The Next Generation CDMA Technologies

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Preface

This book addresses the issues on the development of next generation CDMA technologies and contains a lot of information on the subject from both the open literature and my own research activities in the last fifteen years.

When I initially agreed with the publisher to write a book on the next generation CDMA technologies in 2003, CDMA technology was just at its climax of popularity: everybody was talking about CDMA, and its applications could be found then in various wireless and wired communication systems, virtually everywhere. It seemed to me at that time that CDMA technology would stay in its leading position for a long time. However, recently CDMA technology has faced a serious challenge from other multiple access technologies, in particular from orthogonal frequency division multiple access (OFDMA) technology, and many people have turned away from CDMA to OFDMA and even to some other multiple access technologies.

There are many reasons why CDMA technology has become less popular than it was a few years ago. One of the most plausible reasons is that, as quoted from some people’s opinion, the concept of CDMA technology was developed more than ten years ago and it is suited well only to slow-speed and continuous-time signal transmissions, which are relevant to voice-centric services, as carried by most second generation mobile cellular systems, such as IS-95, etc. Now, we are talking about high-speed burst-type traffic (such as Beyond 3G (B3G) wireless applications) in wireless channels, and thus CDMA technology is obviously not suitable. For almost the same reason, the OFDMA technology came onto the stage and aims at replacing CDMA as the prime multiple access technology for B3G wireless applications. Yes, everything seems to be perfectly right.

However, behind the above explanation on why CDMA technology can not continue taking the lead we have sensed some unrevealed truth, which might also be the cause that has made CDMA technology lag behind. Let us take a look at mobile cellular communication technologies, which have gone through 2G and 3G since the first commercial CDMA cellular system was launched more than ten years ago. In Taiwan, as well as many other regions or countries, we have actually entered the 3.5G era with High Speed Downlink Packet Access (HSDPA) being put in place by several mobile service providers. On the other hand, CDMA technology has remained static (with almost the same core technologies being used in 2G and most 3G systems) and we have not seen any substantial technological advancement related to CDMA so far. Therefore, it is natural and understandable that people have turned to some other better multiple access technologies to replace CDMA, if the CDMA technology itself is not advancing as fast as expected. Why has CDMA stayed in the same place for such a long time? Is it because CDMA technology itself has fully grown up to be mature enough, such that it does not have any room for improvement? It seems that neither of the above questions can be answered with ‘yes’, as shown by the facts to be revealed in this book. Then, what is the real cause slowing down the evolution of CDMA technology? We would like to leave this question open here and will try to explain it in the introduction part of the book.

I have to confess that it has been a painstaking process to write this book in the last three years. In fact, all materials included in this book have already been there for some time. As a matter of fact, we have generated much more information on next generation CDMA technology than what can be
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accommodated in this book due to the page budget limitation. The problem is that I had to translate most of them from various technical reports and documentation written in Chinese into English page by page, which is a very time-consuming process and it took me a long time to finish it. Therefore, while very much enjoying the rich culture in a Chinese community, such as what we have here in Taiwan, sometimes I also feel very sorry to work in such an environment where Chinese has to be an instructing or working language, especially when I write my books and thus I have to dig out a lot of information from all those archival materials written in the Chinese language. Much time has to be spent due simply to the language problem, instead of the technical problems, sadly to say.

Nevertheless, I am really fascinated by the research works on the next generation CDMA technologies as I have obtained a great amount of interesting data and results. It will be shown in this book that CDMA technology will have a great opportunity to stay as a leading multiple access technology for different communication systems (wireless and wired) if we can continue working hard to make it happen. It will be shown through many examples and results given in this book that it is definitely possible to make CDMA systems interference-free (instead of being always interference-limited), which is one of the most important characteristic features for next generation CDMA technology.

This is a research oriented book with in total ten chapters, which contain a lot of state-of-the-art research results on next generation CDMA technology. However, this book can also serve as a supplementary teaching material for any communications-related courses taught for senior undergraduate students or postgraduate students, who major in electrical and computer engineering, computer science, or telecommunication systems. If it is used as a teaching material for senior undergraduate students, the best effect will be achieved if the students have already taken some prerequisites, such as ‘Signals and Systems’, ‘Digital Communications’, and ‘Spread Spectrum Communications’, etc. A good background knowledge of engineering mathematics of the students will also be desirable for them to follow the more advanced part of the materials presented in this book. In addition, this book can also be successfully used as the main teaching material for professional training courses, which may cover as long as a full semester or term.

I am very grateful to my family for their consistent support throughout this book project. In particular, I would like to thank my dear wife, Tsuiping, for her patience and compassion during the holidays and weekends I spent working on this book. I would also like to thank my daughter, Cindy, and my son, Peter, for their understanding rendered to me for not being able to play with them at weekends and holidays.

Many people have helped me during the manuscript preparation of this book. Especially, I would like to thank my students, Jin-Xian Lin, Shin-Wei Chu, Yu Hsin Lin, Chien Yao Chao, Yu Ching Yeh, Guan-Ting Chen, Tsung-Chi Tsai, Hsiang Yi Shih, Cheng Lung Wu, Yao Lin Tsao, I-Lin Sung, Yen-Han Huang, Jen-Ting Liu, Hui-Chin Kuo, Yi-Chang Wu, and Hung-Lun Chen, for helping me in various ways to collect the data and references, etc. Some of the works included in this book partly result from their theses research works.

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About the Author

Hsiao-Hwa Chen was the founding Director of the Institute of Communications Engineering, National Sun Yat-Sen University, Taiwan. He received BSc and MSc degrees with the highest honor from Zhejiang University, China, and a PhD from the University of Oulu, Finland, in 1982, 1985, and 1990, respectively, all in electrical engineering. He worked with the Academy of Finland as a Research Associate from 1991 to 1993 and the National University of Singapore as a Lecturer and then a Senior Lecturer from 1992 to 1997. He joined the Department of Electrical Engineering, National Chung Hsing University, Taiwan, as an Associate Professor in 1997 and was promoted to a full-Professor in 2000. In 2001 he joined the National Sun Yat-Sen University, Taiwan, as a founding Director of the Institute of Communications Engineering of the University.

Under his strong leadership the institute was ranked in the second position in the country in terms of SCI journal publications and National Science Council funding per faculty member in 2004. In particular, National Sun Yat-Sen University was ranked first in the world in terms of the number of SCI journal publications in wireless LANs research papers during 2004 to mid-2005, according to a Research Report (www.onr.navy.mil/sci_tech/special/354/technowatch/textmine.asp) released by the Office of Navel Research, USA.

He was a visiting Professor to the Department of Electrical Engineering, University of Kaiser-slautern, Germany, in 1999, the Institute of Applied Physics, Tsukuba University, Japan, in 2000, the Institute of Experimental Mathematics, University of Essen, Germany in 2002 (under DFG Fellowship), the Chinese University of Hong Kong in 2004, and the City University of Hong Kong in 2007, respectively.

His current research interests include wireless networking, MIMO systems, next generation CDMA technologies, information security, and Beyond 3G wireless communications.

