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 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 documentations 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 langauge. 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 like also 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 Kaiserslautern, 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.

Contents

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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

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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.

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[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 an 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 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

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[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