Illuminating the Local Area:
Towards Adaptive, Efficient, Practical
Optical Access Networks

by Eddie Kai Ho Ng

A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science

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Master of Applied Science, November 2000
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Abstract

Optical code division multiple-access offers high-speed asynchronous low-latency access networking through distributed intelligence. Systems proposed to date, however, suffer from low efficiency, limited user population, lack of flexibility, and impractical implementation.

This work explores and devises an efficient, dynamic, adaptive, and practical means of local-area optical networking. It focuses on multi-wavelength local area networks connected in a star topology. Synchronization among users is not required.

A factor of three improvements to the largest known allowable user population – the code cardinality – is reported. The theory of optimum threshold detection (OTD) for the proposed multi-wavelength system is rigorously derived for the first time. A factor of four improvements in spectral efficiency is reported with the use of OTD in conjunction with forward error correction.

A real-time traffic adaptive scheme is proposed based on the theory of OTD complemented by code set switching. OTD is achievable using a low-cost hardware addition to the conventional receiver. Code set switching is facilitated by electronic memory look-ups.

A new problem rooted in chromatic dispersion is identified: temporal skewing. An intuitive explanation and quantitative analysis introducing the concept of signal-to-interference ratio are presented to explain the influence of this effect on system performance. Two novel dispersion-combating schemes are presented: skewed optimum threshold detection and code pattern pre-skewing.

The results presented in this work pave the way to adaptive, efficient, and practical use of light in the local area network.
Acknowledgement

The success of this work relies on the gracious assistance and tremendous support from many intelligent, amicable, and energetic individuals. I would like to take this opportunity to express my gratitude to those people who were influential to this work.

I would like to thank Professor Sargent for his attentive guidance throughout the course of my thesis. Not only have his innovative and inspiring insights formed some of the most important pillars of this work, his diligent attitude towards scientific research has also inspired personal growth.

I would like to thank Professor Kschischang for the numerous fruitful discussions which enhanced the technical integrity of this work.

I would also like to thank Guy Weichenberg for offering to help run simulations near the end of my thesis when things were most hectic. Guy has also demonstrated superior productivity uncommonly seen in undergraduate students.

I would also like to thank all my friends who offered personal advice and provided occasional escape from my thesis when I needed. I apologize for not putting a long list of names here. I’m trying to keep my thesis under 100 pages.

Special thanks go to Sandy Ng for her unconditional and unlimited support and assistance throughout the course of my graduate study. Her insights have influenced me positively across many levels.

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# Table of Contents

1. High-speed Local Area Networks: A New Approach ........................................... 1

   1.1. Evolution in Local Area Networks ................................................................. 1
       1.1.1. The Past .................................................................................................... 1
       1.1.2. The Present ............................................................................................. 2
       1.1.3. The Future ............................................................................................... 3
       1.1.4. Optical Code Division Multiple-Access: Enabling Future LANs .............. 4

   1.2. Objective and Approach of this Thesis ......................................................... 4

   1.3. Overview ......................................................................................................... 5

2. Optical Code Division Multiple-Access ............................................................... 7

   2.1. A brief History of CDMA ................................................................................ 7

   2.2. Taxonomy of O-CDMA ................................................................................ 8
       2.2.1. Time-Spread Coding ................................................................................. 8
       2.2.2. Spectral Encoding .................................................................................... 9
       2.2.3. Hybrid Coding ......................................................................................... 10

   2.3. New Territory Requiring Exploration ............................................................. 11

   2.4. Original Contributions ................................................................................... 12

3. Theory ................................................................................................................. 14

   3.1. System Model ................................................................................................ 14

   3.2. Multiple-Pulses-per-Row (MPR) Codes ......................................................... 15

   3.3. Basic Operation ............................................................................................. 16

   3.4. Mathematical Model ..................................................................................... 17

   3.5. Summary ....................................................................................................... 18

4. MW-O-CDMA Implementation: Options and Limitations .................................. 20

   4.1. Motivation ...................................................................................................... 20

   4.2. Background and Context .............................................................................. 20
       4.2.1. Transmitter and Receiver: Basic Building Blocks .................................... 21

       4.2.2. Transmitters and Receivers: Principles of Operation ............................ 22

       Fibre Delay Lines (FDLs) ............................................................... 22

       Fibre Bragg Gratings (FGBs) ......................................................... 24

       Optoelectronics ..................................................................................... 26

       4.2.3. Assessment of Transmitter and Receiver Capabilities ............................ 27

       Fibre Delay Lines (FDLs) ............................................................... 28

       Fibre Bragg Gratings (FGBs) ......................................................... 29

       Optoelectronics ..................................................................................... 30

       Summary ................................................................................................. 31
4.3. CONCLUSIONS ........................................................................................................... 32

5. Enabling Efficient, Dynamic Networks using MW-O-CDMA .................................. 34
   5.1. INTRODUCTION ........................................................................................................... 34
   5.2. THEORETICAL FOUNDATIONS ................................................................................ 35
       5.2.1. Optimum Threshold Detection ........................................................................... 35
       5.2.2. Simplified Code Design Methodology ............................................................... 38
   5.3. PERFORMANCE ENHANCEMENT I: NETWORK CAPACITY AND EFFICIENCY ........ 41
       5.3.1. Cardinality ......................................................................................................... 41
       5.3.2. Spectral Efficiency ............................................................................................. 44
       Optimum Threshold Detection ..................................................................................... 45
       Shannon Capacity and Forward Error Correction ....................................................... 46
   5.4. PERFORMANCE ENHANCEMENT II: REAL-TIME SELF-OPTIMIZING TRAFFIC
       ADAPTATION .............................................................................................................. 49
       5.4.1. Small-Scale Adaptation ...................................................................................... 50
       5.4.2. Large-Scale Adaptation ..................................................................................... 51
       5.4.3. Combining the Small- and Large-scale Adaptations ........................................... 53
   5.5. SUMMARY .................................................................................................................. 54

6. Temporal Skewing: Chromatic Dispersion in MW-O-CDMA Systems ............... 55
   6.1. INTRODUCTION ......................................................................................................... 55
   6.2. IMPACT OF DISPERSION ON MW-O-CDMA SYSTEMS ....................................... 56
       6.2.1. Fundamentals ..................................................................................................... 56
       6.2.2. Dispersion Resistance: Characteristics of Systems and Codes ......................... 58
   6.3. COMBATING THE EFFECTS OF DISPERSION ........................................................ 61
       6.3.1. Optimum Threshold Detection ......................................................................... 61
       6.3.2. Code Pattern Pre-skewing ............................................................................... 64
   6.4. SUMMARY ................................................................................................................. 65

7. Original Contributions: Summary, Conclusions, and Future Prospects ............ 66
   7.1. ORIGINAL CONTRIBUTIONS ................................................................................... 66
   7.2. LIST OF PUBLICATIONS ........................................................................................ 68
   7.3. FUTURE PROSPECTS ............................................................................................... 69
       7.3.1. Device Development .......................................................................................... 69
       7.3.2. System Design ................................................................................................... 70
       7.3.3. Coding Theory ................................................................................................ 70
   7.4. A FINAL WORD ......................................................................................................... 70

8. Appendix I: Variable Threshold Bit Error Rate ...................................................... 72

9. Appendix II: Monte-Carlo Simulation Methodologies ......................................... 73
List of Figures

FIGURE 1-1 AN ILLUSTRATION OF THE RING (LEFT) AND BUS (RIGHT) TOPOLOGIES. .......... 2

FIGURE 2-1 SPECTRAL ENCODING O-CDMA SYSTEM [25]. .................................................. 10

FIGURE 3-1 A MW-O-CDMA SYSTEM CONNECTED IN THE STAR TOPOLOGY .......... 15

FIGURE 3-2 A 5x7 MPR CODE WITH 2 PULSES PER ROW (R = 2, Nw = 5, Lr = 7) .......... 16

FIGURE 3-3 ASYNCHRONOUS O-CDMA OPERATION WITH CORRELATION DETECTION ... 17

FIGURE 4-1 GENERIC BLOCK DIAGRAMS FOR O-CDMA (A) TRANSMITTERS AND (B) RECEIVERS ................................................................. 21

FIGURE 4-2 FIBRE DELAY LINE TRANSMITTER FOR MULTI-WAVELENGTH SYSTEMS .... 23

FIGURE 4-3 PARALLEL FIBRE DELAY LINE RECEIVER .......................................................... 23

FIGURE 4-4 TRANSMITTER USING SEGMENTED GRATINGS ............................................... 25

FIGURE 4-5 ENCODING OPERATION USING CMGs [62]. .................................................. 25

FIGURE 4-6 GENERIC ARCHITECTURE IN THE OPTOELECTRONICS APPROACH ............ 26

FIGURE 4-7 THE SIZE OF THE NEW CODE SET IS MUST SMALLER THAN THE MAXIMUM ALLOWABLE GIVEN THE NUMBER OF FDLs. ......................................................... 29

FIGURE 4-8 THE CHIRPED MOIRÉ GRATINGS APPROACH ONLY UTILIZES THE DIAGONALS OF THE WAVELENGTH-TIME CODING SPACING. .................................................. 30

FIGURE 4-9 LOGICAL DECOMPOSITION USING SEGMENTED GRATINGS ..................... 30

FIGURE 5-1 EXISTENCE OF AN OPTIMUM THRESHOLD VALUE. THE BIT ERROR RATE OF A MPR CODE WITH A TOTAL SPREADING FACTOR S OF 5000 AND A WEIGHT OF 70 SUPPORTING 120 USERS IS MINIMIZED BY CHOOSING A THRESHOLD VALUE OF 94 INSTEAD OF THE CONVENTIONALLY-CHOSEN 70 ........................................... 36

FIGURE 5-2 BIT ERROR RATE FOR DIFFERENT CHOICES OF THRESHOLD VALUES (A) PROBABILITY OF FALSE ALARM AND (B) PROBABILITY OF FALSE DISMISSAL DOMINATES. THE BIT ERROR RATE IS GIVEN BY THE TOTAL OF THE SHAPED AREAS. ................................................................. 36

FIGURE 5-3 BIT ERROR RATE AT THE OPTIMUM THRESHOLD VALUE. THE BLANK-OUT AREA IS PLACED IN THE CENTER OF THE BINOMIAL DISTRIBUTION TO ACHIEVE A MINIMIZED BIT ERROR RATE. THE BIT ERROR RATE IS GIVEN BY THE TOTAL AREA OF THE SHAPED AREA. ................................................................. 38
FIGURE 5-4 System and code parameter selection procedure. ........................................ 41

FIGURE 5-5 Achieving higher cardinality by wavelength cyclic shifting. An example of a 3x3 T/S AML code set is used. The cardinality is increased from 2 to 3. ................................................................. 43

FIGURE 5-6 Improvement of cardinality by wavelength cyclic shifting. .......... 43

FIGURE 5-7 Spectral efficiency comparison between WH/T/S [28] and T/S AML [30] codes with conventional threshold detection; and MPR codes using OTD. .................................................. 45

FIGURE 5-8 Spectral Efficiency of MW-O-CDMA system with OTD and FEC .... 47

FIGURE 5-9 Choice of number of simultaneous users achieved through raw BER design. ................................................................. 48

FIGURE 5-10 A receiver design using real-time threshold optimization. .......... 51

FIGURE 5-11 A transmitter design for adaptive self-optimizing networks. .... 52

FIGURE 5-12 Code set library — A fast memory module pre-programmed with code sets optimized for different level of network activity. ............. 53

FIGURE 5-13 Full-scale traffic conditions adaptation .............................................. 53

FIGURE 6-1 The effect of temporal skewing in MW-O-CDMA systems .......... 56

FIGURE 6-2 Temporal skew parameters ............................................................... 58

FIGURE 6-3 Skewed auto-correlation in (A) and cross-correlation in (B). In (B), the expected values of cross-correlation are plotted. The variances of cross-correlation are represented using error bars. The parameters chosen for the two code families are: WH/T/S \((N_w=5, L_r=25, R=1, N_{su}=8)\) and T/S AML \((N_w=5, L_r=19, R=1, N_{su}=9)\). .......................... 59

FIGURE 6-4 Gaussian-approximated BER performance under the effect of dispersion. ................................................................. 61

FIGURE 6-5 Correlation detection under the effects of temporal skewing ....... 62

FIGURE 6-6 Theoretical and simulated optimum threshold values. Under very low traffic conditions in (A), \(N_w R L_4 = 0.36\), analytic and simulated results are in close agreement. Deviations are observed in higher traffic conditions (b), \(N_w R L_4 = 0.64\) ................................................................. 63

FIGURE 6-7 A comparison between simulated and calculated BER .......... 63

VII
FIGURE 6-8 PRE-SKEWING IN A STAR NETWORK WITH UNEQUAL DISTANCES AMONG USERS. ................................................. 64

FIGURE 7-1 TOPICS FOR FURTHER EXPLORATION. ........................................................................................................ 69
List of Tables

Table 4-1 Implementation approaches ................................................................. 31
Table 4-2 Achievable network size ......................................................................... 32
Table 5-1 Spectral efficiencies of O-CDMA codes [78] ........................................ 44
# Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Address Code(word)</strong></td>
<td>See <em>Signature Pattern</em></td>
</tr>
<tr>
<td><strong>Cardinality</strong></td>
<td>The number of distinct codewords in a code set. Also refers to the number of network addresses in the context of this work.</td>
</tr>
<tr>
<td><strong>Chip</strong></td>
<td>The building block of codewords.</td>
</tr>
<tr>
<td><strong>Code Weight</strong></td>
<td>The number of 1’s in a codeword.</td>
</tr>
<tr>
<td><strong>CSMA/CD</strong></td>
<td><em>Carrier Sense Multiple-Access / Collision Detection</em>, a set of rules determining how network devices respond when two devices attempt to use a data channel simultaneously.</td>
</tr>
<tr>
<td><strong>Daisy-Chain</strong></td>
<td>Devices connected in a serial manner.</td>
</tr>
<tr>
<td><strong>Network Address</strong></td>
<td>See <em>Signature Pattern</em></td>
</tr>
<tr>
<td><strong>Network Fabric</strong></td>
<td>The medium connecting transmitters and receivers. It may be passive or active. A passive network fabric may consists of only optical fibres and star couplers whereas an active network fabric may consists of optical amplifiers as well.</td>
</tr>
<tr>
<td><strong>Number of Subscribers</strong></td>
<td>The largest number of users a network can address. Equal to cardinality in a CDMA network.</td>
</tr>
<tr>
<td><strong>Signature Code(word)</strong></td>
<td>See <em>Signature Pattern</em></td>
</tr>
<tr>
<td><strong>Signature Pattern</strong></td>
<td>A distinct codeword, which can be used to identify uniquely a user in a CDMA network.</td>
</tr>
<tr>
<td><strong>Simultaneous Users</strong></td>
<td>Number of users that are transmitting simultaneously on a network.</td>
</tr>
<tr>
<td><strong>Spectral Efficiency</strong></td>
<td>The ratio between the total information rate and total bandwidth consumed in the transmission.</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>BER</td>
<td>Bit error rate</td>
</tr>
<tr>
<td>cw</td>
<td>Continuous wave</td>
</tr>
<tr>
<td>CWS</td>
<td>Cyclic wavelength shifting</td>
</tr>
<tr>
<td>CMG</td>
<td>Chirped Moiré grating</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg Grating</td>
</tr>
<tr>
<td>FDL</td>
<td>Fibre delay line</td>
</tr>
<tr>
<td>Gbps</td>
<td>Gigabits per second</td>
</tr>
<tr>
<td>GHz</td>
<td>Gigahertz, $10^9$ Hertz</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-symbol interference</td>
</tr>
<tr>
<td>LAN</td>
<td>Local area network</td>
</tr>
<tr>
<td>LUT</td>
<td>Look-up table</td>
</tr>
<tr>
<td>MAI</td>
<td>Multiple-access interference</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium access control</td>
</tr>
<tr>
<td>Mbps</td>
<td>Megabits per second, $10^6$ bps</td>
</tr>
<tr>
<td>MPR</td>
<td>Multiple-pulses-per-row</td>
</tr>
<tr>
<td>MW-O-CDMA</td>
<td>Multi-wavelength optical code division multiple-access</td>
</tr>
<tr>
<td>MWOOC</td>
<td>Multi-wavelength optical orthogonal code</td>
</tr>
<tr>
<td>OOC</td>
<td>Optical orthogonal code</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-interference ratio</td>
</tr>
<tr>
<td>Tbps</td>
<td>Terabits per second, $10^{12}$ bps</td>
</tr>
<tr>
<td>TS / AML</td>
<td>Temporal / spatial addition modulo $L_t$</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength division multiple-access</td>
</tr>
<tr>
<td>WH / TS</td>
<td>Wavelength hopping / time spreading</td>
</tr>
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CHAPTER

1. High-speed Local Area Networks: A New Approach

1.1. Evolution in Local Area Networks

The demand for high-speed communication networks has extended from transcontinental links to the local area. With the exploding growth of the Internet and the penetration of digital multimedia into homes and offices, the amount bandwidth that was once supplied to a city is now demanded by a single user. The communications industry is urgently in need of another revolutionary technological advancement to keep pace with surging demand for bandwidth. The historical development of local area networks (LANs) may inform possible future paths, and as such merits a brief review.