He is a recipient of numerous Research and Teaching Awards from the National Science Council, the Ministry of Education, and other professional groups in Taiwan. He has authored or co-authored over 200 technical papers in major international journals and conferences, five books, and several book chapters in the areas of communications, including Next Generation Wireless Systems and Networks (John Wiley & Sons, Ltd, 2006, 512 pages). He has been an active volunteer for IEEE various technical activities for over 15 years. Currently, he is serving as the Chair of IEEE Communications Society Radio Communications Committee. He served or is serving as symposium chair/co-chair of many major IEEE conferences, including IEEE VTC 2003 Fall, IEEE ICC 2004, IEEE Globecom 2004, IEEE ICC 2005, IEEE Globecom 2005, IEEE ICC 2006, IEEE Globecom 2006, IEEE ICC 2007, and IEEE WCNC 2007. He served or is serving as Editorial Board Member or/and Guest Editor of IEEE Communications Letters, IEEE Communications Magazine, IEEE Wireless Communications Magazine, IEEE JSAC, IEEE Network Magazine, IEEE Transactions on Wireless Communications, and IEEE Vehicular Technology Magazine. He is serving as the Chief Editor (Asia and Pacific) for Wiley’s Wireless Communications and Mobile Computing (WCMC) Journal and Wiley’s International Journal
of Communication Systems. His original work in CDMA wireless networks, digital communications and radar systems has resulted in five US patents, two Finnish patents, three Taiwanese patents, and two Chinese patents, some of which have been licensed to industry for commercial applications. He is also an adjunct Professor of Zhejiang University, China, and Shanghai Jiao Tung University, China.
1

Introduction

The world’s first cellular network (i.e., Advanced Mobile Phone System, AMPS) was put into service in the early 1980s, and it was built based on analog radio transmission technologies. Within few years of launching the services, the cellular network began to hit a capacity ceiling as millions of new subscribers signed up for mobile voice services, demanding more and more airtime. Dropped calls and network busy signals became commonplace in many areas covered by mobile cellular networks.

To accommodate more traffic within a limited amount of radio spectrum, the industry developed a new set of digital wireless technologies called time division multiple access (TDMA). DAMPS (Digital AMPS) and GSM (Global System for Mobile) then came onto the stage. DAMPS and GSM use a time-sharing protocol to provide three to four times more capacity than the analog systems (for instance, AMPS systems). But just as DAMPS was being standardized in North America, an even better solution was found, and that is CDMA technology.

The most important milestone in the application of CDMA technologies is the time when Qualcomm successfully developed the first CDMA-based civilian mobile cellular communication standard in the 1990s, which is commonly called IS-95. In fact, the first CDMA network was commercially launched in 1995, and provided roughly ten times more capacity than analog networks, more than TDMA-based DAMPS or GSM. Since then, CDMA-based mobile cellular has become the fastest growing of all wireless technologies, with over 100 million subscribers worldwide today. In addition to supporting more traffic, CDMA-based mobile cellular systems bring many other benefits to carriers and consumers, including better voice quality, broader coverage, lower average power emission, stronger security, and smoother/easier evolutionary upgrading of the networks.

Since then, it has been successfully demonstrated in theory as well as in practice that a CDMA system based on the direct sequence (DS) spreading technique can in fact offer a higher bandwidth efficiency than its predecessors, such as the frequency division multiple access (FDMA) and TDMA techniques, in addition to many other extremely useful technical features, such as low probability of interception, privacy, good protection against multipath interference, attractive overlay operation with existing radio systems, etc., as to be discussed in Chapter 2. Today, DS-based CDMA technology has become one of the prime multiple access radio technologies for many wireless networks and mobile cellular standards, such as cdma2000, W-CDMA, and TD-SCDMA. CDMA technology reached its climax at the beginning of this century. As a direct beneficiary of the great success of CDMA technology, Qualcomm has enjoyed a huge amount of licensing incomes from the applications of the technology even from many other companies in the same industry.

Then, it has been commonly known that the use of CDMA technology has become a very expensive business exercise, and it is to a company’s best interest not to use any CDMA-related
technologies such that the company could effectively reduce the cost of the development process of any wireless communication products. Under such circumstances, the technological evolution of CDMA itself has been affected and most companies in the industry do not want to touch CDMA any more. The investment from the telecommunication industry in CDMA-related technologies has substantially shrunk, especially after the 3G mobile cellular standardization process came to an end. Instead, they would very much like to find some other competing technology which can offer equally good performance for wireless applications. Orthogonal frequency division multiplex (OFDM) or orthogonal frequency division multiple access (OFDMA) technology came to the stage partly because of this reason.

Since the first release of the IS-95A standard in 1995, \(^1\) more than ten years have passed, during which mobile cellular standards have gone through at least two generations, from 2G to 3G, both of which have been widely deployed throughout the world. As a matter of fact, 3.5G technologies have also been put into service in many countries in the world. For instance, several mobile cellular service operators in Taiwan have started to provide their subscribers with 3.5G technology based on the High-Speed Downlink Packet Access (HSDPA) technique, \(^2\) which was developed by 3GPP, to offer high-speed data access for mobile users, especially those who often need to use their notebooks or laptops on the move.

In contrast to the fact that mobile cellular has advanced to its 3.5G technology, it is very sad to see that CDMA technology itself has stayed virtually at the same place, or in its first generation based on the same core techniques, such as direct-sequence spreading, application of unitary spreading codes (which work on a one-code-per-user basis), closed-loop and open-loop power-control, etc., with a strictly interference-limited performance. The sluggishness in CDMA technological evolution has given us a lesson, which teaches us how to create the best environment possible for a technology to continue its evolution without being stopped by unnecessary barriers on its evolutionary path. Technically speaking, we all know that CDMA technology is a powerful and promising technology, which should be paid enough attention for its further advancement. Economically speaking, however, due to the problems with transfer of intellectual property rights (IPR) and associated huge licensing fees, many people have turned away from CDMA to search for some other cheaper and better replacement technologies (such as OFDMA, etc.) for next generation wireless applications. Politically speaking, technology is only technology, which always has its pros and cons, but the most important concern for a company or a country/region is that home-grown technologies/standards should never rely heavily on others’ IPRs. Under this rationale, the technological evolution of CDMA has been effectively handicapped, without being given an opportunity to evolve into its next generation.

\(^1\) Interim Standard 95 (IS-95) is the first CDMA-based digital cellular standard pioneered by Qualcomm. The brand name for IS-95 now is cdmaOne. IS-95 is also known as TIA-EIA-95. cdmaOne’s technical history is reflective of both its birth as a Qualcomm internal project, and the world of then-unproven competing digital cellular standards under which it was developed. The term IS-95 generically applies to the earlier set of protocol revisions, namely P_REV’s one through five. P_REV=1 was developed under an ANSI standards process with documentation reference J-STD-008. J-STD-008, published in 1995, was only defined for the then-new North American PCS band (Band Class 1, 1900 MHz). The term IS-95 properly refers to P_REV=1, developed under the Telecommunications Industry Association (TIA) standards process, for the North American cellular band (Band Class 0, 800 MHz) within roughly the same time frame. IS-95 offered interoperation (including handoff) with the analog cellular network. For digital operation, IS-95 and J-STD-008 have most technical details in common. The immature style and structure of both documents are highly reflective of the ‘standardizing’ of Qualcomm’s internal project.

