CHAPTER 1

REVIEW AND INTRODUCTION

This chapter presents the review and introduction of the work which covers the following aspects:

1.1 History and Evolution of OCDMA Technology

The increase in computer and Internet traffic accelerates the need for an optical network that offers high bandwidth, data rate, and channel capacity. A high-speed network must empower several requirements, including high user-number support, random traffic arrival accommodations, asynchronous and high transmission rates, transparent packet format and protocol, simple configurations, as well as secure, reliable, compatible, and enormous bandwidth. Such demands motivate the communication society to explore new approaches in advanced optical communication technology via OCDMA. This multiple access technique can reach up to 10 Gbps and above in certain test beds. OCDMA allows multiple users to share transmission facilities with a satisfactory quality-of-service (QoS) level and providing user-data encryption via a high chipping rate. The switch from the conventional approach to OCDMA is attributed to scarcities in time division multiplexing (TDM), wavelength division multiplexing (WDM), and frequency division multiplexing (FDM) techniques. OCDMA is an imitation of code division multiple-access (CDMA) because of the success achieved in spreading spectrum techniques. However, OCDMA technique encounters various difficulties at the earlier stage due to the differences of signal characteristics and transmission medium in comparison with CDMA. Wireless CDMA uses a carrier with micro/millimeter wave, wherein spreading of the sequence is achieved in the frequency domain by using direct sequences or frequency hopping in radio frequency form (Teh, 2003).

The signal is transmitted in a linear, non-dispersive medium, which is the free space with signal attenuation over distance (Salehi, 1989). In a CDMA system as shown in Figure 1.1, interference suppression can be achieved via a multi-sectored antenna and a power controller. Propagation is influenced by the far–near and multi-path effects. By contrast, OCDMA uses a carrier component that is generated by a laser source at terahertz. Spreading of sequences and encoding are conducted in the optical domain. The signal is transmitted in a dispersive, non-linear optical fiber with a relatively low attenuation. The trade-off of this technique is multiple user interference, beat noise, and dispersion.

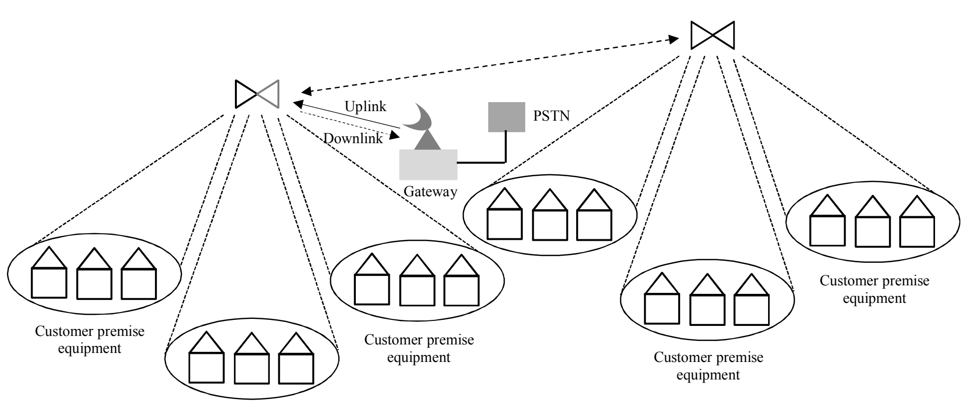

Figure 1.1: Architectural model of wireless CDMA network.

1.2 Overview on Multiple Access Techniques

The multiplexing technique aims to reduce the number of transmission facilities by sharing common transmission media for cost effectiveness. Multiple users are allowed to access transmission links simultaneously via multiple access schemes. Figure 1.2 shows the multiple access techniques and design issues in an optical network. A conventional system adopts several multiplexing techniques, including TDM, FDM, and WDM via time division multiple access (TDMA), frequency division multiple access (FDMA), and wavelength division multiple access (WDMA), respectively. In a code division multiple access network, there are several design issues need to be considered including encoding scheme (encoder type and code set design), modulation techniques and detection schemes.