1.1.1. The Past

At the outset of the computer networking era, networks took the simple form of the client-server model, wherein a large number of dumb terminals were connected to a powerful mainframe. Earlier networks served as a resource-sharing medium: printers, file systems, and data processing power were shared among a large number of terminals. Since the traffic on such networks is generally bursty in nature, line-sharing techniques such as the Daisy-chain were developed to avoid the cost of dedicated connections to individual terminals. This was the precursor to multiple-access schemes in computer networks.
More recently, with the proliferation of low-cost personal computers, data processing responsibility has been passed on to individual terminals. The role of the server has diminished significantly, and interaction among terminals has grown. More sophisticated medium access protocols have been developed to facilitate traffic control in the shared medium in order to avoid high-cost dedicated connections. Terminals are no longer Daisy-chained together; they are connected in ring or bus topologies as depicted in Figure 1-1. The transmission protocols running on these networks are known as token ring and Ethernet. Under these schemes, network resources are assigned to a particular user at any given time. As a result, each user only has access to a fraction of the aggregate bandwidth.

Figure 1-1 An illustration of the ring (left) and bus (right) topologies.

The early generations of token ring and Ethernet provided an aggregate data rate of 10 Mbps. This bandwidth was plentiful in this early age of networking in which data traffic was dominated by simple network operations such as database queries, small file transfers, and print jobs.

1.1.2. The Present

The demand for high-capacity data networking is exploding. Internet traffic is already doubling every year. The emergence of new applications – telemedicine, digital video, and teleconferencing – will further accelerate growth. Present-day needs have been partially satisfied by the advent of the gigabit Ethernet and the high-speed token ring, which provide aggregate bandwidth in the range of Gbps to a collection of users. However, with the current rate of expansion of corporate networks and the Internet, these
gigabit networks will soon saturate. Even with the prospect of scaling to tens of Gbps operation, with a modest number of users (~100), each user can only access the channel on a time-sharing basis with an average bandwidth of tens of Mbps. Real-time transmission of medical images such as magnetic resonance imaging scans and x-rays requires on the order of 100 Mbytes per second, whereas a high-definition digital movie can require on the order of 500 Mbytes per second [1-3]. Thus, the bandwidth available in the near future will not accommodate real-time interactive high-quality video applications. Moreover, with the surging demand for high-performance distributed computing, teleconferencing, other digital broadcasting applications, and the convergence of other services such as high-definition TV (HDTV) and telephone services, aggregate terabit operation will be necessary. The latencies incurred in carrier sensing or token passing will prove to be intolerably inefficient in the terabit range. Such methods are acceptable for low traffic levels but suffer from cumulative delay at high traffic levels as the entire bandwidth is dedicated to one user at any given time [4]. A source of much greater bandwidth with guaranteed quality of service must be devised.

1.1.3. The Future

Future LANs should provide high capacity and reliable connectivity. To lower system costs, users will share the same physical medium. Complete asynchronous operation is important to provide users with concurrent access. Latencies such as the ones incurred from carrier sensing and token passing will be eliminated. Network operations should adapt to changes in user demands. Resources should be efficiently allocated and utilized at all times. With the proliferation of electronic commerce, transaction security must be guaranteed.

Conventional multiple-access schemes do not meet the above requirements. Such schemes are synchronous in nature and are mismatched to the bursty traffic of LANs. Schemes such as frequency-, time-, or wavelength-division multiplexing (FDM, TDM, WDM), in which resources are rigidly partitioned, are inefficient whenever a user is idle. Asynchronous multiplexing schemes are needed to maximize the utilization of resources. Such schemes include contention-based protocols such as carrier sensing, but the latency involved in this particular implementation is intolerable. Security is also a problem in the
conventional schemes: signals can be tapped off and demodulated directly. Sophisticated
encryption techniques are thus often required.

1.1.4. Optical Code Division Multiple-Access: Enabling Future LANs

Optical code division multiple-access (O-CDMA) is an excellent candidate for future
LANs. It may provide concurrent access by a large number of users without access delay.
Information is transmitted on all wavelengths simultaneously; orthogonality is achieved
in the code domain rather than in the wavelength domain. CDMA spreads information
over a much wider bandwidth than the information-bearing signal. It is well suited to
optical networks, in which bandwidth is plentiful. Additionally, the prospect of
performing the encoding and decoding functions all-optically, thereby removing
electronic processing bottlenecks, could potentially lead to terabit networks. Furthermore,
secure transmission is guaranteed by the spreading action. The encoded signal appears
noise-like at mismatched receivers. Data recovery is possible only with knowledge of the
transmitted code. Cryptography can also be used to enhance security at the frame level.
Finally, CDMA is a bit-level transmission scheme which allows protocol-independent
operation.

1.2. Objective and Approach of this Thesis

O-CDMA warrants dedicated attention by virtue of its potential capabilities.

Today O-CDMA is in its infancy. Channel bandwidth is still poorly utilized. Many
limitations and deficiencies have yet to be overcome:

1. Pseudo-orthogonality is only possible with long codes, reducing the system data rate
   for a given required BER.

2. Cardinality of such codes is small, limiting the maximum number of users.

3. Spectral efficiency is low – the ample bandwidth available in optical fibres is not
   utilized.

4. Full reconfigurable and adaptable implementation with respect to network demands is
   not yet available; only limited reconfigurability has been demonstrated.
5. The effect of dispersion on O-CDMA systems has not yet been studied. Nonidealities play a significant role in real deployment and must be taken into account.

The present work returns to fundamentals in order to find innovative ways to transform O-CDMA into a practical enabler of future LANs.

Three specific thrusts form the body of this investigation:

1) *Efficiency* – A novel method is developed in order to increase code cardinality and the number of users allowed on the network. An alternate detection scheme is developed and exploited to improve the efficiency of O-CDMA systems.

2) *Adaptability* – A new transmitter and receiver design is devised along with a new protocol in order to achieve network adaptability.

3) *Practicality* – The effect of dispersion is studied using Monte-Carlo simulation. Schemes for combating such effects are proposed.

1.3. **Overview**

The remainder of this thesis is organized as follows.

Chapter 2 provides a review of past research on O-CDMA. Families of O-CDMA systems and the significant developments in each type are introduced. Opportunities for improvements are identified and the scope of this work is established.

Chapter 3 presents the tools necessary to advance the state of the field. A flexible and versatile code family dubbed the multiple-pulses-per-row code is introduced with a view to enabling generalized study of multi-wavelength codes.

Chapter 4 is a feasibility study of the realization of O-CDMA using current and near-future technologies. The possibilities and limitations of numerous implementation approaches are assessed. These results are used to set the scope of this work to within the range of feasible implementation.

With the guidance of Chapter 4, two key methods of enhancing network utilization are derived and explored for the first time in Chapter 5. Cyclic wavelength shifting is shown to enable tripling of the number of users that can share network resources.
Optimum threshold detection is shown to improve spectral efficiency and enable adaptation to changing traffic demands.

Chapter 6 investigates and proposes practical solutions to the detrimental effects of dispersion. Finally, conclusions and prospects for future work are presented in Chapter 7.

A glossary is provided to standardize the terminology used throughout this work. Detailed derivations of the theories and simulation methodologies original to this work are provided in the Appendices.
CHAPTER

2. Optical Code Division Multiple-Access

2.1. A Brief History of CDMA

In 1949, Claude Shannon and Robert Pierce introduced the idea of code division multiple-access (CDMA) and described the interference averaging effect and the graceful degradation of error performance. A year later, De Rosa-Rogoff formulated the theory for direct sequence spread spectrum systems [5]. In the following decade, several major developments in CDMA, including the invention of the anti-multipath RAKE receiver, laid the foundations for its widespread deployment. Today, 50 years after the inception of spread spectrum technology, CDMA has evolved from the anti-jamming and anti-interception technique used in military application to one of the most popular multiple-access techniques used in the personal communication services (PCS) commercial network.

In CDMA, multiple-access capability is achieved by coding – the mapping of data to a mathematical description of time-frequency representation. The data to be transmitted are spread over a much larger bandwidth than normally necessary. This imposes a stringent constraint on RF designs due to the limited availability of strictly-regulated bandwidth.

In contrast, low-loss unregulated bandwidth is abundant in the optical fibre channel. Hui was the first to recognize this opportunity in 1985 [6]. The transferal from the RF
domain to the optical domain was difficult. For ease of implementation, signal reception in the optical domain is performed incoherently. Signal reception is based on power instead of amplitude. The non-negativity of the optical channel limits the information alphabet to \{0/1\}. The bipolar alphabets \{±1\} employed in RF CDMA cannot be transferred to incoherent optical systems directly. New codes had to be invented to adapt to the positive nature of the optical channel. In the late 1980’s, Salehi and Prucnal [7-14] proposed code generation algorithms with good unipolar correlation properties and implementation approaches in the optical domain.

2.2. Taxonomy of O-CDMA

Since the first proposal of CDMA in the optical domain, optical spread spectrum techniques have evolved into many different strains. These may be classified by their coding techniques into time-spread coding [7, 8, 10-13, 15-21], spectral encoding [22-26], and hybrid coding [27-31].

2.2.1. Time-Spread Coding

As in RF CDMA, correlation detection is used for optical signal de-spreading. However, unlike in RF CDMA, correlation in the positive optical channel corresponds to the logical OR operation instead of X-NOR with the bipolar wireless channel. As a result, new codes are designed to minimize the cross-correlation — the time-shifted similarity — among codes. A small number of 1’s is placed strategically within the string of 0’s in order to allow users to share the channel simultaneously. Optical Orthogonal Codes (OOC) proposed by Salehi et al. [9, 11-14, 32] and prime codes by Prucnal et al. [7, 8, 10] are representative examples of codes designed with this philosophy.

OOC\( (F, K, \lambda_u, \lambda_c) \) is a family of unipolar sequences of length \( F \) and weight \( K \) with a maximum out-of-phase auto-correlation of \( \lambda_u \) and cross-correlation of \( \lambda_c \). Several algorithms have been proposed to generate these unipolar sequences mathematically or geometrically [8, 12-14, 20, 32, 33] with good correlation properties (\( \lambda_u \) and \( \lambda_c = 1 \)). The cardinality \( |C| \) or the maximum number of network addresses of OOCs is derived based on the Johnson bound [13, 32]:

8
\[ | C | \leq \left\lfloor \frac{F - 1}{K(K - 1)} \right\rfloor \] (2-1)

Prime codes, on the other hand, are generated based on finite field mathematics using a prime number as generator [8, 10, 34-36]. The code algorithm relies on a design wherein a code consists of many blocks, each containing a single pulse. Codes are comprised of \( p \) blocks of length \( p \) for any prime number \( p \). The codes generated have a length of \( p^2 \) and a weight of \( p \). The cardinality of prime codes is equal to the generating prime number. The cross-correlation of the prime codes is at most 2. Their shifted auto-correlation may be as high as \( p-1 \).

The poor shifted auto-correlation property of prime codes creates a stringent synchronization and thresholding requirement at the receivers. This property effectively limits the use of prime codes to synchronous CDMA systems. Recent developments have led to the Extended Quadratic Congruence (EQC) codes [37]. The high auto-correlation sidelobes are removed in EQC codes and the auto-correlation is at most 1. EQC codes, however, have a length of \( p(2p - 1) \), almost twice that of prime codes.

### 2.2.2. Spectral Encoding

In spectral encoding systems [23-25], the spectral content of the data signal is encoded by means of an ultrashort light pulse which is modulated or reshaped in the frequency domain into a low-intensity pseudonoise burst. These systems allow the use of bipolar codes [38, 39] with excellent crosstalk rejection.

Figure 2-1 illustrates a spectral encoding system.
The output from the light-emitting diode (LED) is modulated by the data to be encoded. Pulses of light pass through the encoder, which consists of a pair of diffraction gratings, a pair of confocal lenses, and a mask. The first grating spatially decomposes the pulse into its spectral constituents. The mask introduces pseudorandom amplitude suppression among different spectral components. The pseudorandom perturbation of the spectral content corresponds to different network addresses. The second grating recombines the spectral content of the encoded pulse, which is in turn combined with signals from other users on the network. At the receiver, the optical signal from the network is split into two branches inside the decoder. One mask is the complex conjugate of the encoder mask and the other one is the same as the encoder mask. The electrical signals from the two photodetectors are then subtracted to reconstruct the data.

2.2.3. Hybrid Coding

Hybrid coding was proposed as a means to overcome limitations imposed by long code lengths in the previous coding schemes, in which information is spread only in one domain, time or frequency. Hybrid coding involves combining the two domains, thereby relaxing the demands on the individual multiplexing schemes. The most popular hybrid coding schemes are spatial CDMA and wavelength hopping / time spreading (WH/TS).
Spatial CDMA combines the time and spatial domains through the use of multiple single-mode fibres or multi-core fibres. WH/TS spreads signals over the time and wavelength domains. Encoded signals are conveyed over the network through many wavelength channels within a single fibre. Components such as tunable lasers and wavelength selective filters may be transferred from WDM to WH/TS systems. Data encoding can be divided into two stages: wavelength hopping and time spreading. Wavelength hopping is performed by selecting the appropriate wavelength from the tunable laser. Time spreading is achieved by the same means as the time-spread coding schemes. Prime codes (or EQC) have been modified to become two dimensional by allowing wavelength hopping [27-29]. In the new code structure, every pulse of the prime code is transmitted at a different wavelength. The proposed codes achieve zero auto-correlation sidelobes and a cross-correlation of at most one. The cardinality is equivalent to that of a standard time-spread CDMA network reusing prime codes over multiple wavelengths.