\(^2\) HSDPA is a mobile telephony protocol, a 3.5G technology, which provides a smooth evolutionary path for UMTS-based 3G networks allowing for higher data transfer speeds. Current HSDPA deployments support 1.8 MBit/s or 3.6 MBit/s in downlink. Further steps to 7.2 MBit/s and beyond are planned for the future. As an evolution of the W-CDMA standard, HSDPA achieves the increase in the data transfer speeds by defining a new W-CDMA channel: a high-speed downlink shared channel (HS-DSCH) that operates in a different way from all existing W-CDMA channels and is used for downlink communications to the mobile.
Also, in such a circumstance (in which all people try to avoid using CDMA as much as possible in order not to be liable for license fee charges), people have turned to other replacement air-link architecture to develop their own Beyond 3G wireless systems. This has been reflected in most Beyond 3G wireless applications developed recently. One of the most important standardization efforts in this respect should be long-term evolution (LTE) and evolved UTRAN (E-UTRAN) technology proposed by 3GPP [1]. Very likely, this proposed 4G standard will use single-carrier FDMA for its uplink channel technique and OFDMA for its downlink channel air-link scheme, without using CDMA technology. The reasons for its reluctance to use CDMA technology are very complex, but one of them for sure is just to avoid possible IPR conflicts with the company which owns most CDMA IPRs.

Now, the question is, at least from the technical point of view, whether or not CDMA-based technology is inferior to OFDMA. The answer may not be obvious. It is noted that, although many wireless products on the market (mostly developed for WLANs and digital broadcasting applications) have been using OFDM or its related techniques, the OFDMA and OFDM technologies have not been fully tested and widely deployed in a relative large system/network such as mobile cellular applications. Therefore, the robustness of OFDMA and OFDM technologies for their applications in a mobile cellular communication system to cover large areas is still an unclarified concern to many people, especially its operation under severe weather conditions.

I would like to share the experience of using OFDM-based DVB-T services at my home in Taiwan. In fact, the DVB-T standard is a European standard developed for digital television broadcasting services and it can be effectively viewed as an analogy to the downlink channel transmission in a mobile cellular system, although there are still some differences between the two. Nevertheless, the DVB-T standard basically uses 4096 point IFFT/FFT as a major signal multiplex scheme to encode baseband television signals into frames before sending them into channels via amplitude modulation, which is quite similar to the technique used in downlink channels of a cellular system. Of course, the OFDMA signaling format used in downlink channels in a mobile cellular system may adopt much more signal protective schemes against channel impairment factors, such as multipath and Doppler effects.

Since I installed a set-top box for DVB-T services at my home, I have been enjoying free high-quality digital TV channels from the service providers, but only under good weather conditions. As the signal reception quality in the DVB-T is much more susceptible to weather conditions than a traditional analog TV tuner, I have to retain my old analog TV set in case no signal is available from my DVB-T set-top box, especially in the summer seasons when we usually have a lot of thunder storms with very heavy rain in Taiwan. The susceptibility to severe weather conditions of the DVB-T set-top box has much to do with the amplitude modulation (AM) used in all OFDM- or OFDMA-based air-link technologies. It is a well-known fact that AM is extremely sensitive to noise and interference because it carries information on its carrier’s amplitude. In addition, there is no processing gain available in those OFDM- or OFDMA-based schemes and thus it is impossible to gain any extra protection from spectrum expansion. On the other hand, a CDMA technology can offer numerous operational advantages which OFDM- or OFDMA-based schemes lack.

Obviously, the main objective of this book is not to compare the operational advantages of CDMA and OFDMA technologies. Instead, this book wants to convey a clear and strong signal that CDMA is not a legacy technology. It is not true that CDMA has inherent problems impossible to be overcome by itself and thus has to be replaced by some other emerging technology like OFDMA. In fact, CDMA is still a viable and strong candidate for wide application in Beyond 3G wireless systems. CDMA technology should not be considered as a technology owned by only very few companies and others should be afraid of using it due to the IPR issues. The IPRs should be used to encourage more research initiatives and free competition, instead of building up high barriers to slow down technological evolution of the technology.

The motivation for writing this book is to encourage more initiatives to push CDMA technology to its second and third generations, just like mobile cellular technologies. Since its concept was first implemented in the IS-95 standard, CDMA technology unfortunately has basically stayed at the same place. The identical core CDMA technologies have been repeatedly used in 2G and 3G mobile cellular
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systems. We would like to call it ‘the first generation CDMA technology,’ which should be innovated and evolved into next generation. What, then, is the next generation CDMA technology (which is the focus of this book)?

I have been working on CDMA technology since my PhD research carried out in the Telecommunications Laboratory, University of Oulu, Finland, in 1988,\(^3\) which was the time when CDMA technology was just being brought forward for discussions on its possible applications in commercial mobile cellular systems. The first generation CDMA technology can be characterized by the following key techniques:

- Unitary spreading codes/sequences, which work on a one-code-per-user basis and have been used by all currently existing CDMA-based mobile cellular systems, such as IS-95, cdma2000, W-CDMA, and TD-SCDMA. Those codes/sequences include Gold codes, Kasami codes, \(m\)-sequences, Walsh-Hadamard sequences, and orthogonal variable spreading factor (OVSF) codes.

- Direct sequence (DS) spreading modulation, which is used to spread the bandwidth of the original data information into wideband signal by covering a complete spreading code/sequence onto a bit duration.\(^4\)

- Precision power control technique, in which both open-loop and closed-loop power control will be used to adjust mobile transmission power level such that all signals from different mobiles will reach roughly the same level viewed at a base station receiver. Power control is a must for all current CDMA systems to operate successfully due to the near-far effect in a CDMA system based on traditional unitary codes.

- RAKE receiver, which has been used in all traditional CDMA systems to overcome multipath-induced inter-symbol interference (ISI) or simply multipath interference (MI). A RAKE receiver consists of several ‘fingers,’ each of which is made up of a correlator or code-matched filter to capture a particular multipath return. All captured multipath returns will then be coherently or non-coherently combined to form a strengthened decision variable. Therefore, RAKE receiver is one of the most important components in first generation CDMA technology.

- Multi-user detection (MUD) schemes, which are useful to detect multi-user signals through signal decorrelation processes carried out in a CDMA receiver. The commonly used MUD schemes include decorrelating detection (DD), minimum mean squared error (MMSE) detector, parallel interference cancelation (PIC) detector, and serial interference cancelation (SIC) detector.

- Multi-carrier parallel transmission, which consists of a serial-to-parallel converter, followed by a multi-carrier modulator. A multi-carrier modem can split up a wideband data signal stream into several narrowband sub-streams, each of which carries part of the original data stream and occupies a much narrower bandwidth than the original signal. In multi-carrier transmissions, each of the sub-streams is less likely to suffer frequency selective fading than the original wideband data stream. Even if a sub-stream falls into a fading null, the errors can be recovered by using some proper interleaving and error-correcting coding schemes.

With the help of all aforementioned techniques, a communication system based on the first generation CDMA technology can offer bandwidth efficiency and detection efficiency better than the one based

\(^{3}\)Therefore, it has been widely believed that the initial concept of CDMA cellular was conceived also in November 1988.

