Khimii Obshchestva (Physics, Pt. I)*, vol. **28**, pp. 1–14, 1896.

[4] C. E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, vol. **27**, pp. 379–423 & 623–656, 1948.

[5] V. H. MacDonald, "The Cellular Concept," *Bell System Technical Journal*, vol. **58**, no. 1, pp.15–42, 1979.

[6] A. Norton, *Dynamic Fields and Waves: The Physical World*, Institute of Physics in Association with the Open University, Bristol, p. 38, 2000.

[7] G. Marconi, "Improvements in Apparatus for Wireless Telegraphy," British patent No. 7,777, April 26, 1900 (Application) and April 13, 1901 (Accepted).

[8] M. Cave, "*Independent Review of Radio Spectrum Management*," Consultation Paper, HM Treasury and Department of Trade and Industry, London, 2001.