2.3. New Territory Requiring Exploration

Although a diverse collection of coding schemes has been developed, all members of this collection suffer similar deficiencies such as low spectral efficiency and small cardinality. OOCs, for example, have to be very sparse and lengthy in order to achieve good correlation properties. To achieve a bit-error rate (BER) of less than $10^{-9}$, a code length of 6000 and weight of 8 are required. This code is only capable of admitting 100 users in total and 85 simultaneously at a user bit rate of 1.67 Mbps assuming 10 GHz processing rate is available. Prime codes suffer from similar problems, in addition to an inflexible code structure – code lengths are invariably set to $p^2$. The long code length property of time-spread codes restricts the total system throughput to the sub-Gbps range. On the other hand, spectral encoding operates at the data rate, but crosstalk among users severely limits the BER performance of such systems. Furthermore, components such as free-space gratings and confocal lenses are difficult to package commercially. Hybrid coding schemes partially alleviate the processing demands on electronics; however, each scheme suffers its own unique set of problems. Spatial CDMA requires precise matching of fibre lengths across the network since any mismatch in the connection length will
affect the synchronization among different paths. The existing two-dimensional codes used in WH/TS suffer the same inflexibility as prime codes. The aspect ratios of such codes are limited to $p_1 \times p_2$ where $p_1$ and $p_2$ are prime numbers.

The previously proposed systems also rely on future technologies for commercial deployment on any practical scale. The realization of O-CDMA systems using today’s or near future technology is necessary in order to take immediate advantage of current O-CDMA research.

Previous works in O-CDMA have focussed on code design and system realization; very little attention has been devoted to higher network functionality such as reconfigurability and adaptability. While basic code designs and implementation methods are fundamental to the development of O-CDMA, higher level functionality is critical to the realization of a high-performance commercial network.

Chromatic dispersion has played a major role in optical communication systems, particularly since the advent of optical amplifiers. It is anticipated that the effect of dispersion will be aggravated in multi-wavelength O-CDMA systems due to the temporal misalignment caused by chromatic dispersion. However, there have not yet been any studies of the effect of dispersion in such O-CDMA systems. Countermeasures in this realm are urgently needed in preparation for wide commercial deployment.

2.4. Original Contributions

In this work, I seek to transform O-CDMA from research curiosity into practical deployable reality. This goal will be pursued by considering efficiency, reconfigurability, adaptability, and the effects of non-idealities in O-CDMA systems using analytical and numerical techniques newly derived herein, and validate using Monte-Carlo simulation.

New theories are developed to improve efficiency. Specifically, the WH/TS hybrid coding scheme is treated. Its sparsity and low cardinality are first addressed by introducing multiple-pulses-per-row (MPR) codes, a denser version of two-dimensional codes. Cyclic wavelength shifting is introduced to increase the cardinality of existing codes by several factors. Treatment of such codes is kept general, thus rendering the
theories developed applicable to codes of any two dimensions. Spectral efficiency is also improved by exploiting forward error correction (FEC).

Network traffic adaptation is realized on two levels: fine-tuning and large deviation adaptation. Fine-tuning adaptation is provided by means of dynamic threshold detection, wherein the threshold level at the receiver is varied in response to the traffic level such that BER is minimized for a given code set. When the desired level of BER is no longer sustainable with dynamic optimum threshold detection, transmitters switch to a new code set with a larger capacity through a memory table lookup (LUT).

Finally, the effect of dispersion on O-CDMA is studied. The effect of dispersion on several code families is compared. Code families are characterized by their degree of dispersion-resistance. A novel dispersion-management scheme is also introduced.
CHAPTER

3. Theory

As reviewed in Section 2.2, many coding methodologies exist under the heading of O-CDMA. In this work, the wavelength hopping / temporal spreading (WH/TS) scheme is chosen to exploit the abundant bandwidth available in the optical fibre and to boost the overall throughput. This chapter describes the key aspects of this system including a mathematical description to facilitate the analytical discussion in the remainder of the work.

3.1. System Model

A maximum of \(|C|\) users are admitted into a network connected with in a star topology depicted in Figure 3-1. Of these \(|C|\) subscribers, \(N_u\) users transmit simultaneously on the network with a given bit error rate (BER). No two users transmit to the same destination – transmitters and receivers are paired up. This requirement must be enforced at the media access control (MAC) level. ¹

For analytical calculations, each transmitter/receiver pair is assumed to be chip synchronized. Shot noise and thermal noise are taken to be of negligible power compared to the signal; the focus is upon on the influence of multiple-access interference (MAI).

¹ A scheme similar to the CSMA media access rule deployed in Ethernet [48] can be used where transmitters serialize their transmission to the same recipient by listening to the channel for the recipient code pattern. If the recipient code pattern is present on the channel, the transmitter waits for a random period of time before making another attempt to transmit.
The effect of shot and thermal noise can readily be added in cases of interest [33]. The wavelength channels are assumed to be spaced according to WDM standards (e.g. 100GHz), and the coherence lengths of low-cost transmitters (e.g. light-emitting diodes and multi-longitudinal mode Fabry-Perot lasers) are much less than node separation. As a result, optical beat noise among adjacent channels may be neglected at the receivers.

Figure 3-1 A MW-O-CDMA system connected in the star topology.

This work applies to unicast and to multicast transmission. A number of signature patterns can be reserved as multicast groups addresses. In this case, the receivers must be able to decode multiple codes (signature and multicast codes) simultaneously.

3.2. Multiple-Pulses-per-Row (MPR) Codes

Multiple-pulses-per-row (MPR) codes are a family of two-dimensional O-CDMA codes which span the time and wavelength domains. Schematically, a MPR code can be represented by a rectangular grid or matrix with $N_w$ wavelength channels (or rows) and $L_t$ time slots (or chips, columns). An example of a $5 \times 7$ MPR code is shown in Figure 3-2. The black squares represent the presence of optical pulses, white squares the absence of a pulse. Figure 3-2 illustrates a code which employs two pulses per wavelength channel. MPR codes employ $R$ pulses per row, where $R$ is an integer ranges from 1 to $L_t$. The requirement of fixed $R$ ensures the uniform distribution of energy (or spread of information) across all wavelength channels. MPR codes with $R > 1$ can be considered as a form of a wavelength reuse strategy within a bit period: network resources are better utilized when $R$ is chosen appropriately [49].
MPR codes are versatile – they do not imply a specific code construction algorithm. Our analysis therefore applies to a wide selection of codes. These include the well-known temporal / spatial addition modulo $L_t$ (T/SAML) codes [28], wavelength hopping / time spreading (WH/TS) codes [30], multi-wavelength optical orthogonal codes (MWOOC) [50], and two-dimension (0,1) matrix codes of Iversen et al [51]. Our analysis is applicable to any two-dimensional codes – the dimensions in question need not correspond to wavelength and time.

### 3.3. Basic Operation

In multi-wavelength O-CDMA networks, each user is assigned to a MPR codeword matrix as its own network address. Users transmit a data bit '1' using a unique pattern of optical pulses spread in the time-wavelength space according to the intended receiver. Encoded signals from all users are then superimposed at the star coupler. Transmitted signals from different users exhibit arbitrary phase relationships in this asynchronous network. At the receiver, a matched filter decoder is used to perform correlation detection – summation of optical power at the locations in the time-wavelength space specified by the codeword matrix – on the received signal. Only at the intended receiver can all of the spread pulses be reassembled to a single optical pulse with the original power. This pulse, whose intensity should exceed the threshold, is decoded as a data bit ‘1’. At other receivers, the original pulse is not reconstructed, resulting in a series of short bursts which will be decoded as a ‘0’. On the other hand, when users transmit data bit ‘0’, no optical power will be transmitted during the bit period. The process of encoding and decoding is illustrated in Figure 3-3.
Figure 3-3 Asynchronous O-CDMA operation with correlation detection.

3.4. Mathematical Model

The incoherent optical fibre channel is a positive system: it cannot manipulate its non-zero signals to add to zero [12]. In asynchronous positive systems, complete orthogonality is impossible. In order to maximize the discrimination between the desired code pattern and other signals, the set of O-CDMA code patterns must possess the following properties:

1. Each codeword matrix must have a large auto-correlation peak:

$$\Theta_a = \sum_{i=0}^{L_x-1} \sum_{j=0}^{L_x-1} x_{i,j} \leq W \gg 0$$  \hspace{1cm} (3-1)$$

where $x_{i,j} \in \{0,1\}$ is an element of codeword matrix $X$.

2. Each codeword matrix must be easily distinguishable from a shifted version of itself. That is, for a codeword matrix $X$, the auto-correlation sidelobes must be small:

$$\Theta_a(\tau) = \sum_{i=0}^{L_x-1} \sum_{j=0}^{L_x-1} x_{i,j} x_{i,j+\tau} \leq \lambda_a$$  \hspace{1cm} \text{for } 0 \leq \tau \leq L_x - 1 \hspace{1cm} (3-2)$$

$\lambda_a$ is known as the auto-correlation constraint and $\Theta$ denotes modulo-n addition.
3. Each pattern must be easily distinguishable from every other pattern in the set. That is, for a pair of codeword matrices \( X \) and \( Y \), their cross-correlation must be small:

\[
\Theta_{\tau}(\tau) = \sum_{i=0}^{N_u-1} \sum_{j=0}^{L_r-1} x_{i,j} y_{i,\tau+j} \leq \lambda_c \quad \text{for} \quad 0 \leq \tau \leq L_r - 1
\]  

(3-3)

Throughout this work, the MPR codes in use are assumed to satisfy an auto- and a cross-correlation constraint of 1. Algebraic codes such as the T/S AML codes [28] and WH/Ts codes [30] satisfy this requirement and are used in subsequent simulations and comparisons.

Finally, the bit error rate (BER) for the MPR code is derived. With random time shifts, there exist \( R^2 \) possible distinct overlapping patterns in any one row in the superposition of two MPR codes. There are a total of \( N_u R^2 \) overlaps in \( N_u \) rows and the probability of overlap is \( N_u R^2 / 2L_r \). Since the nature of the threshold process implies that an error will result only when a 0 is sent but a 1 is output by the receiver correlator, the bit error rate is equal to the summation of the probability of overlap from the threshold value \( N_u R \) to the maximum number of interferers \( N_{su} - 1 \). With the threshold for the correlation receivers equal to the weight of the code, the following expression is obtained:

\[
BER = \frac{1}{2} \sum_{i=N_u R}^{N_{su}-1} \left( \frac{N_u R^2}{2L_r} \right)^i \left( 1 - \frac{N_u R^2}{2L_r} \right)^{N_u R - i}
\]  

(3-4)

This result is valid for codes which satisfy the cross-correlation constraint \( \lambda = 1 \).

**3.5. Summary**

\( N_{su} \) users are assumed, throughout this work, to transmit simultaneously in a star topology results in a certain level of BER. Each user encodes information with a recipient-specific codeword, dubbed MPR code without synchronization relative to other users. Correlation detection is performed at the receivers.

A mathematical description of a system was also provided to facilitate quantitative discussion in the body of this work. The anticipated performance of a MPR code set can be characterized and specified by its correlation properties as well as other system...
parameters such as the number of wavelength channels and the number of simultaneous users. An analytical expression of the BER performance of such code is given in Equation (3-4).
4. MW-O-CDMA Implementation: Options and Limitations

4.1. Motivation

Significant effort has been devoted to the development of code designs and experimental optical CDMA systems. While promising research has been conducted in both facets, work in these two areas has been unconnected. To take advantage of the full potential of O-CDMA, code optimization and system implementation must be treated as interdependent elements of a single challenge: the realization of an effective, efficient, practical system. In this chapter, the intimate relationships between coding designs and their hardware implementations are examined in preparation for the future fusion of the two fields of research. Present capabilities and future prospects are studied, and the results of these investigations set the scope for the original contribution of the remainder of this work.

4.2. Background and Context

As discussed in Chapter 3, an O-CDMA system can be divided into 3 parts: 1) the transmitter, which consists of a light source and an encoder; 2) the network fabric, which consists of fibre and a star coupler; 3) the receiver, which consists of a matched-filter decoder and a threshold element. The implementation of these subsystems has always presented a challenge in the O-CDMA research. High power loss, high cost per node,
poor scalability, and limited reconfigurability are some of the major obstacles standing in the way of the commercial deployment of such systems.

O-CDMA systems are decentralized: the intelligence responsible for network operation lies within the transmitters and receivers. This chapter is therefore devoted to the exploration of different implementation schemes for transmitter and receiver designs.

Approaches to transmitter and receiver designs proposed in the pasts include fibre delay-lines (FDLs) [18, 26, 52, 53], fibre Bragg gratings (FGBs) [18, 26, 46, 52-58], and optoelectronics [27, 52, 59, 60]. Since the majority of past developments in O-CDMA have focused on single-wavelength systems, the implementations proposed are predominantly for one-dimensional codes. In subsequent sections, these approaches are applied to multi-wavelength O-CDMA systems and the effectiveness of each method is examined.

4.2.1. Transmitter and Receiver: Basic Building Blocks

The building blocks of transmitters and receivers are depicted in Figure 4-1.

![Figure 4-1 Generic block diagrams for O-CDMA (a) Transmitters and (b) Receivers](image)

Each building block is described as follows:

- **Data source** – The party that initiates the data transfer and generates the digital data stream.

- **Light source** – Light sources to be used in the MW-O-CDMA systems can be classified into two categories: broadband and multi-wavelength sources. Broadband
sources can be obtained from light-emitting diodes (LEDs) [25], amplified spontaneous emission from Er-doped fibre amplifiers, or ultrashort pulses. These broadband sources are spectrally sliced using waveguide-grating arrays (WGAs) [61] or serial grating arrays [62] for separation into wavelength channels. Alternatively, a semiconductor laser array or tunable laser may be deployed directly.

- **Encoder/Decoder** – Encoders and decoders are structurally similar owing to the fact that one provides the time-reversed function of the other: the encoder spreads the signal in either the time or frequency domain, and the decoder de-spreads.

- **Photodetector** – Avalanche photodetectors (APDs) are often used instead of pin detectors due to their improved responsivity owing to the avalanche multiplication effect. The effect of shot noise, however, is aggravated due to the stochastic nature of photon generation in the avalanche multiplication effect.

- **Threshold element** – This element compares the input signal with a threshold value (either preset or dynamically determined) and outputs a binary result. Both optoelectronic and all-optical implementations exist. In the optoelectronic approach, the optical signal is converted into an electrical signal on which the thresholding operation is executed. In the all-optical approach, nonlinear devices are often proposed [63-65].

- **Data sink** – The consumer of data, identified by a unique signature code pattern or destination address.

### 4.2.2. Transmitters and Receivers: Principles of Operation

In this section, three different implementation approaches – FDL, FBG, and optoelectronics – are tailored for application in a MW-O-CDMA system.

**Fibre Delay Lines (FDLs)**

Fibre delay lines were first employed as optical buffers in all-optical switches [66, 67]. With different copies of a pulse travelling in parallel through a number of delay lines of different lengths, delays of different times are introduced among the copies of the pulse, thereby archiving temporal spreading. The extent of the temporal spreading is
controlled by the relative lengths of the fibres. Examples of implementations can be found in [29, 53].