\(^{4}\)In this book, we consider only short-code spreading modulations, in which one spreading code will cover a complete bit duration. We do not consider the long-code scrambling operation, in which a very long spreading sequence is used to cover many bits.
on FDMA and TDMA technologies. However, the performance of a communication system based on the first generation CDMA technology can only offer a strictly interference-limited capacity, meaning that the capacity of a mobile cellular system based on the IS-95 standard, for example, can only support a number of users far less than the processing gain of the spreading codes used by the system.

Many problems of a communication system based on the first generation CDMA technology in fact stem from the unitary spreading codes/sequences. Those unitary codes include many famous user-separation codes, such as Gold codes, Kasami codes, m-sequences, Walsh-Hadamard codes, and OVSF codes, all of which work on a one-code-per-user basis. They were proposed a relatively long time ago by researchers working in information theory. The problem is that people working in information theory then might not have had sufficient knowledge on wireless channels, in which many impairing factors exist, such as external interferences, multipath propagation, Doppler effect, etc. All of those spreading codes used in the first generation CDMA systems, such as IS-95, cdma2000, W-CDMA, and TD-SCDMA, were proposed much earlier than the time when the CDMA cellular concept was conceived. The most serious problem with these unitary spreading codes is that their correlation properties are far from ideal. Here, what we mean in terms of correlation properties stands for the auto-correlation function of a code and the cross-correlation function between any two codes in the same code family or set. In other words, the orthogonality of all those codes is bad in general, and some of them are not orthogonal at all when they are used in asynchronous transmission channels, such as uplink channels in a mobile cellular system. Unfortunately, both 2G and 3G mobile cellular systems based on the first generation CDMA technology have used these unitary codes for CDMA purposes. In this sense, their strictly interference-limited performance is inevitable.

To develop the next generation CDMA technologies, much innovation is required in spreading code design approaches. We have been working hard for years to search for new approaches to generate innovative spreading codes/sequences. Many interesting results have been obtained and will be presented in this book. Those results include many promising spreading codes/sequences, which possess much better correlation properties than all existing unitary codes. Those proposed codes include super complementary codes, generalized pair-wise complementary codes, column-wise complementary codes, optical complementary codes, etc. Among them, the super and column-wise complementary codes are perfectly orthogonal codes in the sense that they offer zero cross-correlation functions between any two codes for any relative shift in both synchronous and asynchronous transmission channels. With this desirable property, a CDMA system can achieve multiple access interference (MAI) free operation for both uplink and downlink transmissions. In addition, the super and column-wise complementary codes can offer an ideal auto-correlation property such that their auto-correlation functions will be zero for all relative shifts except zero shift in both synchronous and asynchronous transmission modes. The ideal auto-correlation in the super and column-wise complementary codes ensures multipath interference-free operation in both uplink and downlink channels. The joint effect of ideal cross-correlation functions and ideal auto-correlation functions makes a CDMA system using them virtually interference-free, making our dream come true: to make a truly noise-limited CDMA system!

On the other hand, the generalized pair-wise complementary code is not a perfectly orthogonal spreading code. However, each user is only assigned a pair of codes for CDMA and thus the CDMA transceiver can be made much simpler, being able to be implemented using a single carrier modem with the help of two orthogonal carriers, i.e., $\sin \omega_c t$ and $\cos \omega_c t$. In addition, the correlation properties of the generalized pair-wise complementary codes are much better than those of all traditional unitary spreading codes, helping to effectively improve the overall performance of a CDMA system using generalized pair-wise complementary codes.

The optical complementary codes were developed by us for their applications in next generation optical CDMA systems. The design approach of the optical complementary codes is based on the ideal auto-correlation function (with the auto-correlation functions for any relative shifts being zero except for the zero shift) and minimized cross-correlation function ($\lambda_c = 1$). In this way, an optical
CDMA system using the resultant optical complementary codes offers a performance much better than all existing optical CDMA systems.

In particular, Chapter 6 of this book will introduce a unique joint code and system design approach, which is called the real environment adaptation linearization (REAL) approach and is used to design spreading codes/sequences by taking into account almost all real operational conditions in a wireless communication system, such as multipath propagation, random signs in continuous bit stream, bursty traffic, etc. Thus, the obtained spreading codes/sequences can inherently address almost all of those impairing factors without using other external auxiliary sub-systems to overcome those impairments. This revolutionary approach also gives us two important conclusions. First, it proves that an interference-free CDMA is possible if and only if orthogonal complementary codes are used. Second, the maximal number of users supportable in such an interference-free CDMA is equal to the flock size of the orthogonal complementary codes. This is the first time that the existence of an interference-free CDMA and its close relationship with the orthogonal complementary codes has been shown in the literature. The conclusions made from the REAL approach are significant and have laid the foundation for development of the next generation CDMA technologies.

This book will also introduce a type of very interesting orthogonal complementary code in Chapter 6, called column-wise complementary codes because they can be constructed based on their column-wise correlation properties. Based on this particular code-construction process, we are allowed to view their unique characteristics from their orthogonality formulation process, such that we can find many interesting applications for them. More specifically, it is seen from the column-wise complementary codes that some of them can establish their orthogonality based on either time-domain correlation or frequency-domain correlation or both. For example, if the orthogonality of a column-wise complementary code set is established purely on the frequency-domain correlation, we can apply the code set in those applications where time-selective fading is a serious problem, such as in vehicle-to-vehicle (V2V) communications, high-speed railway communications, etc. In this way, CDMA systems based on column-wise codes can offer robust performance even under a very large Doppler spread. On the other hand, if the orthogonality of a column-wise complementary code set is based mainly on the time-domain correlation, the codes can be used in those applications where frequency-selective fading is a big problem. Therefore, the next generation CDMA technologies can be tailor-made for different applications by carefully choosing the appropriate column-wise complementary spreading code sets.

In addition to the spreading codes/sequences, spreading modulation is another important issue which should be addressed sufficiently in development of next generation CDMA technologies. Almost all communication systems based on the first generation CDMA technology use DS spreading modulation to spread the original data signal bandwidth and implant signatures for different users. The DS spreading modulation scheme offers a relatively low spectral efficiency and rigid bandwidth spreading mechanism, such that it is very difficult to support quality-of-service (QoS) sensitive variable rate transmissions. We will introduce a parameter, called spreading efficiency (SE), in particular to measure the bandwidth efficiency of a spreading modulation scheme. The SE is measured by the number of bits of information carried by each chip. Therefore, the SE for a traditional DS spreading modulation scheme is merely \( \frac{1}{N} \) bits per chip, if the spreading code length is \( N \) and every bit is spread by a complete spreading code with \( N \) chips. Obviously, there is much room left for improvement.

In Chapter 7 of this book, an innovative spreading modulation scheme, namely offset stacking (OS) spreading modulation, will be proposed. The OS spreading modulation should work jointly with orthogonal complementary codes and it offers a very high spreading efficiency, which can be up to one bit per chip, thus being \( N \) times higher than that of the traditional DS spreading modulation scheme. In addition, OS spreading offers a unique flexibility in adjustment of the data transmission rate through the change of relative offset chips between two consecutive bits. Therefore, OS spreading is in particular suitable for high-speed multimedia signal transmissions with variable QoS requirements.

\[ ^5 \text{In this book, we will concentrate on DS spreading modulation and will not discuss other traditional spreading modulation schemes, such as frequency hopping (FH) and time hopping (TH).} \]
It is also noted that OS spreading modulation is a general spreading modulation scheme, and DS spreading is only a special case of OS spreading with its relative offset chips being equal to the code length $N$. In this sense, study of OS spreading is theoretically important as it can help us to understand much better (in a much wider scope) how to optimize the performance of a spreading modulation scheme in terms of bandwidth efficiency and transmission flexibility.

Recently, space-time (S-T) coding techniques have been widely applied to various wireless communication systems. The MIMO technology based on S-T coding schemes will certainly play an extremely important role in future wireless communication systems, because it can help to increase the data transmission rate and improve the signal detection efficiency without consumption of scarce bandwidth and time resources. Several important S-T coding schemes have been proposed in the literature, such as space-time block coding (STBC), space-time trellis coding (STTC), and space-time differential coding (STDC), all of which have been found useful applications in many wireless systems. In Chapter 8, we will introduce a new S-T coding scheme, called space-time complementary coding (STCC), which operates based on the application of orthogonal complementary codes. A CDMA communication system based on the STCC scheme can enjoy both interference-free operation and full spatial diversity gain, such that the overall performance can be substantially improved. In fact, in Chapter 8, we will introduce two different types of STCC CC-CDMA systems, one being STCC DS/CC-CDMA and the other being STCC OS/CC-CDMA using generalized pair-wise complementary codes. We will also compare their performance with traditional S-T coded CDMA systems, such as STBC CDMA.

Another important ingredient of next generation CDMA technologies will be multi-dimensional spreading techniques, which will also be discussed in Chapter 5. As a matter of fact, all CDMA schemes proposed in this book are based largely on various complementary codes. Each user in a complementary-code-based CDMA system is assigned a flock of $M$ element codes as its signature code, and all $M$ element codes should be sent via different channels (either frequencies or time slots) in parallel (via frequency division multiplex) or in serial (via time division multiplex) to a receiver. If we use $M$ sub-carriers to send $M$ element codes, two-dimensional spreading takes place at a transmitter. Now, we have two dimensions to spread original data information, one being in the time domain through $N$ different chips in each element code, and the other being in the frequency domain via $M$ different sub-carriers. The vast number of different orthogonal complementary codes generated in this book allows us to choose many different orthogonal complementary code sets with different combinations of their element code length $N$ and their flock size $M$, to form different $N \times M$ rectangular-shaped code matrices according to different applications. In some applications, we should reduce the spreading dimension in the frequency domain $M$ (to avoid frequency-selective fading), while in others we should shorten the spreading dimension in the time domain $N$ (to avoid time-selective fading), while still keeping their product $N \times M$ unchanged for a fixed processing gain. Therefore, two-dimensional spreading offers us a much greater degree of freedom in design of a wireless system based on next generation CDMA technology for a particular application. Furthermore, we can also add the third dimension (or the space domain) to the two-dimensional spreading schemes, forming three-dimensional spreading techniques, which can be another important enabling technology to implement next generation CDMA technologies.

$M$-ary CDMA, which is covered in Chapter 9, may be yet another important part of next generation CDMA technologies. Very much different from a normal DS-CDMA system, an $M$-ary CDMA system uses multiple spreading codes at each user. Data information will be directly encoded in the patterns of sent codes from a particular user. For instance, if each user is assigned $H$ codes, then there will be $3^H - 1$ patterns of sent codes and each pattern can be used to represent one of $2^m$ different symbols if $H$ and $m$ are selected as long as they satisfy the relation $3^H - 1 \geq 2^m$. Obviously, if so there must be many ways to choose $2^m$ from $3^H - 1$ patterns of sent codes such that each symbol consists of $m$ bits. This gives us a nice optimization problem to maximize the mean Euclidean distances among $2^m$ different constellation points, which are selected from a collection of $3^H - 1$ constellation points. An $M$-ary CDMA system can offer much higher bandwidth efficiency
than a traditional DS-CDMA system as it can carry $m$ bits of information in every bit duration, while a conventional DS-CDMA system can carry strictly one bit only.

In Chapter 10, we will also discuss the issues on next generation optical CDMA systems based on optical complementary codes, which were proposed in our research recently. In contrast to a wireless system, an optical communication system is very different and carries many unique properties. In particular, an optical system will send binary data through ‘0’ and ‘1’, instead of ‘−1’ and ‘+1’ as is the case for a wireless system. Therefore, this peculiarity should also be reflected in the spreading code design process for an optical CDMA system. We will propose a new spreading code, namely optical complementary code (OCC), for its applications in next generation optical CDMA (OCDMA) systems. We will also carry out performance comparison among various OCDMA systems with different optical spreading codes, to verify the superiority of the proposed optical complementary codes.

At the end of this book, a few appendices are given to explain the derivations or proofs of several important equations or relations used in the book. In addition, we have listed commonly used complete complementary codes and super complementary codes in Appendices E and F, respectively.

Before the end of the introduction of this book, I would like also to give some information about several special issues or feature topics on the related research topics in some IEEE journals or magazines, for which I was/am the Guest Editor.

I, together with two other guest editors, edited a feature topic on ‘Multiple Access Technologies for 3G Wireless Communications’ [2] in IEEE Communications Magazine, which was published in February 2005. This feature topic covers various important issues on which type of multiple access technologies should be used in Beyond 3G wireless communications.

I was the lead Guest Editor of the special issue on ‘The Next Generation CDMA Technologies’ [3] of IEEE Journal on Selected Areas in Communications, which was published in the first Quarter of 2006. This special issue is the first of its kind and the call - for - papers received a great response from the community, clearly reflected in the number of submissions received for the issue. In this issue many interesting ideas have been brought forward, and in fact we received too many papers, making the acceptance ratio for this issue very low.

Another special issue for which I was the lead Guest Editor has just been published by IEEE Vehicular Technology Magazine, entitled ‘Evolution of Air-Interface Technologies for 4G Wireless Communications’ [4].

Very recently, I have proofread the guest editorial for a special issue on ‘Evolution toward 4G Wireless Networking’ [5] for IEEE Network Magazine, which appeared in January 2007. In this issue some up-layer issues on the 4G wireless networks have been covered.

Currently, I am in the process of reviews for all submissions for a special issue on ‘Next Generation CDMA vs. OFDMA for 4G Wireless Applications’ [6], for IEEE Wireless Communications Magazine, which will be published in June 2007. This issue will be another important special issue covering the topics explicitly on two contending multiple access technologies, CDMA and OFDMA. Therefore, I believe that it will offer many informative discussions and comparisons on the two major air-link technologies.

I am deeply fascinated by the research on the next generation CDMA technologies, and a great amount of research data has been obtained, which is very encouraging. Due to the limited page budget allowed in this book, I could not put all of them inside. Hopefully, I can publish them in another book or in the revision of this one. I hope that readers will find this book informative and useful. All are warmly welcome for any comments or suggestions on this book. Please feel free to contact me via email at hshwchen@ieee.org. Thank you very much!
Basics of CDMA Communications

As its title implies, this book will be focused on the issues of the next generation CDMA technologies. Therefore, in this chapter we would like to start with discussions on code division multiple access (CDMA) technology, which was developed based on spread spectrum (SS) techniques and has become one of the most important multiple access technologies in contemporary mobile cellular communication systems, as reflected by the fact that almost all 3G standards have been engineered based on CDMA technologies.