![Figure 4-2 Fibre delay line transmitter for multi-wavelength systems.](image)

In the transmission of a ‘1’, as depicted in Figure 4-2, a light pulse originating from the data source is split into a total of \(N_wL_\tau\) copies. The copies are injected into a set of parallel FDLs with different propagation delays, each a multiple of the chip period. Different recipients can be selected by changing the configuration of the optical gates. Finally, a \(N_wL_\tau\times1\) coupler combines the \(W\) pulses to form the desired code pattern.

![Figure 4-3 Parallel fibre delay line receiver](image)

At the receiver, the time-reversed operation is performed. As illustrated in Figure 4-3, the encoded pulse is split into \(W\) copies, each passing through a delay line with time delays prescribed by the recipient address code. At the receiver of the intended recipient, the total delay experienced by each chip pulse should be equal a bit period to ensure that all of the pulses are aligned temporally at the \(W\times1\) coupler. The sum of the power of these aligned pulses is equal to or greater than the code weight. If the threshold value of the
threshold element is set below the code weight, a bit ‘1’ will be output. For each of the other users, the time-reversed delay function will not match the encoded pattern. Chips will thus be misaligned, yielding a correlation peak less than the threshold, resulting in a ‘0’ bit decoding decision.

This design offers programmability through electro-optically controlled gates. Different recipients are selected electronically by the code selector. The states of the optical gates remain the same throughout the transmission so that relatively low-speed electronics are adequate. This scheme is suited to direct sequence, low-weight codes, in which the chip rate is too high for direct electronic modulation and the number of delay lines is small due to the low code weight. Drawbacks of the scheme include the large number of splitters required at the transmitter. In particular, the $L_{x1}$ splitter is often large and difficult to realize. The total length of the FDL required precludes the realization of a compact transceiver module.

**Fibre Bragg Gratings (FGBs)**

The use of Fibre Bragg Gratings (FGBs) in encoding/decoding O-CDMA sequences offers compact size, ease of manufacture, and all-fibre implementation [43, 46, 56, 58, 62]. There are two main types of FBGs used in O-CDMA encoders and decoders: segmented FBGs and chirped FBGs.

Proposed by Templex Technology (and dubbed Temporally Accessed Spectral Multiplexing (TASM™)) [46, 58, 68], segmented gratings are composed of a linear array of uniform subgratings, all having the same grating period but different sub-grating index amplitudes and spatial phases relative to a fixed coordinate system. When a short pulse is incident on the grating, the reflected light, now encoded, will diffract into a number of pulses with relative time-delays and amplitudes specified by the subgrating spacings and peak refractive index modulation. A matched (time-reversed and phase-conjugated) segmented grating is used to decode (or de-spread) the encoded pattern. Each segmented grating performs temporal spreading only on a single wavelength. Multiple gratings can be used to generate MPR codes. This concept is illustrated in Figure 4-4.
Another approach to implementing O-CDMA encoders and decoders is to use chirped FBGs. In general, chirped FBGs decompose a broadband pulse in time and wavelength domains simultaneously. Time spreading results from the round-trip propagation delay of light within the medium; wavelength decomposition results from variation of the grating period along its length. In particular, Smith and Chen have succeeded in demonstrating an optical CDMA system using chirped moiré gratings (CMG) [56, 62]. A CMG and its physically reversed structure have the same amplitude response, and, to first order, opposite group delay. The encoding operation is illustrated in Figure 4-5.

Figure 4-5 Encoding operation using CMGs [62].
**Optoelectronics**

The use of optoelectronics in O-CDMA systems can be traced back to the 1980's, when CDMA was first transferred to the optical domain. Its complete flexibility allows the realization of various kinds of O-CDMA systems including coherent [59], incoherent [12, 32], and spatial [31] O-CDMA. Optoelectronics remains one of the most popular schemes.

Direct sequence (DS) O-CDMA is often employed in conjunction with the optoelectronic implementation approach to investigate the performance and functionality of O-CDMA systems. The results can readily be extended to multi-wavelength systems since MPR codes can be treated as a form of DS-O-CDMA in two dimensions. The generic architecture for such a system is illustrated in Figure 4-6.

![Generic architecture in the optoelectronics approach.](image)

At the transmitter, the incoming data stream is encoded electronically with the recipient code pattern using a multiplier. The encoded data pattern will be used to control the electro-optic modulator as a normally-closed gate: a ‘1’ in the code pattern biases the electro-optic modulator to full transmission; a ‘0’ biases the electro-optic modulator to zero-transmission. This results in the conversion of the encoded chip pattern into optical form by external modulation of the continuous wave (cw) laser source. At the receiver, an identical electro-optic modulator is used to de-spread the signal by sampling the signal at the marked time instances of the signature pattern. The samples are then integrated over a bit period. A bit ‘1’ is registered if the result is greater than the preset threshold, and a bit ‘0’ is decoded otherwise.
4.2.3. Assessment of Transmitter and Receiver Capabilities

The intimate relationships between physical implementation and coding design for MW-O-CDMA systems merit examination. The choice of physical implementation and the use of coding theory could potentially impose restrictions the configuration of the system. The key to unleashing the full potential of CDMA in the optical domain is to understand the interdependencies between these hitherto disjoint fields of research so that resources may be exploited to develop the best overall deployable O-CDMA system. The focus of this section is summarized by the following two questions:

- Does a particular implementation impose any restrictions on the coding design? Does it fail to support any key functional requirements?
- Could the particular implementation take advantage of the latest advances in coding theory? and be future-ready?

To investigate these questions in a relevant context, the detailed implementation of MW-O-CDMA MPR codes in each of the above-described approaches is considered. MPR codes embody all two-dimensional codes with a fixed weight per row. Thus they includes the T/S AML codes of Selvarajan et al. [28], the WH/TS codes of Andonovic et al. [30], the MWOOC codes of Kwong et al. [50], and 2-D matrix codes of Iversen et al. [51]. The three major implementation approaches are compared and the effectiveness of each approach is measured against the following criteria:

- Accessibility of the two-dimensional coding space – Does the choice of implementation allow complete independent access to the time and wavelength domains? What, if any, constraints exist?
- Reconfigurability – How readily can a transmitter switch between two intended coding addresses? Without rapid reconfigurability, the system can hardly be considered a network, a term applied to a system which provides any-to-any connectivity on demand. It is necessary to reconfigure within an acceptable time period in order to offer for low-latency access to users.
- Reprogrammability – Can the network be reprogrammed to transmit and receive using a different set of codes optimized to the immediate needs of the work and its
users? As will be shown in Chapter 5, reprogrammability is critical in maintaining efficient use of network resources.

- **Electronics speed requirements** – Barring the advent of optical computers, an optical-electronic interface will be needed at some point, even in all-optical networks. In some designs, such as the optoelectronic approach, electronics constitutes an integral part of the system. Currently, electronic speeds are limited to the gigahertz range – 100 GHz for the most advanced devices, 10 GHz for compound semiconductor systems such as GaAs and SiGe, and a few GHz for silicon. While it is anticipated that the speed of electronics will continue to improve, electronic speed limits practical code size for a given data rate.

- **Power efficiency** – The generation of O-CDMA codes involves splitting or spreading of a pulse spectrally, temporally, or both. These splitting and spreading losses are a function of the implementation. Power efficiency is an important determinant of the dynamic range of achievable SNR of a transmitter.

**Fibre Delay Lines (FDLs)**

FDLs allow complete access to both the wavelength and temporal domains. Each electro-optic modulator (see Figure 4-2) can be controlled independently to modulate the relative positions of the different wavelength components in time. This capability also allows the transmitter to target its data stream to different users by configuring the signature pattern accordingly.

While switching among codewords is straightforward, switching to a different code set may be problematic. The allowable span in the wavelength and the temporal domains depends on the number of delay lines available. The transmitter only allows switching of code sets to one with a smaller span in both domains, as depicted in Figure 4-7. In the worst case, the transmitter will switch among different destinations after the transmission of every bit. Thus, the electro-optic modulators are only required to switch at the bit rate. This is a significant relaxation in electronics requirements as the bit rate is often a few orders of magnitude lower than the chip rate.
The size of the new code set is much smaller than the maximum allowable given the number of FDLs.

The dynamic range of SNR is limited by the power efficiency. In the case of MPR codes, the power efficiency is limited to $R/L$. The splitting loss can be compensated using a fibre amplifier at the output of the transmitter.

**Fibre Bragg Gratings (FGBs)**

For chirped moiré gratings, the centre frequencies of the stopbands change serially in space and the energy of different wavelength components is reflected sequentially in time. As a result, the relative positions of the pulses in the wavelength-time space always assume a diagonal shape as depicted in Figure 4-8. The coding space has essentially collapsed to a one-dimensional domain, which significantly limits the coding flexibility and the achievable cardinality. The access to the 2-D space can be improved by using segmented gratings, wherein the different stopbands may be ordered arbitrarily, as depicted in Figure 4-9. Multiple gratings may be used to produce more than one pulse per wavelength channel. The number of possible wavelength channels depends on the bandwidth of the initial broadband pulse and the effective bandwidth of the individual section in the gratings. Both ultrashort pulses and precise stopband control of gratings are difficult to realize and costly. The power efficiency, however, could potentially be extremely high, since all the reflected light is contributed to the encoded signal.

Switching among different users is also limited by the tuning range of FGBs. Thirty-three wavelength channels have been demonstrated using the strain-tuning mechanism [69]. The relative position of the pulses in wavelength-time space cannot be reconfigured independently. The user population is thus significantly limited if any-to-any communication is desired.
The chirped moiré gratings approach only utilizes the diagonals of the wavelength-time coding spacing.

The FBG approach also lacks reprogrammability. The gratings are permanently written and the delays among sub-gratings are fixed except for limited tuning. Switching to a different set of codes is not possible.

All-optical operation is possible in the FBG scheme, and the speed of electronics is thus not a concern.

**Optoelectronics**

The on-off actions of each electro-optic modulator are controlled independently by an electronic code pattern generator which can be reprogrammed to generate different codewords or even code sets. The optoelectronic approach is therefore completely reconfigurable and reprogrammable. It provides complete freedom in accessing the wavelength-time coding space. Access to the two-dimensional coding space is
constrained if a tunable laser source is used: this prohibits two chips existing in different wavelengths to occupy the same chip period.

Unlike in the FDL approach, however, the electro-optic modulators switch at the chip rate instead of at the bit rate. Currently, electronics operate at gigahertz rates at best. With codes possessing temporal lengths of thousands of chips, which is not uncommon, the user data rate is limited to the megabit per second range. This is very constraining, and calls for more efficient code designs employing shorter temporal lengths.

**Summary**

The following table provides a summary of the performance of different implementation in multi-wavelength O-CDMA systems.

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<th>Table 4-1 Implementation approaches.</th>
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<tbody>
<tr>
<td>Complexity / Scalability</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Physical footprint</td>
</tr>
<tr>
<td>Access to 2-D coding space</td>
</tr>
<tr>
<td>Reconfigurability</td>
</tr>
<tr>
<td>Reprogrammability</td>
</tr>
<tr>
<td>Electronics speed requirements (Threshold)</td>
</tr>
</tbody>
</table>

*For typical networks, the relative magnitude of the parameters is: $R<N_w<L_c$.

Missing from the above table is a comparison of achievable network size. Unlike other parameters, the achievable network size of the three approaches changes with time. The exact number depends on the advancement of the particular technology. Table 4-2 tabulates the achievable network sizes with different technologies.
Table 4-2 Achievable network size.

<table>
<thead>
<tr>
<th></th>
<th>Present-day technology</th>
<th>Future technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FDL</td>
<td>Optoelectronics</td>
</tr>
<tr>
<td>$N_w$</td>
<td>$\leq 32$ using AWGs [45, 70]</td>
<td>$\leq 33$ [69]</td>
</tr>
<tr>
<td>$L_e$</td>
<td>limited by fibre length</td>
<td>$\leq \left\lfloor \frac{B_e}{B} \right\rfloor$</td>
</tr>
</tbody>
</table>

Legend:

$\left\lfloor x \right\rfloor$: the floor function – gives only the integer part of $x$.

$B_e$: electronic rate

$B$: bit rate

4.3. Conclusions

Optical CDMA technology has attracted much attention in the last decade with a view to enabling high-capacity fibre-optic multiple-access LANs. Code design and implementation have each posed important research challenges. While researchers have made significant contributions to each area, the results have generally been unconnected. High performance codes have been designed with little consideration given to implementation; similarly, implementation have been designed around specific device capabilities rather than real network needs. A perspective integrating these two aspects is imperative to the design of a better system.

This chapter provides the first step towards this goal. The intricate relationships between code design and physical implementation have been examined in detail. In particular, emphasis has been placed on high-level functionality that is desirable for efficient and high-performance network operations.

Three implementation approaches have been considered: fibre delay lines (FDLs), fibre Bragg gratings (FGBs), and optoelectronics. The FDL approach allows full access to the wavelength-time coding space, but has limited reprogrammability and low power efficiency. The FGB approach allows all-optical operation, but has poor reconfigurability. Finally, the optoelectronics approach is the most flexible one. It

---

$^1$ Assume data rate of 1GHz, the maximum fibre grating length is 100cm. Assuming segmented gratings with subgrating length of 10mm and spacing of 8mm [69], the maximum number of subgratings is 55.
supports almost all of the desired high-level networking functions. However, its performance is ultimately limited by the speed of electronics.

The present-day capabilities and future prospects are summarized in this chapter set the scope of study for the body of this work. In Chapters 5 to 6, all code designs, systems analyses, and assessments of network performance will be focused on the regimes of practical implementation.
CHAPTER

5. Enabling Efficient, Dynamic Networks using MW-O-CDMA

5.1. Introduction

In local area packet-based networks, traffic is bursty. Many applications demand low latency. To allow a large population to access network resources simultaneously in an efficient manner, it is thus desirable to achieve asynchronous operation and exploit statistical multiplexing without relying on sophisticated, high-speed centralized control. While the O-CDMA concept perfectly fits these criteria, its inchoate status precludes any immediate commercial deployment. The key to the proliferation of O-CDMA networks will lie in its functionality and cost-effectiveness. Currently, an O-CDMA systems start-up, Codestream Technologies Corporation [73], plans to provide systems with an aggregate bandwidth of approximately 500 Mbps with a speculative per-user cost in the $20,000 range in a few years. This performance-cost ratio is only one-tenth that of the gigabit Ethernet. While prices for optical components will decline with improved automation, the cost-effectiveness of such systems can be further improved by advancing engineering design.

Despite a decade of research in O-CDMA, the efficiency of such systems remains poor – the information rate is only a few percent of the allocated bandwidth. The size of the network, equal to the maximum number of subscribers |C|, is limited by the low cardinality of the available codes [8-10, 13, 15, 20, 28, 30, 33, 38, 41, 53, 58, 60]. Furthermore, resource allocation schemes cannot adapt to changes in traffic conditions.
Systems are consequently designed for worst-case performance scenarios and resources are seldom fully exploited.

New schemes are developed in this chapter to address these problems central to the realization of practical optical CDMA networks. In Section 5.2, theoretical foundations are developed to enable a unified systems analysis. These results are then applied in Sections 5.3 and 5.4 with a view to realizing efficient, adaptive networks.

5.2. Theoretical Foundations

This section comprises a collection of tools to aid in bringing the commercial proliferation of MW-O-CDMA closer to reality.