It is to be noted that the SS techniques, as discussed in many published books [7–24], provide only a means to extend the bandwidth of transmitting signals to obtain some other extra operational advantages, which may not be possible if using only a bandwidth comparable to that spanned by the original information signals. However, by spreading the spectrum of the original data signals, we can also obtain other benefits, such as allowing more users to share the same communication medium simultaneously in time and frequency without introducing considerable interference with each other. Therefore, we should be very clear about the fact that SS techniques form the basis for the later CDMA technology, whose success was simply impossible without many pioneer research works on SS techniques [7–10].

The following are the major attractive features of CDMA technologies:

- multiple access capability
- protection against multipath interference
- privacy, interference rejection
- anti-jamming capability
- low probability of interception
- possibility to overlay with existing radio systems
- low transmit power emission, which is important to reduce health risks.

Obviously, due to its unique features CDMA has emerged as one of the most important multiple access technologies for the second and third generations (2G-3G) wireless communication systems, exemplified by its wide applications in many important mobile cellular standards, such as IS-95 [25–52], cdma2000 [53–82], UMTS-UTRA [83–88], WCDMA [89], and TD-SCDMA [90–97].
which were proposed by TIA/EIA of the USA (IS-95 and cdma2000), ETSI of Europe (UMTS-UTRA), ARIB of Japan (WCDMA), and CATT of China (TD-SCDMA), respectively. It is noted that a new type of CDMA technology has also been introduced in another China-born standard, called TD-LAS [98–104]. It is possible that CDMA will continue to be a primary air-link architecture for Beyond 3G (B3G) wireless communications, although some other multiple access technologies have also gained great attention in the community recently, such as orthogonal frequency division multiple access (OFDMA) and even some other renovated versions of TDMA.

As its name suggests, CDMA, in contrast to its predecessors (frequency division multiple access, FDMA, and time division multiple access, TDMA), is a multiple access technology that divides users based on orthogonality or quasi-orthogonality of their signature codes or simply CDMA codes. There are three primarily different types of CDMA technologies that have been extensively investigated in the past two decades: direct sequence (DS) CDMA, frequency hopping (FH) CDMA and time hopping (TH) CDMA. Each user in a DS-CDMA system should use a code to spread its information bit stream directly by multiplication or modulo-2 addition operation, which is also the simplest and most popular CDMA scheme among the three. FH-CDMA uses a multi-tone oscillator to generate multiple discrete carrier frequencies and each user in the system chooses a particular frequency-hopping pattern among those carriers that are governed by a specific sequence, which should be orthogonal or quasi-orthogonal to the others. Depending on the hopping rate relative to the data rate, FH-CDMA can also be further classified into two sub-categories: slow-hopping and fast-hopping FH-CDMA techniques. The majority of currently available FH-CDMA systems use a slow-hopping scheme. One typical example of the application of slow FH technique is the GSM system [105–129], which is a 2G digital technology based on TDMA air-link architecture. The third type of CDMA, TH-CDMA, is found to be much less widely used than the previous two due mainly to its implementation difficulties and the hardware cost associated with its transmitter, which should provide an extremely high dynamic range and very high switching speed. As mentioned in the existing literature, the ultra-wideband (UWB) technique can also be viewed as a type of TH-CDMA system.

In addition, there are also many different types of hybrid CDMA schemes, which can be formed by various combinations of DS, FH, and TH, together with multi-carrier (MC) and multi-tone (MT) techniques, as shown in Figure 2.1, where the family tree of various forms of CDMA technologies is depicted. It is stressed that this book will mainly be concerned with DS-based CDMA systems and their evolution issues. However, the conclusions drawn here may also be found equally relevant to other CDMA schemes.

One of the most important characteristics of a CDMA system is that it allows all users to send their information at the same frequency band and same time duration simultaneously but using different

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**Figure 2.1** Family tree of various CDMA technologies.
codes. Therefore, it is obvious that the orthogonality or quasi-orthogonality among the codes or sequences plays an extremely important role. In fact, we should define the two important roles of the codes or sequences used in a CDMA system: one is to act as signature codes (to accomplish code division multiple access) and the other is to spread the data bits (to spread signal bandwidth to achieve a certain processing gain). It should be emphasized that the roles of the former and the latter are not necessarily given to the same code in a particular CDMA air-link architecture. For instance in the uplink channels of IS-95A/B [25–52], the signature codes are long $m$-sequences and the spreading codes are 64-ary Walsh-Hadamard functions. On the other hand, the downlink of the IS-95A/B standard uses 64-ary Walsh-Hadamard sequences as both the spreading codes and signature codes, due to its synchronous transmissions in the downlink channels.

Then, it comes to the question of why CDMA has become the most popular air-interface technology for the current 2G and 3G, and possibly also for B3G, wireless communications. The main reasons are summarized below. First, so far CDMA is still one of the technologies (the another candidate is OFDMA, which can also be used to effectively mitigate the intersymbol-interference (ISI) problem caused by multipath propagation) that can mitigate multipath interference (MI) using a relatively cost-effective way, which otherwise would have to be tackled by using other much more complicated sub-systems in FDMA and TDMA systems. Second, on the average current CDMA technology can offer a far better capacity than its counterparts, such as FDMA and TDMA, to meet the increasing demand for mobile cellular applications in the world. Third, the overall bandwidth efficiency of a CDMA system is much higher than that with conventional multiple access technologies, thus giving an operator a much bigger incentive to adopt it due to the extremely high price of spectra. Finally, the relatively low-peak emission power level of a CDMA transceiver offers a unique capability for CDMA-based systems to overlay existing radio services currently in operation without introducing noticeable interference with each other.

However, we have to admit that current CDMA systems are still far from perfect. It is a well-known fact that a CDMA system is always considered as an interference-limited system due mainly to the existence of multiple access interference (MAI) and MI, which are the two major causes of the limitation of capacity and performance in any CDMA-based systems currently in operation, including all mature 2G and 3G architectures. The following questions may come to the mind of anyone who has learned the basic knowledge of CDMA: (1) Do CDMA systems always deserve only interference-limited performance? (2) Why does a CDMA system have to work with so many complicated auxiliary sub-systems, such as closed-loop and open-loop power control, RAKE receiver, rate-matching algorithms, uplink synchronization control, multi-user detection, etc., to just name a few as examples? (3) Can we get rid of all of these complicated sub-systems to make a simple and yet well-performing CDMA?

Many people may think it is only a dream that never comes true to make an interference-free CDMA, but I would like to offer some different views in this book by addressing the issues related to the evolution of CDMA technologies from currently available 2G and 3G systems to the next generation CDMA technologies for the future. Here I will also present some of my thoughts on engineering a new CDMA architecture with a greatly enhanced capability to mitigate MAI and MI, a critical issue associated with next generation CDMA technology.

Several assumptions should be made to facilitate the discussions given in this book. First, we should limit our discussions to DS-CDMA systems only and we will not address the issues related to other CDMA schemes, such as FH-CDMA or TH-CDMA. Second, in such a DS-CDMA system of interest to us, data signal spreading will be performed using short codes (with the chip width being $T_c$), whose length is exactly the same as the duration of one entire data bit ($T_b$), or the processing gain (PG) of such a DS-CDMA system is equal to $N = T_b = T_c$. In other words, we will not deal with the situation where long spreading codes, whose length is longer than the width of one data bit, may be used to spread the data bit stream. Third, we will consider a wireless system with full-duplex operation, which consists of mobile terminals and a base station (BS). The transmission link from mobiles to a BS is referred to as the uplink, and the transmission link in the reverse direction is
called the downlink. The block diagram of a generic DS-CDMA system considered in this chapter (as well as in this book) is shown in Figure 2.2, where we are interested in a DS-CDMA system with $K$ users, each of which is assigned one unique code for CDMA purposes, and the signal of concern is data source 1, unless explained by additional words.

### 2.1 CDMA CODES AND THEIR PROPERTIES

The properties of CDMA codes will play a critical role in a CDMA system. As mentioned earlier, the fundamental principle of CDMA communications demands the use of different codes to separate different users. Therefore, a CDMA system differs from traditional FDMA and TDMA systems in terms of its unique way of separating users or channels in a communication system or network. While FDMA and TDMA systems require ‘different frequency bands’ and ‘different time slots’ to offer good separation among different channels, a CDMA system relies on the ‘orthogonal properties’ of CDMA codes to separate different users or channels. Therefore, the properties of CDMA codes will largely govern the performance of a CDMA system. If we choose the wrong codes, the CDMA system will never operate satisfactorily as we expect.

#### 2.1.1 CDMA CODES

The discussions on CDMA codes will be carried out in much greater detail in later chapters, and we only give a brief introduction here.

Clearly, the CDMA codes, whose characteristics will determine the advantages and limitations of a CDMA system, play an essential role in CDMA system architecture. For instance, the use of orthogonal variable spreading factor (OVSF) codes in the UMTS-UTRA [83–88], WCDMA [89], and TD-SCDMA [90–97] standards requires that a dedicated rate-matching algorithm be used in the transceivers involved whenever the user data transmission rate changes to match a specific spreading factor or the system wants to admit as many users as possible in a cell. In addition, the rate change in UMTS-UTRA and WCDMA can be made only in multiples of two, meaning that continuous rate change is impossible. This requirement is a direct consequence of the OVSF code generation tree.
structure, where the codes in the upper layers bear a lower spreading factor, whereas those in the lower layers offer a higher spreading factor. Therefore, occupancy of a node in the upper layers virtually blocks all nodes in the lower layers, meaning that fewer users can be accommodated in a cell. The rate-matching algorithms indeed consume a great amount of hardware and software resources and affect the overall performance, such as increased computation load and processing latency. Therefore, we have a strong reason to question whether it is a wise choice to use OVSF codes in UMTS-UTRA, WCDMA, and TD-SCDMA systems. Therefore, the selection or design of CDMA codes is extremely important and should be exercised very carefully at a very early stage of CDMA system design; otherwise the shortcomings of the system architecture due to the use of unsuitable CDMA codes will carry on for ever with the standard, and there is no way to correct shortcomings due to the wrong codes.

2.1.2 PROPERTIES OF CDMA CODES

There are many different ways to characterize CDMA codes, but nothing can be more intuitive and effective than the auto-correlation function (ACF) and cross-correlation function (CCF), which are discussed in more detail below.

Auto-Correlation Function

The ACF is defined as the result of chip-wise convolution, correlation or matched-filtering operation between two time-shifted versions of the same code, which can be further classified into two sub-categories: periodic ACF and aperiodic ACF, depending on the same and different signs of two consecutive bits, respectively, as illustrated in the two left-hand branches in Figure 2.3. In a practical CDMA system, usually the periodic and aperiodic ACFs appear equally likely due to the fact that the binary data of ‘+1’ and ‘−1’ always appear with equal probability in binary bit streams.

The in-phase ACF or ACF peak, which is often equal to the length or PG value ($N$) of the codes, will affect detection efficiency of the desirable signal in a CDMA receiver, where a correlator or matched filter is used. On the other hand, the out-of-phase ACFs of a CDMA code will be harmless if no multipath effect is present and perfect synchronization is achieved. However, they will contribute to MAI and may seriously impair system performance under the influence of multiple propagation effect.

Cross-Correlation Function

The cross-correlation function (CCF) is defined as the result of a chip-wise convolution operation between two different spreading codes in a family of codes. For a similar reason to that mentioned earlier for the ACF, there are also two different types of CCF, i.e. periodic and aperiodic CCF. The former is mainly found in synchronous transmission channels, such as downlink channels in a wireless

![Figure 2.3 Classification of correlation functions of CDMA codes.](image-url)
system, and the latter can appear in either synchronous (if MI is present) or asynchronous channels. In contrast to out-of-phase ACF, which will contribute to MAI only under multipath channels, the CCF always contributes to MAI, no matter whether or not multipath propagation is present. On the other hand, the out-of-phase ACF will become harmful if and only if a multipath channel is present; otherwise it will never yield MAI at a correlator receiver. Obviously, MAI is one of the most serious threats to jeopardize detection efficiency of a CDMA receiver using either a correlator or RAKE and thus has to be kept below a sufficiently low level to ensure satisfactory performance.

Tables 2.1 and 2.2 list all correlation functions of a CDMA code and their merit behavior in a CDMA system.

### Spectral Properties of CDMA Codes

The ACF and CCF determine the time domain characteristics of a CDMA code family or set. The ACF governs the performance of a CDMA system against the ISI caused by multipath propagation, while the CCF determines the capability of a CDMA system to mitigate MAI.

<table>
<thead>
<tr>
<th>Table 2.1</th>
<th>Auto-correlation functions (ACFs) of CDMA codes and their merit behavior in a CDMA system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACF</td>
<td>IPEP(^1)-ACF</td>
</tr>
<tr>
<td>Cause</td>
<td>Correlator</td>
</tr>
<tr>
<td>Frequency</td>
<td>Once a bit</td>
</tr>
<tr>
<td>Behavior</td>
<td>Wanted signal</td>
</tr>
<tr>
<td>ITD(^6)</td>
<td>Enhance</td>
</tr>
</tbody>
</table>

\(^1\)IPEP: In-phase even periodic.  
\(^2\)OPEP: Out-of-phase even periodic.  
\(^3\)IPOP: In-phase odd periodic.  
\(^4\)OPOP: Out-of-phase odd periodic.  
\(^5\)MPC: Multi-path channel.  
\(^6\)ITD: Impact to detection.