5.2.1. Optimum Threshold Detection

In previous works [28, 30, 74, 75] the threshold value used in a correlation receiver was set equal to the code weight. Due to the non-negative nature of the optical channel, optical power can be superimposed, but not cancelled. As a result, setting the threshold value to the code weight ensures that no decision error will be made when a bit ‘1’ is sent. This scheme works well when the multiple-access interference (MAI) – the product of the number of simultaneous users and the expectation value of their cross-correlation with the signal to be received – is small compared to the code weight. The probability of error associated with a data bit ‘0’ increases when the average interference power in the optical channel is high. This, however, may be remedied by increasing the threshold value beyond the code weight. It is thus of interest to consider a more general choice of threshold value $\alpha$. The following new expression for the bit error rate is derived in Appendix I:

$$
BER = \frac{1}{2} \left[ \sum_{i=0}^{a-1} \binom{N_{su} - 1}{i} \left( \frac{N_w R^2}{2L_t} \right)^i \left( 1 - \frac{N_w R^2}{2L_t} \right)^{N_w - 1 - i} \right] + \sum_{i=\alpha}^{N_{su} - 1} \binom{N_{su} - 1}{i} \left( \frac{N_w R^2}{2L_t} \right)^i \left( 1 - \frac{N_w R^2}{2L_t} \right)^{N_w - 1 - i} \right]
$$

(5-1)

Figure 5-1 depicts the bit error rate as a function of the threshold value for a specific set of parameters. The bit error rate is minimized at a threshold value greater than the
code weight. The results indicate that, when multiple-access interference is high, a substantial improvement in BER performance can be achieved by treating the threshold value as a free parameter to be chosen optimally.

Figure 5-1 Existence of an optimum threshold value. The bit error rate of a MPR code with a total spreading factor S of 5000 and a weight of 70 supporting 120 users is minimized by choosing a threshold value of 94 instead of the conventionally-chosen 70.

In Equation (5-1), the probability of false dismissal and false alarm correspond to two disjoint regions under the same binomial distribution. These two regions are separated by a distance equal to the code weight $N_{u}R$ as shown in Figure 5-2.

Figure 5-2 Bit error rate for different choices of threshold values (a) probability of false alarm and (b) probability of false dismissal dominates. The bit error rate is given by the total of the shaded areas.

In order to minimize the total probability of error, it is necessary to minimize the sum of the probability of false dismissal and false alarm. This is equivalent to minimizing
the total shaded areas under the binomial distribution curve. In the high MAI regime\(^2\), the binomial distribution approaches the symmetric shape shown in Figure 5-2. With all other parameters held constant, varying the threshold value is equivalent to sliding along the horizontal axis a blank column with a fixed width equal to the code weight \(N_w R\). The goal is to maximize the area covered by the fixed width column so that the area covered by the probability of false dismissal and false alarm is minimized. This is achieved by centering the column about the mean of the binomial distribution as shown in Figure 5-3. With the mean of the binomial distribution given by:

\[
m = \left( N_{su} - 1 \right) \left( \frac{N_w \cdot R^2}{2L_t} \right)
\]  

(5-2)

the optimum threshold value is then given by:

\[
\alpha_{opt} = m + \frac{N_w R}{2} = \frac{N_w R}{2} \left( \frac{N_{su} \cdot R}{L_t} + 1 \right)
\]  

(5-3)

The value of the threshold \(\alpha\) should never be set below the code weight \(N_w R\). \(P(\text{error}|1)\) is identically zero for \(\alpha \leq N_w R\). Since \(P(\text{error}|1)\) remains zero for \(\alpha \leq N_w R\), whereas \(P(\text{error}|0)\) increases, setting the threshold value below the code weight can only increase the total probability of error. The optimum threshold value which minimizes the total probability of error is given by:

\[
\alpha_{opt} = \begin{cases} 
    m + \frac{N_w R}{2} = \frac{N_w R}{2} \left( \frac{N_{su} \cdot R}{L_t} + 1 \right), & \frac{N_{su} \cdot R}{L_t} \geq 1 \\
    N_w R, & \frac{N_{su} \cdot R}{L_t} < 1
\end{cases}
\]  

(5-4)

\(^2\) A large user population is generally required to sustain operation in high MAI regime. The number of users required could exceed the cardinality of some codes such as the T/S AML and WH/TS codes. Fortunately, the cardinality of such codes can be dramatically increased by performing cyclic shifts in the wavelength domain [77].
Figure 5-3 Bit error rate at the optimum threshold value. The blank-out area is placed in the center of the binomial distribution to achieve a minimized bit error rate. The bit error rate is given by the total area of the shaded area.

Treated as a continuous parameter, the optimum threshold value need no longer be an integer as was the case when it was set equal to the code weight.

Equation (5-4) suggests that O-CDMA operation is divided into two regimes: a heavy traffic regime corresponding to \( \frac{N_{su} \cdot R}{L_t} \geq 1 \) and a low traffic regime corresponding to \( \frac{N_{su} \cdot R}{L_t} < 1 \). In the heavy traffic regime, optimum threshold detection (OTD) may be used to minimize the BER. In the low traffic regime, the threshold is best set at the code weight.

5.2.2. Simplified Code Design Methodology

The selection of code and system parameters in MW-O-CDMA networks is a difficult multi-variable problem in view of the interdependencies among parameters in Equation (3-4). The design process is often iterative and involves intensive numerical computation which is time-consuming and may fail to provide intuitive insight into the generalized code design problem.

In this section, it is demonstrated that not only is system performance greatly improved, but the code design problem is also greatly simplified, if the system employs optimum threshold detection.
The Equation (5-1) for the BER can be simplified with the help of the Central Limit Theorem [76]. At the optimum threshold, the probability of false dismissal equals the probability of false alarm and the bit error rate becomes:

\[
BER = \frac{1}{2} [P(\text{error} | 1) + P(\text{error} | 0)] \\
= P(\text{error} | 1) \\
= \sum_{i=0}^{N_{su}-1} \binom{N_{su}-1}{i} \left( \frac{N_w \cdot R^2}{2L_1} \right)^i \left( 1 - \frac{N_w \cdot R^2}{2L_1} \right)^{N_{su}-1-i}
\]  

(5-5)

The mean and variance of this binomial distribution are given by:

\[
m = (N_{su} - 1) \left( \frac{N_w \cdot R^2}{2L_1} \right)
\]  

(5-6a)

\[
\sigma^2 = (N_{su} - 1) \left( \frac{N_w \cdot R^2}{2L_1} \right) \left( 1 - \frac{N_w \cdot R^2}{2L_1} \right)
\]  

(5-6b)

A Gaussian approximation of Equation (5-1) can then be obtained using the Central Limit Theorem when the number of simultaneous users \(N_{su}\) is sufficiently large that \(N_{su} - 1 \approx N_{su}\),

\[
BER \bigg|_{\text{approx}} = \frac{1}{\sqrt{2\pi} \sigma_{approx}} \int_{-\infty}^{\infty} e^{-t^2/2\sigma^2} dt \\
= Q \left( \frac{\alpha_{opt} - m}{\sigma} \right) \\
= Q \left( \frac{N_w R/2}{\sigma} \right) \\
= Q \left( \sqrt{N_{su} N_w R^2 \frac{1 - N_w R^2}{2 \cdot L_1}} \right) \\
= Q \left( \frac{\sqrt{N_{su} N_w R^2 \left( 1 - \frac{N_w R^2}{2 \cdot L_1} \right)}}{2 \cdot L_1} \right)
\]

(5-7)

where \(Q(\bullet)\) is the \(Q\)-function [76] defined as:
Equating the parameters in the $Q$-function in the last two steps of Equation (5-7) allows solution for the number of simultaneous users:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-u^2/2} du$$  \hspace{1cm} (5-8)

This is the number of simultaneous users a network with optimum threshold detection can support while satisfying constraints imposed by other parameters including the bit error rate (given by $Q^{-1}(BER)$) and user data rate (given by $B_e / L_r$). A simple expression for $N_{su}$ is obtained from Equation (5-9) when $1 - N_{w}R^2 = \frac{1}{2}$. With this observation, the following set of equations is produced:

$$\omega T L_r = N_{w} \cdot R^2 = W \cdot R \hspace{2cm} (5-10a)$$

$$\omega T S = N_{w} \cdot L_r = (N_{w} \cdot R)^2 = W^2 \hspace{2cm} (5-10b)$$

$$\omega T N_{su} = \frac{W^2}{P^2} = \frac{S}{P^2} \hspace{2cm} (5-10c)$$

$$\alpha_{opt} = \frac{W}{2} \left( \frac{N_{su} \cdot W}{S} + 1 \right) = \frac{W}{2} \left( \frac{W}{P^2} + 1 \right) \hspace{2cm} (5-10d)$$

where $W$, the code weight, is equal to $N_{w}R$ and the superscript $OT$ emphasizes the fact that these expressions are direct consequences of optimum threshold detection.

Spectral efficiency, defined as the ratio of information rate to total bandwidth consumed, can be obtained from Equation (5-10):

$$\eta = \frac{Total \ Information \ Rate}{Total \ Bandwidth} = \frac{N_{su}}{N_{w} \cdot L_r} = \frac{1}{p^2} \hspace{2cm} (5-11)$$

The spectral efficiency of MPR codes at optimum threshold is constant once the desired bit error rate is specified.
If $B_e$ represents the rate at which chips can be sent using the available hardware, the temporal spreading factor $L_t$ is then tied to the individual user data rate according to:

$$\text{User Data Rate} = \frac{\text{Electronic Processing Rate}}{\text{Temporal Spreading Factor}} = \frac{B_e}{L_t}$$  \hspace{1cm} (5-12)

Equation (5-10) reduces the complex interdependencies of the system and code parameters into a set of simple relationships. In a deployment-oriented network design problem, each parameter can be completely specified with the knowledge of bit error rate, number of simultaneous users, and user data rate, as illustrated in Figure 5-4.

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th>Optimized Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{su}$</td>
<td>$p = Q^{-1}(BER)$</td>
</tr>
<tr>
<td>BER</td>
<td>$L_t = \frac{\text{Electronic Rate}}{\text{Data Rate}}$</td>
</tr>
<tr>
<td>Data Rate</td>
<td>$\sigma_r S = N_{su} p^2$ by (5-10a)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_r W = \sqrt{S}$ by (5-10c)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_r R = \frac{L_t}{W}$ by (5-10b)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_r N_{w} = \frac{W}{R}$ by (5-10b)</td>
</tr>
</tbody>
</table>

Figure 5-4 System and code parameter selection procedure.

### 5.3. Performance Enhancement I: Network Capacity and Efficiency

#### 5.3.1. Cardinality

In a bursty traffic environment such as a LAN, the total number of subscribers is often much larger than the number of simultaneous users $N_{su}$. A large number of network addresses, hence cardinality $|C|$, is desired so that services may be available to a population which is larger than the number of active users at any given time. Under such conditions, the benefits of statistical multiplexing become apparent.

Two-dimensional (2-D) codes with improved cardinality have recently been proposed [28, 30]. These reported cardinalities nevertheless remain low, limiting the size of such networks and confining their operation to the low traffic regime. In this regime, the
system cannot take advantage of OTD – without increased cardinality, the efficiencies in resource utilization made possible in this work are not accessible.

In the present work, a new method is proposed and analyzed by which to increase the cardinality of existing codes by a factor of between two to three. This method involves first performing cyclic wavelength shifting (CWS) to produce more codeword candidates. Qualified codewords are then selected based on their correlation properties – the satisfaction of auto- and cross-correlation constraints among all codewords. The idea of cyclic wavelength shifting was first introduced in [77], however, the code selection procedure was not performed to ensure that all of correlation properties were indeed satisfied.

In CWS, $N_w - 1$ groups of codewords are produced by the cyclic shift. Codewords within each group satisfy the correlation constraints of the original set. However, the correlation properties of the cyclically derived code sets are not guaranteed to be equivalent to those of the original code set. As a final step in this scheme, the augmented set of codewords is produced by selecting codewords from each group that satisfy the cross-correlation constraints of the codewords in the original code set. Figure 5-5 illustrates an example of the process of forming an augmented set using CWS. A 3x3 T/S AML original code set, comprised of two codewords, is used. Two more groups of two codewords are produced using cyclic shifting. Within the two new groups of codewords, one satisfies the cross-correlation constraint of the codewords in the original set. This codeword is selected to form an augmented set, increasing the cardinality to three.
Figure 5-5 Achieving higher cardinality by wavelength cyclic shifting. An example of a 3x3 T/S AML code set is used. The cardinality is increased from 2 to 3.

On a more realistic scale, cyclic shifting improves cardinality of 2-D codes by a factor of two to three. Figure 5-6 depicts the improvement of cyclic shifting on the cardinalities of the WH/TS and T/S AML codes.

Figure 5-6 Improvement of cardinality by wavelength cyclic shifting.

The cardinalities of the WH/TS and T/S AML codes before the application of WCS are depicted using the red traces in Figure 5-6. After the application of WCS, the codewords
that fail the correlation constraints are rejected. The remaining codewords form the final code sets whose cardinalities are depicted using the blue traces in Figure 5-6. These new network addresses allow O-CDMA systems to admit more service subscribers and to operate in the high traffic regime, thus enabling performance optimization via OTD.

5.3.2. Spectral Efficiency

In a multiple-access local area data network, spectral efficiency impacts the per-user communication rate, the number of users allowed on the network, and consequently the per-user cost of the system. Spectral efficiency may be defined as the ratio of information rate to total bandwidth consumed:

$$\eta = \frac{\text{Total Information Rate}}{\text{Total Bandwidth}} = \frac{N_w \cdot B_e / L_t}{N_w \cdot B_e} = \frac{N_w}{N_w \cdot L_t}$$

(5-13)

where $B_e$ is the electronic processing rate of the system. The spectral efficiency is a combination of two conventional performance figures of merit: network capacity – the number of simultaneous users $N_{su}$ – and system throughput – the inverse of temporal length $1/L_t$. The spectral efficiency may be improved by increasing either or both of these parameters.

Extensive research has been conducted into improving different aspects of O-CDMA systems. Surprisingly, spectral efficiencies of all such systems remain poor – on the order of a few percent. This comes despite the fact that the Shannon capacity of the optical channel, if suitably deployed, is very high.

Table 5-1 lists the spectral efficiencies for different O-CDMA codes [78]:

| Family  | Code   | Temporal Length ($L_t$) | # Wavelength Channels ($N_w$) | Cardinality ($|C|$) | Spectral Efficiency |
|---------|--------|-------------------------|-------------------------------|---------------------|---------------------|
| ooc     | Ooc    | $N=961$                 | 1                             | $(N-1)w(w-1)+l=17$  | 1.77%               |
| Block   | Prime  | $P_w=961$               | $l$                           | $p=31$              | 3.22%               |
| Block   | Eqc    | $P(2p-1)=1035$          | $l$                           | $p-1=22$            | 2.13%               |
| $2^p$   | Modpr  | $N=961(p=31)$           | $l$                           | $<p-2=27$           | 2.81%               |
| $2^p$   | Bmcoe  | $N=960$                 | $l$                           | $(N-w)w(w-1)+l=18$  | 1.88%               |
| 2D      | WH/TS  | $p^1=961$               | $p=31$                        | $p(p-1)=930$        | 1.79%               |
| 2D      | T/S AML| $p^1=179$               | $p^2=163$                     | $p^2-1=162$         | 0.84%               |

Table 5-1 Spectral efficiencies of O-CDMA codes [78].
Motivated by these disappointing spectral efficiencies, two new schemes—dynamically optimized threshold detection and forward error correction—are proposed in Sections 0 and 0 to improved spectral efficiency of O-CDMA networks. It is shown that these two schemes may be combined to increase dramatically the spectral efficiency of such systems.

**Optimum Threshold Detection**

Aided by the code design algorithm proposed in 5.2.2, the performance of WH/TS [28] and T/S AML [30] codes using conventional threshold detection is now compared with the performance of MPR codes using OTD.

![Figure 5-7 Spectral efficiency comparison between WH/TS [28] and T/S AML [30] codes with conventional threshold detection; and MPR codes using OTD.](image)

Figure 5-7 indicates that MPR codes with OTD sustain a higher constant spectral efficiency than the diminishing spectral efficiencies of the WH/TS and T/S AML codes. These follow a highly nonlinear multi-variable relationship, whereas the spectral efficiencies of the code with optimum threshold detection is only a function of the bit error rate, as derived in Section 5.2.1:

\[ \eta = p^{-2} \quad (5-14) \]

Equation (5-14) is conceptually consistent with the general information theory result that the most efficient use of the multiple-access channel is achieved not by creating
many orthogonal or nearly-orthogonal sub-channels, but by having every user superimpose its signal onto one channel and having a decorrelator determine the single hypothesis which could yield the measured superposition of signals [79]. This result underscores the value of forward-error correction (FEC) in allowing a desired error rate to be achieved while simultaneously drastically improving spectral efficiency [80].

**Shannon Capacity and Forward Error Correction**

Using OTD, the transition probabilities from “1 to 0” and “0 to 1” are equalized. The resulting system presents a binary symmetric channel (BSC). The Shannon channel capacity is then given by [81]:

\[ C = 1 + P_e \log_2 P_e + (1 - P_e) \log_2(1 - P_e) \]  

(5-15)

where \( P_e \) is the transition probability from 1 to 0 or 0 to 1 – in this case equal to the BER.

Knowledge of the channel capacity enables the determination of the minimum redundancy required to achieve arbitrarily error-free communication. For instance, since \( P_e=10^{-3} \) yields \( C = 0.989 \), an optimal coding scheme could allow 0.989 bits/sec to be transmitted with arbitrarily low probability of error. In this case, the redundancy is \( (1-C) = 0.011 \) bits/sec. For the purposes of this work, this redundancy is associated with the overhead of the *best-case Error Control Code (ECC)* – it represents a lower bound on the redundancy needed to achieve arbitrarily low error rate transmission given the raw error rate. In this idealization, the spectral efficiency is given by:

\[ \eta_{FEC} = \frac{N_{in} \cdot B \cdot C}{N_w \cdot \Omega} = \frac{C}{p_d^2} \]  

(5-16)

where \( B \) is the user data rate, \( C \) is the channel capacity in Equation (5-15), and the subscript ‘FEC’ denotes the use of the best-case ECC. \( p_d \) in Equation (5-16) becomes the inverse Q-function evaluated at the raw BER, since the corrected BER is intended to be made arbitrarily small. Equation (5-16) provides the upper bound of the achievable spectral efficiency with FEC. Real FEC techniques are necessarily imperfect, though codes have been found which approach the Shannon limit within 1 dB [82].
For the sake of practicality, system spectral efficiency is considered not only in the best case, but also using real, deployable, known ECCs. This consideration is carried out in the context of the flexible BCH family of codes [83], a generalization of the Hamming codes, which are readily designed and implemented. A block length of $n=511$ is used, allowing correction of up to 121 bit errors in each frame. This is sufficient for the present discussion in which the raw BER ranging between $\{10^{-1} \text{ to } 10^{-9}\}$ is to be corrected to a final value of $10^{-9}$. With the use of BCH code, the spectral efficiency is given by:

$$\eta_{BCH} = \frac{N_w \cdot B \cdot R}{N_w \cdot \Omega} = \frac{R}{P_d^2}$$

(5-17)

where $R$ is rate of the code.

![Figure 5-8 Spectral Efficiency of MW-O-CDMA system with OTD and FEC.](image)

The achievable spectral efficiencies with no FEC, idealized FEC, and BCH codes are depicted in Figure 5-8. The system without FEC achieves high spectral efficiency as the BER degrades. At the other raw BER extremum of $10^{-9}$, a disappointing bandwidth utilization of a few percent, consistent with Table 5-1, is obtained. With the best-case ECC, a much improved spectral efficiency is achieved with an arbitrarily low corrected error rate when a high raw BER is allowed. More practically, when BCH codes are used to transform raw BERs ranging between $\{10^{-1} \text{ and } 10^{-9}\}$ down to a final BER of $10^{-9}$, the spectral efficiency achieves its peak for a design BER of $10^{-2}$. Using a realizable forward error correction scheme, a corrected BER of $10^{-9}$ is achieved with four times higher
spectral efficiency than if the same error rate were achieved purely by MAI suppression of the raw BER.

As shown in Section 5.2.1, the number of simultaneous users admitted, given by:

$$N_{su} = \frac{N_w L_c}{2 \cdot p^2 \left(1 - \frac{N_w R^2}{2 \cdot L_c}\right)}$$

is also influenced by the choice of raw BER for which the system is designed – the number of allowable simultaneous users increases as a higher design BER is permitted. This effect is illustrated in Figure 5-9. With 4 wavelength channels, a temporal spreading factor of 500, and a single-pulse-per-row, the system allows 179 simultaneous users at a 10^{-2} design BER. Only 27 users are allowed at a 10^{-9} design BER.

The preceding result, in focusing exclusively on MAI, neglects an essential consideration: the number of allowable simultaneous users is also limited by the cardinality of the code. In a LAN with bursty traffic, the number of subscribers should be much larger than the number of active users, i.e. |C| >> N_{su}. This requirement may necessitate the use of a large temporal spreading factor. In the preceding example, |C| = 500, and the cardinality greatly exceeds the MAI-limited number of simultaneous users able to share the channel with a raw BER of <10^{-1}.

![Figure 5-9 Choice of number of simultaneous users achieved through raw BER design.](image)
5.4. Performance Enhancement II: Real-time Self-Optimizing Traffic Adaptation

Despite a significant and growing body of literature on the subject of performance optimization in 2-D multi-wavelength CDMA codes, there remain a number of key unanswered questions regarding the adaptability and deployment of prospective systems:

- Is performance preserved in the presence of inevitable fluctuations in traffic level? Previous proposed O-CDMA systems performance analyses and optimizations [10, 14, 16, 20, 23, 37, 50, 68, 78, 84, 85], including the OTD scheme presented in the Section 5.3, assume a static network environment. Optimization is not always achievable in LANs, which have time-dependent heterogeneous traffic demands. A scheme for true real-time optimization has yet to be developed.

- Can networks scale to accommodate a large and long-term change of user population and resource demands? For example, do proposed schemes lend themselves to scaling to larger user populations without complete replacement of transceiver hardware? Networks with specific code sets and transceiver hardware can only maintain desirable performance over a certain range of traffic conditions. A scheme for dynamic scalable network operation is needed in a fixed hardware environment for cost-effective deployment.

A truly adaptive reconfigurable system must be able to accommodate a variable number of users (perhaps corresponding to changing traffic patterns) given a fixed physical infrastructure (e.g. number of wavelength channels).

In response to these issues and opportunities, a real-time adaptive scalable network operation is devised. Adjustment is made such that an acceptable BER is always maintained while maximizing network resource utilization (e.g. maximizing number of simultaneous users). Traffic adaptation is divided into two classes: small- and large-scale adaptation responsible for small- and large-scale change in network activity. Each adaptation scheme is enabled by an addition to the conventional receiver and transmitter design. The system is assumed to have fixed hardware capabilities:

1. Fixed number of optical wavelength channels, $N_w$;
2. Fixed parallel processing speeds at the encoders and correlators.

These are complemented by flexible software-selectable code characteristics:

1. Software-selectable time-spreading (number of chips per bit);

2. Software-selectable code weight.

In addition, for ease of illustration, all users are assumed to transmit at the same data rate. The change in traffic loads is therefore characterized by the change in the number of active users.

5.4.1. Small-Scale Adaptation

During small-scale adaptation, the code set in use is not changed. This minimizes system response time, making real-time adaptation possible while maintaining a constant user data rate. This implies, however, that the signal-to-noise ratio among users is not changed. An intelligent detection scheme is therefore needed to handle performance optimization in response to a small change in network activity. Optimum threshold detection is the natural choice for such a task.

The deployment of optimum threshold detection allows the network to maintain optimal operation under varying traffic conditions without modification to the code set in use. According to Equation (5-4), the optimum threshold value depends only on the number of simultaneous users on the network given a particular code set. The number of simultaneous users can be inferred from the total average power – a quantity which increases in proportion with the number of users transmitting simultaneously. Figure 5-10 illustrates a novel receiver design capable of implementing dynamic optimum thresholding.
Figure 5-10 A receiver design using real-time threshold optimization.

The lower arm of the receiver is a conventional O-CDMA receiver using correlation detection. The noise-like multi-wavelength signal is de-spread by the correlator and the energy of the de-spread pulse is then measured using a photodetector. A binary decision as to the received bit is based up on the pulse’s energy compared with the threshold level.

Dynamic optimum threshold detection is realized by the addition of the upper arm to the conventional receiver design. A photodetector is used to measure the total optical power summed over all wavelength channels [61]. This signal is then processed by a low-pass filter to eliminate short time-scale fluctuations. The average optical power is used to compute the optimum threshold level to be used by the threshold element. Both the optimum threshold computation circuitry and the threshold element can be easily implemented with electronics running at the bit rate.

5.4.2. Large-Scale Adaptation

In the event of a surge in network activity which causes network performance to become unsustainable using the existing code, a new code set with larger capacity must be employed. By the same token, in the event of a large decline of network activity, a new code set with appropriate capacity can be deployed to reallocate resources efficiently.

In a system with fixed physical infrastructure (e.g. number of wavelength channels), code length and code weight are natural choices of free parameters. As such, optimization
through the reallocation of resources takes the form of variation in the user data rate; user rate and network capacity are exchangeable.

Near-instantaneous reconfiguration can be achieved by a modification to the transmitter design. A memory look-up table (LUT) approach is proposed to realize such a scheme. A schematic of such a transmitter design is depicted in Figure 5-11.

![Diagram of transmitter design for adaptive self-optimizing networks.](image)

Figure 5-11 A transmitter design for adaptive self-optimizing networks.

As in the case of small-scale adaptation, the average optical channel power, measured by a photodetector and a lowpass filter, is used to estimate the level of network activity. If the network activity falls outside of the range of efficient resource utilization for the current code set, a new optimal code set is used. The switching operation involves associating the code selection logic with a new set of codes from a code set library, a collection of code sets optimized under a wide range of traffic conditions, pre-programmed in a fast memory module. Figure 5-12 shows a schematic representation of a code set library. The switching can be completed on the order of milliseconds\(^3\), as it only involves changes of a few electronic connections between the code selection logic and the code set library.

---

\(^3\) The switching time across the entire network could be longer as the response time of each node may vary due to variations in geographic separation.
Figure 5-12 Code set library — a fast memory module pre-programmed with code sets optimized for different level of network activity.

5.4.3. Combining the Small- and Large-scale Adaptations

In a real system, the small- and the large-scale adaptations can be combined to provide scalability and adaptability to a wide range of traffic conditions. Traffic conditions - as characterized by the number of simultaneous users - can be used to divide network activity into different levels, as shown in Figure 5-13. At each network activity level, a code set is assigned to ensure the efficient use of resources and guarantee that the BER can be sustained within an acceptable range. Within each level, OTD ensures that performance is optimized and resources are efficiently employed. As network activity deviates from the capacity limits of the current code set, the system switches to a new region of operation in which a new code set is employed.

![Figure 5-13 Full-scale traffic conditions adaptation.](image-url)
5.5. Summary

Prior to this work, spectral efficiencies of both predicted and demonstrated O-CDMA systems had been extremely low, on the order of a few percent. All network operations were inflexible and not reconfigurable. It was sought in this chapter to find ways to improve the spectral efficiency in MW-O-CDMA networks and to enable real-time self-optimizing adaptability.

The first step in this chapter was to focus on cardinality. It was shown for the first time that cardinality can be increased by a factor of two to three through the combination of cyclic wavelength shifting and code selection based on the correlation properties.

These dramatic improvements in cardinality made it possible to consider optimum threshold detection. It was shown that in the high traffic regime, OTD allows the use of a simplified network design algorithm, eliminating the need for computationally intensive operations. In conjunction with forward error correction, OTD increases the spectral utilization by as much as a factor of four.

The innovation and exploration of OTD led to the possibility of real-time, self-optimizing, adaptive network operation. Network performance is continuously optimized through real-time adjustment of the threshold value in response to changes in traffic conditions. While this mechanism responds well to small-scale fluctuations in traffic demands, a second mechanism is used for adapting to larger traffic fluctuations. In code set switching, each transmitter is equipped with a code set library in anticipation of a wide range of traffic demands. The two mechanisms work in tandem to provide seamless, adaptive, optimal operation.
CHAPTER

6. Temporal Skewing: Chromatic Dispersion in MW-O-CDMA Systems

6.1. Introduction

Chromatic dispersion describes the phenomenon in which the group velocity of propagation of an electromagnetic wave is a function of wavelength. Dispersion is responsible for the temporal widening of an optical pulse as it propagates over a long distance in an optical fibre system. This limits the bit-rate-distance product of conventional long-haul high bit-rate systems.

In short-distance local area networks, chromatic dispersion poses a new threat to MW-O-CDMA systems: temporal skewing. Unlike in WDM systems, the decoding operations in MW-O-CDMA systems are sensitive to the relative temporal position of optical pulses transmitted along wavelength channels simultaneously. Chromatic dispersion will result in relative temporal shifts of the optical pulses in different wavelength channels, destroying the rectangular structure of MW-O-CDMA signature patterns. The resulting temporal skewing of the MPR code is depicted in Figure 6-1. A natural consequence of this distortion of the signature pattern is a higher rate of errors following the decoding operation.
The adverse effects of chromatic dispersion in single-wavelength O-CDMA systems have been studied in the context of inter-symbol interference [86], pulse width and peak power limitation [87], and pulse distortion [88]. Compensation schemes [87, 89, 90] in coherent and spectral encoding O-CDMA systems have been proposed. It is shown in [91] that this pulse broadening effect is less severe in such systems and may even be avoided in incoherent systems by using a time slot longer than the dispersion-induced broadening time.

The consequences of temporal skewing in multi-wavelength systems, though certainly detrimental to the performance of hybrid O-CDMA networks, have not been examined in the literature.

Practical solutions to the detrimental impact of temporal skewing are investigated and proposed in this chapter. A generalized exploration is launched for MW-O-CDMA LANs operating in the low traffic regime as defined in Chapter 5. The quantitative effects of temporal skewing on such systems are investigated in Section 6.2 and a qualitative explanation is obtained. Two novel methods aimed at combatting the temporal skewing effects of chromatic dispersion are proposed in Section 6.3.