<table>
<thead>
<tr>
<th>Table 2.2</th>
<th>Cross-correlation functions (CCFs) of CDMA codes and their merit behavior in a CDMA system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCF</td>
<td>IPEP(^1)-CCF</td>
</tr>
<tr>
<td>Cause</td>
<td>Syn. channel</td>
</tr>
<tr>
<td>Frequency</td>
<td>Once a bit</td>
</tr>
<tr>
<td>Behavior</td>
<td>MAI</td>
</tr>
<tr>
<td>ITD(^5)</td>
<td>Impair</td>
</tr>
</tbody>
</table>

\(^1\)IPEP: In-phase even periodic.  
\(^2\)OPEP: Out-of-phase even periodic.  
\(^3\)IPOP: In-phase odd aperiodic.  
\(^4\)OPOP: Out-of-phase odd aperiodic.  
\(^5\)ITD: Impact to detection.

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1In this book, we will use either ‘code family’ or ‘code set’ to denote a collection of codes which can be used together in the same cell or sector for user separation purposes in a CDMA system. Therefore, they have the same meaning.
Another important parameter to determine the suitability of a CDMA code family is its spectral properties in the frequency domain. Obviously, the most direct way to influence the spectral occupancy of CDMA signals is the chip width of a CDMA code, or $T_c$. The bandwidth occupancy of a CDMA signal will roughly equal the reciprocal of the chip width or $1/T_c$. As a matter of fact, the chip width of a CDMA system is not determined by the code length only. Instead, it should be determined by taking into account both peak data transmission rate $R = 1/T$ and the length of spreading codes $N$, assuming that each data bit should be spread by a complete code, such that the short code assumption will be applied here. Therefore, the bandwidth occupancy of a CDMA signal will be determined by $1/T_c = N/T$, where $N$ is often called the processing gain of the CDMA system of interest.

It is noted that all the above discussions on the spectral properties of CDMA codes are based on the assumption that all chips use square waveform. Usually, this assumption does not hold well in most CDMA systems, which always use some kind of pulse shaping waveforms, such as raised-cosine waveform and so on, to shape the chip waveform to make it more spectral efficient. In fact, pulse shaping techniques have been used in all different kinds of digital communication systems, not only spread spectrum systems, to enhance their bandwidth efficiency. It is noted that pulse shaping techniques are very effective to improve the bandwidth efficiency by only using more spectral efficient pulses to shape the waveform of the chips. The improvement in the bandwidth efficiency virtually does not sacrifice any other features of the system, and thus they have found extremely wide applications in all communication systems.

We have been working in the research on spectral efficient pulse-shaping waveforms design for many years and some interesting works have been published, as shown in [130]. Pulse waveform shaping is a traditional research subject, but there is a lot of scope for further exploration. The results from work in this area can directly help to improve the overall system bandwidth-efficiency without compromising any other system requirements of a CDMA system. Therefore, there is a huge benefit we can exploit if more bandwidth-efficient chip waveforms can be used in a CDMA system. We have also listed several other publications in this area for more information at the end of this book [131–140].

**Complexity of CDMA Code Generation**

Another property for a CDMA code family is its generation complexity with the help of some logic circuitry.

In fact, the generation complexity for a CDMA code family has twofold meanings. First, the complexity can be defined in terms of the computational complexity of the code design process to search for suitable codes. In this sense, the complexity level can vary from code to code, depending very much on their performance requirements, such as their ACF and CCF requirements and their processing gains, etc.

For instance, an $m$-sequence can be easily generated by using a shiftregister with the help of a simple feedback logic according to a particular primitive polynomial. Therefore, the $m$-sequence could be considered as a CDMA code set that can be generated with the least hardware complexity.

As the concept of primitive polynomials can be very useful to understand some issues related to CDMA code generation, we need to explain it a bit more here. A primitive polynomial is defined in modern algebra as a polynomial that generates all elements of an extension field from a base field. Primitive polynomials are also called ‘irreducible polynomials’. For any prime or prime power $q$ and any positive integer $n$, there exists a primitive polynomial of degree $n$ over Galois field $GF(q)$. There are

$$a_q(n) = \frac{\phi(q^n - 1)}{n}$$

(2.1)

primitive polynomials over $GF(n)$, where $\phi(n)$ is the totient function.²

²The totient function $\phi(n)$, also called Euler’s totient function, is defined as the number of positive integers less than $n$ that are relatively prime to (or, do not contain any factor in common with) $n$, where 1 is counted as being relatively prime to all numbers.
A polynomial of degree \( n \) over the finite field GF(2) (i.e. with coefficients either 0 or 1) is primitive if it has polynomial order \( 2^n - 1 \). For example, the polynomial \( x^2 + x + 1 \) has order 3 since

\[
\frac{x + 1}{x^2 + x + 1} = \frac{x + 1}{x^2 + x + 1} \pmod{2} \tag{2.2}
\]

\[
\frac{x^2 + 1}{x^2 + x + 1} = 1 + \frac{x + 1}{x^2 + x + 1} \pmod{2} \tag{2.3}
\]

\[
\frac{x^3 + 1}{x^2 + x + 1} = x + 1 \pmod{2} \tag{2.4}
\]

Plugging \( q = 2 \) into Equation (2.1), we have the numbers of primitive polynomials over GF(2) calculated as

\[
a_2(n) = \frac{\phi(q^2 - 1)}{n} \tag{2.5}
\]

Table 2.3 gives the primitive polynomials (mod 2) of orders 1 through 5.

For more readings on primitive polynomials, readers may find references at the end of this book [141–149].

On the other hand, we may need some more complex methods to generate the CDMA codes we want. Taking orthogonal complementary code as an example, we will show in the later chapters of this book that the generation of orthogonal complementary codes involves a much more complex process than what we have discussed earlier on the generation of \( m \)-sequences. Some special approach is needed to find orthogonal complementary codes, which can offer truly orthogonal properties unavailable in all other unitary CDMA code sets.\(^3\)

On the other hand, although the generation process complexity of CDMA codes is the problem we need to consider, we should not overestimate its importance in deciding which CDMA codes should be used in a CDMA system, in particular under the context of implementation of next generation CDMA technologies, which is the main topic of this book. It is noted that in most communication systems spreading codes or sequences can be generated in an offline way and they will be saved in a look-up table formed by a random access memory (RAM) chip, which can be called up whenever needed. Therefore, the spreading codes do not need to be generated on a real-time basis for most CDMA application scenarios. In this sense, the orthogonal properties of the codes become much more important than their generation complexity.

<table>
<thead>
<tr>
<th>( n )</th>
<th>Primitive polynomials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 + x</td>
</tr>
<tr>
<td>2</td>
<td>1 + x + x^2</td>
</tr>
<tr>
<td>3</td>
<td>1 + x + x^3, 1 + x^2 + x^3</td>
</tr>
<tr>
<td>4</td>
<td>1 + x + x^4, 1 + x^3 + x^4</td>
</tr>
<tr>
<td></td>
<td>1 + x^2 + x^3, 1 + x + x^2 + x^3 + x^5</td>
</tr>
<tr>
<td>5</td>
<td>1 + x^3 + x^5, 1 + x + x^3 + x^4 + x^5</td>
</tr>
<tr>
<td></td>
<td>1 + x^2 + x^3 + x^4 + x^5, 1 + x + x^2 + x^4 + x^5</td>
</tr>
</tbody>
</table>

\(^3\)A unitary CDMA code set is defined as one which works on a one-code-per-user basis in a CDMA system. Its counterpart is a complementary code set, which works on a one-flock-per-user basis.