6.2. Impact of Dispersion on MW-O-CDMA Systems

6.2.1. Fundamentals

While temporal skewing and pulse broadening are both symptoms of chromatic dispersion, they differ significantly in the manner in which they degrade system performance. Pulse broadening introduces transmission error via inter-symbol
interference (ISI) – overlapping of pulses due to temporal broadening. In contrast, temporal skewing introduces transmission errors via code pattern distortion – destruction of the rectangular code pattern.

To facilitate further discussion, the following parameters are defined:

- **Adjacent channel temporal skew, $\Delta \tau [\text{ps}]:$$\Delta \tau = |D_{\lambda}| \cdot \Delta \lambda \cdot L \quad (6-1)$

$D_{\lambda}$ is the dispersion parameter of single-mode fibres, for which typical values are 16 ps/km-nm for standard telecom fibre and 2 ps/km-nm for dispersion-flattened fibre at telecom wavelength of 1.55 $\mu$m [61]; $\Delta \lambda$ is the adjacent channel spacing, for which typical values are 0.8 nm or 1.6 nm for standard 100 GHz and 200 GHz channel spacing systems respectively; and $L$ is the geographical span of the network which is usually no greater than 2 km for LANs.

- **Normalized adjacent channel skew, $S_{AC} [\text{chips}]:$$S_{AC} = \frac{\Delta \tau}{T_c} \quad (6-2)$

$T_c$ is the temporal width of chip pulses, ranging from the picoseconds to the tens or even hundred of picoseconds in the systems under consideration. Normalized adjacent channel skew is a universal parameter which describes the relative temporal shifting of two adjacent channels. It is a measure of the number of chips, by which pulses in adjacent wavelengths are shifted in time.

- **Normalized total system skew, $S_T [\text{chips}]:$$S_T = S_{AC} \cdot N_w \quad (6-3)$

Normalized total system skew is a generalized parameter which incorporates the dependence on the number of wavelength channels to provide an overall measure of the amount of skew of a signature code. This allows a direct comparison among systems with different numbers of wavelength channels.

A schematic illustration of the above parameters is provided in Figure 6-2.
In the analysis which follows, attention is focussed on the behaviour and impact of temporal skewing in the low traffic \( \frac{N_{\text{tu}} R}{L_i} < 1 \), low dispersion \( S_T < 1 \) regime, one of the useful deployment regimes of MW-O-CDMA LANs.

### 6.2.2. Dispersion Resistance: Characteristics of Systems and Codes

It is clear from equations (6-1) to (6-3) that several system parameters may be adjusted to minimize the undesirable effects of temporal skewing. To render a system less vulnerable to skew due to dispersion, it should have chips with large temporal chip width, tight channel spacing, small fibre dispersion parameters, and a small number of wavelength channels. Many of these parameter choices are in direct conflict with network capacity requirements and practicality of implementation. In systems intended to support large user populations, a large spreading factor is necessary. This necessitates codes with many wavelength channels or time chips. For a given data rate requirement and electronic capability, long code lengths can only be realized through shorter pulse duration. Tighter channel spacing relies on better wavelength stabilization and filtering, both of which are difficult and expensive to implement. Finally, a small but non-zero dispersion parameter (e.g. 2 ps/km-nm) may be needed. However, if nonlinearities are an issue in the system in view of the high optical powers co-propagating at points in the network, local walk-off due to chromatic dispersion may be desired. For these reasons, it is essential to develop alternative means of combating the deleterious effects of temporal skewing.
Zero-dispersion analysis revealed in Chapter 5 that the BER is dictated by the signature pattern correlation properties: a high auto-correlation peak and low cross-correlation and shifted auto- and cross-correlation for improve performance. Similarly, skewed correlation properties determine the BER under the effect of dispersion. Figure 6-3 depicts the evolution of the non-shifted auto-correlation and shifted cross-correlation with increasing dispersion.

Figure 6-3 Skewed auto-correlation in (a) and cross-correlation in (b). In (b), the expected values of cross-correlation are plotted. The variances of cross-correlation are represented using error bars. The parameters chosen for the two code families are: WH/TS \(N_a=5, L_t=25, R=1, N_m=8\) and T/S AML \(N_a=5, L_t=19, R=1, N_m=9\)\).

As illustrated in Figure 6-3 (a), the skewed auto-correlation peaks of the T/S AML and WH/TS codes follow an identical trend under low traffic conditions. This trend, to be exploited later in greater detail, suggests that, to optimize performance, a dynamically-adjusted threshold level at the receiver will be required. The stochastic nature of the system is revealed in the indeterminism of the cross-correlation, as shown in Figure 6-3 (b). In order to relate the skewed correlation properties to BER performance, a signal-to-interference ratio (SIR) is defined. The signal power is associated with the peak auto-correlation and the interference power is associated with the expected values of the cross-correlation from all the interferers. The SIR may the be expressed as:

\[
SIR = \frac{AC - E[MAI]}{VAR[MAI]} \tag{6-4}
\]

where \(AC\) is the auto-correlation peak; and \(E[MAI]\) and \(VAR[MAI]\) are the expected value and variance of the MAI, respectively, which are given by:
In the Gaussian approximation for the MAI and the assumption of equiprobable data, the BER of the system is given by:

\[ BER = \frac{1}{2} Q\left(\sqrt{SIR}\right) \]  

where \( Q(x) \) is the Q-function as defined in Equation (5-4). Figure 6-4 illustrates the BER of T/S AML and WH/TS codes as predicted using Equation (6-7)\(^5\). The error performance of each code monotonically increases with dispersion, and the WH/TS code exhibits more dispersion-resistance according to Equation (6-7).

By virtue of the use of the generalized parameter \( S_T \), the results depicted in Figure 6-4 may be employed to gauge the relative performance of several systems each employing different parameters for dispersion coefficient, number of wavelength channels, and geographic span.

---

4 The parameter \( N_{su} \) is included for the purpose of simulation. It is not needed in the calculation.

5 The validity of the Gaussian approximation increases with the traffic level. In the low traffic regime under consideration \( N_{su}/L < 1 \), this Gaussian approximation could deviated from the simulated results by as much as two orders of magnitude. Nevertheless, the results shown here predict the general trend of the BER performance of the system.

6 Equation (6-7) assumes the auto-correlation peak as the threshold value. This may be revealed readily by comparing Equation (6-7) to the Q-function described in Equation (5.4).
6.3. Combating the Effects of Dispersion

In high-speed long-haul systems, dispersion is countered through electronic regeneration, pre-chirping, pulse compression using FBGs, and phase conjugation [61]. Such methods aim to restore signal integrity at the pulse level. In LANs, however, this pulse broadening effect is less severe and is overshadowed by the performance degradation engendered by temporal skewing. In this section, two new methods are proposed to combat the degradation due to temporal skewing.

6.3.1. Optimum Threshold Detection

According to the theory developed in Section 5.2, in the absence of dispersion the optimum threshold level should be set to the code weight in the low traffic regime. Under the influence of temporal skewing, however, the auto-correlation peak decreases with dispersion. The threshold value must be decreased accordingly: it should be set equal to the effective code weight – the skewed auto-correlation peak.

An analytical expression for the optimum threshold value under low traffic and low dispersion conditions can be derived, to a first approximation, by considering the value of the skewed auto-correlation peak. Temporal skewing distorts the temporal relationship among pulses in different wavelength channels within a code pattern. This effect translates into a decrease in the auto-correlation peak at the receiver during correlation detection, as depicted in Figure 6-5.
Figure 6-5 Correlation detection under the effects of temporal skewing.

The value of the zero-dispersion, or non-skewed, auto-correlation peak is the code weight $W$, which is equivalent to the sum of the red squares in Figure 6-5. The value of the skewed auto-correlation peak, which is equivalent to the sum of the purple squares, given by:

$$
T^{S} \alpha_{opt} = \text{code weight (red squares)} - \text{spilled energy (blue squares)}
= W - (R \cdot S_{AC} + 2 \cdot R \cdot S_{AC} + 3 \cdot R \cdot S_{AC} + \ldots + (N_{w} - 1) \cdot R \cdot S_{AC})
= W - \frac{(N_{w} - 1) \cdot N_{w}}{2} R \cdot S_{AC}
$$

(6-8)

where the superscript $T^{S}$ denotes that the choice of this optimum threshold value is under the effect of temporal skewing.

As predicted by Equation (5-4), the optimum threshold value is identical to the code weight under low traffic and low dispersion conditions, in which case the level of interference is low and the total system dispersion $S_{T}$ is less than a chip. Thus, the value of skewed auto-correlation peak in Equation (6-8) is equivalent to the optimum threshold value under low traffic conditions.

Figure 6-6 shows that the optimum threshold value predicted by Equation (6-8) is indeed the skewed auto-correlation peak as depicted in Figure 6-3 (a). At very low traffic levels, Equation (6-8) predicts the simulated optimum threshold values exactly. Under higher traffic conditions, however, the simulated system performance deviates appreciably from this predicted trend. A description of the simulation methodology used in this chapter is included in Appendix II.
Figure 6-6 Theoretical and simulated optimum threshold values. Under very low traffic conditions in (a), \( \frac{N_0}{L} = 0.36 \), analytic and simulated results are in close agreement. Deviations are observed in higher traffic conditions (b), \( \frac{N_0}{L} = 0.64 \).

Using the optimum threshold value prescribed by Equation (6-8), the BER is minimized under the effect of dispersion. In particular, the BER performance of the T/S AML and WH/TS codes is depicted in Figure 6-7. The simulated BER trends follow the general shape predicted by Equation (6-7). However, the overlap of the trends for the two families of codes disagrees with Equation (6-7), which predicts a performance difference between the two code families. The simulated results are consistent with parameter selection alone – the same spreading factor, number of users and code generation algorithm (both are prime-code based) yield almost identical BER performance. On the other hand, the deviation of the predicted BER from the simulated BER can be explained by the sensitivity of the Q-function Gaussian approximation to the small differences between the skewed cross-correlation properties of the two code families.

Figure 6-7 A comparison between simulated and calculated BER.
6.3.2. Code Pattern Pre-skewing

The philosophy behind pre-skewing is similar to that of pre-chirping used in high-speed systems for pulse-shape restoration. Analogous to pre-distorting the spectral components of a pulse, pre-skewing pre-distorts the relative position of wavelength channels in time. In a given system, the amount of pre-skewing is calibrated according to the distance between the transmitter-receiver pair. In this manner, code patterns that arrive at the intended receivers are always temporally aligned, while arriving skewed at receivers that are at a different distance than the intended receiver. This concept is illustrated in Figure 6-8. The transmitter-receiver pairs \( i \) and \( k \) are separated by 200 m and 500 m, respectively.

![Figure 6-8 Pre-skewing in a star network with unequal distances among users.](image)

There is, however, a major drawback to this approach: a stringent requirement exists on control of the amount of pre-skewing. Faster-than-chip-rate electronics is needed. In light of this, the pre-skewing compensation scheme may not be practical or cost-effective. Fortunately, there is one simple and cost effective remedy to the troublesome issues of
pre-skewing different amounts for different users and pre-skewing by non-integral multiples of chips. The solution requires that all the users in the network be connected with fibre of identical length, regardless of the actual distances between transmitter-receiver pairs. The length of each fibre would be equal to the minimum distance above the maximum separation of a transmitter-receiver pair in the network that would ensure any pre-skewing to occur on a chip level. Once this length is determined, a constant amount of pre-skewing can be pre-programmed and the requirement of ultra-high-speed electronics is thus eliminated. Furthermore, with all the users connected with identical length fibres in a star topology, every code pattern arrives at every receiver temporally aligned. The operation and performance of the system is then equivalent to that of the zero-dispersion systems described extensively in preceding chapters.

6.4. Summary

This chapter presented the first analysis of temporal skewing due to chromatic dispersion in MW-O-CDMA systems. From consideration of skewed correlation properties, an intuitive qualitative explanation and a quantitative model were developed by which to predict BER degradation due to temporal skewing. These analyses provided general guidelines in system design and comparison.

Optimum threshold detection and code pattern pre-skewing were proposed as two novel schemes to alleviate the adverse effect of temporal skewing. Optimum threshold detection minimizes the BER of the system by tracking the skewed auto-correlation peaks under the effects of dispersion. Code pattern pre-skewing pre-distorts the relative temporal positions in different wavelength channels to achieve alignment at the receiver end. Under a symmetric network configuration, in which all users are connected using fibres of identical lengths, zero-dispersion equivalent performance can be achieved using code pattern pre-skewing.
7. Original Contributions: Summary, Conclusions, and Future Prospects

7.1. Original Contributions

The aim of this work was to explore and devise an efficient, dynamic, adaptive, low-latency local area data network. Explosive growth in the demand for bandwidth and connectivity create a powerful impetus for innovation in this field.

Chapter 1 revealed that optical code division multiple-access is a promising technology to enable network operation needed in the future. It could potentially enable asynchronous low-latency access with distributed intelligence.

It was seen in Chapter 2 that, while previous researchers have explored O-CDMA fundamentals such as code construction, performance analysis, and system demonstration, O-CDMA systems has yet to live up to hopes and expectations. Low efficiency, limited user population, lack of operational flexibility, and dispersion-induced temporal skewing plague this otherwise promising approach. The literature review provided in Chapter 2 revealed a tremendous opportunity: to transform O-CDMA into an efficient, cost-effective, adaptive, and practical technology. An approach was required which would link coding theory, systems analysis and design, network performance and optimization, and practicality of implementation.

The theoretical tools fundamental to this work were presented in Chapter 3. This was followed in Chapter 4 by a feasibility study of various implementation options — fibre
delay lines, fibre Bragg gratings, and optoelectronics – tailored to multi-wavelength O-CDMA. Special attention was devoted to the limitations imposed and functions potentially enabled by each implementation approach. Of the three implementation options, the optoelectronic approach was shown to be the most versatile and to allow the widest range of operation. The results of this investigation established the realizable and meaningful range of parameters on which the remainder of this work was focussed.

Efficiency and adaptability were addressed in Chapter 5. Using the cyclic wavelength shifting technique, a factor of two to three improvement to the largest allowable user population – the code cardinality – was reported. The theory of optimum threshold detection (OTD) for multi-wavelength systems was proposed and rigorously derived for the first time. The opportunities unleashed by the theory of OTD were found to be numerous and significant:

- A simplified code and system parameter selection algorithm was derived. The algorithm enables rapid parameter selection according to performance and capacity requirements such as number of simultaneous users, BER, and system throughput. The parameters selected can be used in real network implementations and numerical simulations.

- A factor of two improvement in spectral efficiency was reported with the use of OTD alone. This improvement can again be doubled when used in conjunction with forward error correction. This improvement of spectral efficiency can potentially be translated to a reduction of the per-user cost of systems of a given offered bit rate per user.

- A real-time traffic adaptive scheme was proposed based on the theory of OTD. The OTD is implemented using a simple, low-cost hardware addition to the conventional receiver. The operation of OTD is then exploited to adapt to fluctuations in traffic conditions, maintaining optimal operation at all times.

This small-scale adaptation scheme is complemented by a large-scale adaptation scheme achieved using code set switching through electronic memory look-up, resulting in seamless optimal operation.
An implementation-oriented study of the performance effects of dispersion was launched in Chapter 6. A new problem rooted in chromatic dispersion was identified: temporal skewing. An intuitive qualitative explanation and a systematic quantitative analysis introducing the concept of signal-to-interference ratio were presented to explain the performance trends of systems under such effect. Two novel dispersion-combating schemes were presented: optimum threshold detection and code pattern pre-skewing. Optimum threshold detection tracks the effective auto-correlation peak given a certain amount of dispersion in the system; in contrast, the code pattern pre-skewing scheme predistorts the code patterns temporally so that code patterns arrive perfectly aligned at the intended receiver.

7.2. List of Publications

The original research contributions of this thesis are reported in the following journals and conferences:

7.3. Future Prospects

Current trends in communication systems suggest that the ideal of ubiquitous connectivity – high capacity and reliable connection available anywhere, anytime – is within reach. Achieving this goal requires additional breakthroughs and further maturity in high-speed data networking, wireless communications, novel interface devices, and wearable computing.

This work paves the way for further development and optimization in the area of high-speed optical data networking. Topics for exploration in this area can be further classified into: device development, system design, and network and code development. A summary of these topics is presented in Figure 7-1.

<table>
<thead>
<tr>
<th>Device</th>
<th>System &amp; Network</th>
<th>Coding Theory</th>
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<tbody>
<tr>
<td>• Cost Reduction</td>
<td>• QoS Protocol</td>
<td>• Bipolar Codes</td>
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<td>• Integration</td>
<td>• MAC Protocol</td>
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<td>• Miniaturization</td>
<td>• Nonlinearities</td>
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<tr>
<td>• Speed Enhancement</td>
<td>• Dispersion</td>
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Figure 7-1 Topics for further exploration.

7.3.1. Device Development

Cost-appropriateness is a necessary condition for proliferation of a given technology in a given application. Most current implementation schemes for the use of light in LANs do not satisfy this criterion. New, economically mass-producible devices are needed. These cost savings may come in the form of new material, better engineering design, or improvements in the manufacturing process.

Compact integration of large-scale circuitries allows cost reduction in inventory control and parts assembly, thereby increasing market penetration. High-speed connectivity to desktop, and even to palmtop, will be possible. Currently, integration and interconnection of photonic devices are performed by V groove aligned fibre interconnection [92], which is labour-intensive and involves precise alignment. New
manufacturing processes should be developed and applied in order to allow seamless integration and automated manufacturing. Once integration techniques are in place, O-CDMA transceivers-on-a-board or even transceivers-in-a-chip will be readily realizable, making O-CDMA a natural successor of gigabit Ethernet.

### 7.3.2. System Design

Current development of O-CDMA systems is focussed on the physical and optical layers. Protocols need to be developed to regulate the use of network – media access control (MAC) – and to guarantee the quality of transmission – quality of service (QoS).

To ensure the practicality and implementability of O-CDMA systems, the effects of fibre nonlinearities such as four-wave mixing and stimulated Raman scattering should be studied in the context of multi-wavelength O-CDMA. The effects of dispersion in the high traffic regime have also yet to be investigated.

### 7.3.3. Coding Theory

Many of the inefficiencies and challenges in code design have originated from the unipolar nature of the optical channel. Bipolar codes would release systems from this constraint. The deployment of bipolar codes in O-CDMA systems has been proposed in [39, 52, 60]. All of these schemes, however, involve sophisticated devices and system design, and are often associated with a significant decrease in system throughput. Recently, development in optical signal processing may enable the direct transfer of bipolar CDMA codes to the optical domain. Further theoretical and experimental developments are needed on this front to render bipolar codes a viable, superior, alternative to unipolar codes.

### 7.4. A Final Word

It was sought in this work to arrive at an architecture and implementation for efficient, flexible, practical high-speed local-area networking. Substantial improvements in efficiency have been made possible: cyclic wavelength shifting has been shown to extend allowable user populations in O-CDMA networks to three times previous values, and achievable spectral efficiency has been shown to increase by a factor of four through
the use of optimum threshold detection in conjunction with forward error correction. Real-time traffic adaptation has been made possible through optimum threshold detection and code set switching. Practicality of implementation has been enhanced through the exploration of dispersion-induced temporal skewing and the demonstration that this effect may be remedied through the use of skewed optimum threshold detection and pre-skewing.

This work paves the way to adaptive, efficient, and practical use of light in the local area network.


APPENDIX

8. Appendix I: Variable Threshold Bit Error Rate

To obtain the bit error rate (BER) for the MPR code, the superposition of two MPR codes with a random time shift is considered. The cross correlation constraint \( \lambda_c \) is limited to 1 and there exist \( R^2 \) possible distinct overlapping patterns in any one row. There are a total of \( N_w R^2 \) possible overlaps in \( N_w \) rows and the probability of overlap is \( N_w R^2 / 2L_t \). It is assumed that each transmitter is equally likely to transmit a data bit 1 or 0 and the threshold value of the correlation receiver is set to be \( \alpha \). The probabilities of error when data bits '1' and '0' are sent are given by:

\[
P(\text{error} | 1) = \sum_{i=0}^{\alpha - 1} \binom{N_s - 1}{i} \left( \frac{N_w R^2}{2L_t} \right)^i \left( 1 - \frac{N_w R^2}{2L_t} \right)^{N_w - 1 - i} \tag{A.1a}
\]

\[
P(\text{error} | 0) = \sum_{i=\alpha}^{\alpha - 1} \binom{N_s - 1}{i} \left( \frac{N_w R^2}{2L_t} \right)^i \left( 1 - \frac{N_w R^2}{2L_t} \right)^{N_w - 1 - i} \tag{A.1b}
\]

\( P(\text{error}|1) \) and \( P(\text{error}|0) \) are known as the probability of false dismissal and the probability of false alarm, respectively [81]. Combining equations (A.1a) and (A.1b), the following expression for the bit error rate is obtained:

\[
BER = \frac{1}{2} \left[ P(\text{error} | 1) + P(\text{error} | 0) \right]
\]

\[
= \frac{1}{2} \left[ \sum_{i=0}^{\alpha - 1} \binom{N_s - 1}{i} \left( \frac{N_w R^2}{2L_t} \right)^i \left( 1 - \frac{N_w R^2}{2L_t} \right)^{N_w - 1 - i} + \sum_{i=\alpha}^{N_s - 1} \binom{N_s - 1}{i} \left( \frac{N_w R^2}{2L_t} \right)^i \left( 1 - \frac{N_w R^2}{2L_t} \right)^{N_w - 1 - i} \right] \tag{A.2}
\]
APPENDIX

9. Appendix II: Monte-Carlo Simulation Methodologies

The error performance of MW-O-CDMA systems can be modeled using the Monte-Carlo simulation technique – a technique that exploits the law of large number to perform statistical sampling experiments. A powerful and flexible simulation core is developed in this work based on this technique.

The simulation models $N_{tu}$ users transmitting simultaneously on a star topology network. No two users transmit to the same destination – transmitters and receivers are paired up. MAI and dispersion-induced temporal skewing are considered to be the only sources of signal degradation.

The main features of the simulation are as follows:

- *Asynchronous operation* – Random time shifts are introduced among transmitters. As a result, the transmissions among users are completely asynchronous. The asynchronous operation allows a realistic assessment of the network error performance.

- *Dispersión-induced temporal skewing* – The amount of dispersion can be specified with a dispersion parameter. Zero-dispersion simulation is also possible by setting the dispersion parameter to zero.

---

7 The BER performance predicted by Equation (3-4) represents the worst-case scenario since it assumes transmission among users to be chip synchronous.
• **Code family selection** – T/S AML or WH/TS codes can be selected.

• **Variable threshold** – More than one threshold value can be specified, allowing the determination of optimal threshold value and the associated BER.

• **Flexible parameter selection** – Parameters including $N_{su}$, $N_w$, $L_t$, and $R$ may be specified for different desired BER. The choice of some parameters may be subject to the limitations imposed by the code design algorithm. For instance, for the WH/TS code with $N_w = 5$, $L_t$ is 25 by definition.

• **Simulation accuracy** – Simulation accuracy may be controlled by the number of errors collected before the termination of the simulation. The more errors collected before the termination of the simulation, the higher the accuracy. A minimum of 100 errors were collected to ensure the validity of the simulation results.

An example of running the simulation and the program listing of the simulation `ocdma.m` written in Matlab are provided below.

**Simulation example:**

To simulate a network with 40 users, a desired BER of $10^{-4}$, with a spanning diameter of 500 m using standard telecom fibre (16 ps/nm-km), 50 ps pulse width and 100 GHz wavelength channel spacing, the WH/TS code with $p = 11$ can be used. This information can be translated to the following parameters:

• $N_{su} = 40$
• $N_w = 11$
• $L_t = 121$
• $R = 1$
• $S_{AC} = \frac{0.5 \text{km} \cdot 0.8 \text{nm} \cdot 16 \text{ ps/nm-km}}{50 \text{ ps}} = 0.128 \text{ chips}$
• Code Algorithm = 2
• Number of Errors = 200

In Matlab prompt, type:

```matlab
>> ocdma (2, 121, 1, 11, 200, 40, 0.5, 0.128, [0:0.1:22], 'output.dat');
```
The threshold values are chosen in the range of 0 to 22 with 0.1 increments for the determination of optimal threshold value. The simulated BER at each threshold value will be recorded in a file named output.dat.
Program listing:

```matlab
function [berr] = async_OTD (codeAlg, Lt, Nw, R, err_nums, Nsu, Sac,
threshold, fname)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Simulation on W-O-CDMA networks with 2-D Codes

% Author: Eddie Ng
% Date of Creation: Nov 3, 1999
% Date of Last modification: June 13, 2000

t = cputime;
W= Nw*R;

if codeAlg==1
    tmp = min(factor(Lt))-1;
    if (Nsu > tmp)
        Nsu = tmp;
    end
   UserCode = TSAML(Lt,Nw);
elseif codeAlg==2
    tmp = Nw*(Nw-1);
    Lt = Nw^2;
    if (Nsu > tmp)
        Nsu = tmp;
    end
    UserCodes = wavehop(Nw);
else
    error('Invalid Code Algorithm Choice');
end

UserCodes=UserCode(1:Nsu,:);

fid = fopen(fname, 'w');
fprintf(fid, 'Lt = %i\nNw = %i\nR = %i\nWeight = %i\n', Lt, Nw, R,W);%Concatenate 2 bits together.
al=zeros(size(UserCodes));
a2=a1;
for i=1:Nw
    fprintf(fid, '\nDistance [km] = %f', distance);
    fprintf(fid, '\nDelta_Lambda [nm] = %f', d_lambda);
    fprintf(fid, '\nDispersion parameter [ps/nm/km] = %f', D);

D=D*1e-12;

total_num_bits = 0;
```

76
il = find((UserCodes >= (i-1)*Lt) & (UserCodes < i*Lt));
al(il) = al(il) + (i-1)*Lt;
a2(il) = a2(il) + i*Lt;
end;
UC_2bits = [(UserCodes + al) (UserCodes + a2)];

% free up some memory
clear al;
clear a2;
modUC = mod(UC_2bits, 2*Lt);

% Dispersion Profile
dispersion(1) = 0;
for i = 1:(Nw-1)
    % continuous chromatic dispersion
dispersion(i+1) = i*Sac; % pulse width of 50 ps
end
dispersion = dispersion(:, floor((R:((R+R-1))/R))); % expand to from 1xNw
to 1xW
dispersion = [dispersion dispersion]; % make specs for 2 bits
dispersion = dispersion(ones([1, Nsu]), :);

% Thresholding
threshold = threshold(ones([1, Nsu]), :);

% keep track of the number of errors occurred at different threshold
num_errors = zeros([1, size(threshold, 2)]);

% num_bits => number of bits simulated
num_bits = 0;
while (min(num_errors) < err_nums*Nsu)
    % data will be represented by +/-1
    tx_data_p = 2*randint(Nsu, 1) - 1;
    tx_data_c = 2*randint(Nsu, 1) - 1;
    data = [tx_data_c(:, ones([W, 1])) tx_data_p(:, ones([W, 1]))];

    % Continuous phase shift
    phase = rand([Nsu, 1])*Lt;
    phase = phase(:, ones([2*W, 1]));

    Shift = dispersion + phase;

    TxCodes = UC_2bits;
    il = find(modUC < Shift);
    TxCodes = TxCodes - Shift;
    TxCodes(il) = TxCodes(il) + 2*Lt; % wrap around 2 bits index
    clear il;

    % Data Encoding
    TxCodes = TxCodes .* data;
    % This program assumes no hard-limiter.
    TxCodes = TxCodes(find(TxCodes >= 0));
if (size(TxCodes, 1) > size(TxCodes, 2))
  TxCodes = TxCodes';
end;
  clear il;

if (isempty(TxCodes) == 0)
  TxCodes = TxCodes(ones([1, Nsu]), :);

  %%%%%%% % Data Decoding
  phasel = phase(:, 1);

  modTxCodes = mod(TxCodes, 2*Lt);
  bstart = Lt - phasel;
  bstart = bstart(:, ones([size(modTxCodes, 2), 1]));

  bend = 2*Lt - phasel;
  bend = bend(:, ones([size(modTxCodes, 2), 1]));

  i1 = find((modTxCodes >= bstart) & (modTxCodes < bend));
  rx_sig = -l*ones(size(TxCodes));
  rx_sig(i1) = TxCodes(i1);
  clear i1;

  % convert INDEX
  phasel = phasel(:, ones([size(rx_sig, 2), 1]));
  rx_sig = rx_sig - Lt + phasel;

  for l = 1:Nw
    i2 = find((rx_sig >= 2*l*Lt) & (rx_sig < 2*(l+1)*Lt));
    rx_sig(i2) = rx_sig(i2) - l*Lt;
  end
  clear phasel;

  clear corr_out;
  for k=1:Nsu
    A = UserCodes(k, :);
    B = rx_sig(k, :);
    corr_out(k) = sum(ismember(B, A));
    C=ceil(B);
    il = find(ismember(C, A));
    C=floor(B);
    corr_out(k) = corr_out(k) + sum(B(il) - C(il));
    i1 = find(ismember(C, A));
    D=C(il)-B(il);
    D=D(find(D<0));
    corr_out(k) = corr_out(k) + sum(1+D);
  end

  % Thresholding
  corr_out = corr_out';
  corr_out = corr_out(:, ones([size(threshold, 2), 1]));
  c_out = corr_out;
  i2 = find(abs(corr_out-threshold)<1e-5);
  corr_out(i2) = round(corr_out(i2));
  c_out(find(corr_out>=threshold)) = 1;
  c_out(find(corr_out<threshold)) = 0;
clear corr_out;
else
  \% all users are transmitting zeros
  c_out = zeros (size(threshold));
end

\% compare the receive bits
  tx_data_p = (tx_data_p(:, ones([size(threshold, 2), 1]))+1)/2;
  error_bits = xor(tx_data_p, c_out)
  num_errors = num_errors + sum(error_bits, 1);
  num_bits = num_bits + 1;
end; \%while
  total_num_bits = total_num_bits + num_bits*Nsu;
  fprintf(fid, \'%i \%6.2e \', Nsu, num_errors/(num_bits*Nsu));
  fprintf(fid, '\n');
  t = cputime-t;
  fprintf(fid, 'Number of Bits Simulated per User = %i\n',
            total_num_bits);
  fprintf(fid, 'Time Taken = %6.2f seconds\n', t);
  fclose(fid);
REFERENCES


Volga Tehnology, "Fibre Interconnection and Optical Circuit Technologies," http://www.volgatech.win-uk.net/IOC.HTM.