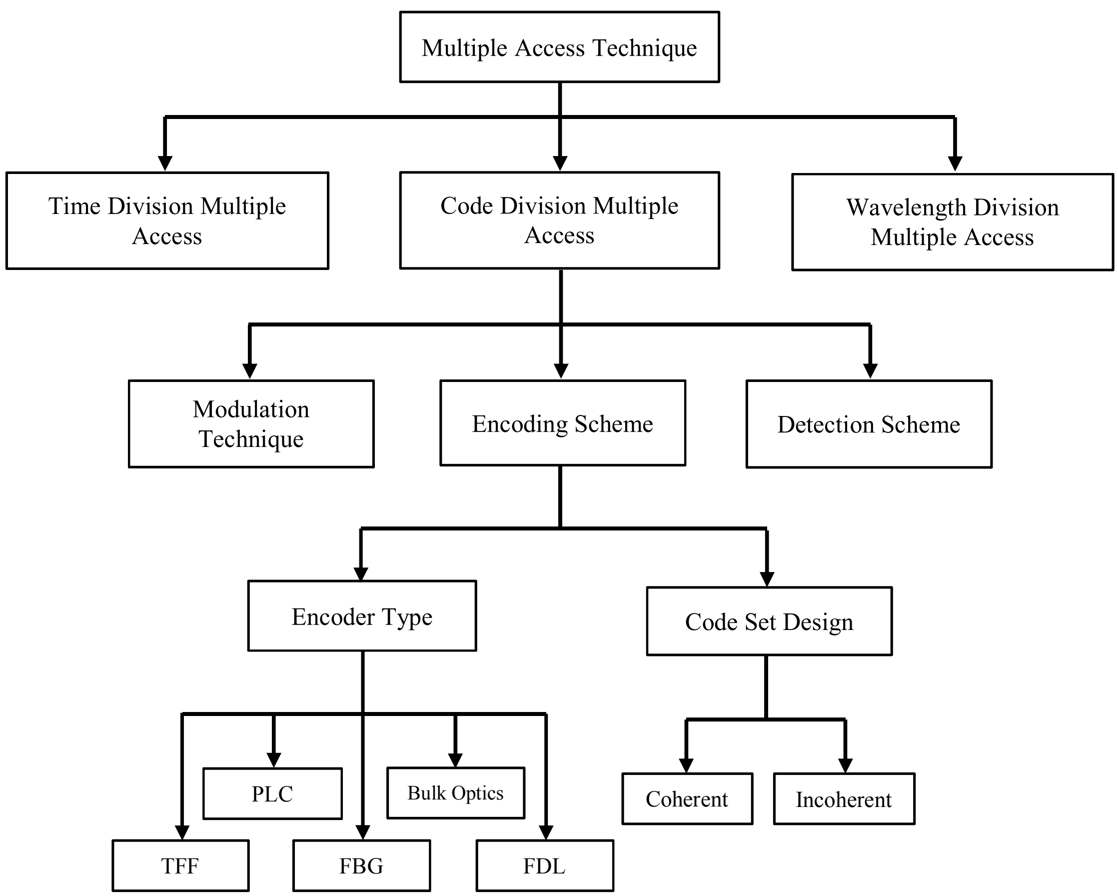

Figure 1.2: The multiple-access techniques and design issues in an optical network.

1.2.1 Time Division Multiple Access (TDMA)

In an electrical time division multiplexing (TDM) system, different time slots are used to distinguish and identify various users. Samples from several users are interlaced periodically into a frame. Thus, synchronization between the commutator at the transmitter and the decommutator at the receiver is critical. The distributor at the receiver should select the sample from the correct frame at the correct timing, and then, send it to the correct output. Brute-force synchronization is used in a TDM system via a marker in the frames. This technique requires an established channel and precise synchronization, may not be suitable for bursty traffic, and may exhibit a deteriorating performance when user number increases. Employing the electrical TDM technique in an optical fiber transmission system requires a distributed feedback laser, an optical modulator, a radio frequency (RF) amplifier, an electrical TDM multiplexer, an erbium-doped fiber amplifier (EDFA), a photodiode, and clock recovery. Optical TDM can be conducted by using an optical pulse source, EDFA, an optical modulator, optical delay lines, an optical time division multiplexer, and clock recovery (Dexter, 2010).

1.2.2 Frequency Division Multiple Access (FDMA)

FDM identifies different users through different sub-carrier frequencies. The timing issue is not crucial in this system. Several signals from different users are modulated at different sub-carrier frequencies. These modulated waveforms will be summed up by a mixer and regarded as the baseband signal to be modulated by a common carrier. A group of orthogonal frequencies is required to support many users. However, imperfect spectral separation, system non-linearity, the orthogonality of carrier frequencies, and unwanted signal coupling degrade system performance.

A guard band, which is the spectral separation, must be introduced to resolve crosstalk problems and co-channel interferences. Thus, the total bandwidth is the sum of the baseband signal with the guard bands used (Aljunid, 2005).

1.2.3 Wavelength Division Multiple Access (WDMA)

WDM is introduced because of the limitations in a single wavelength system. WDM can be achieved by partitioning the total bandwidth to obtain optimum spectral efficiency. In a WDM system, *N* number of wavelengths can be superimposed simultaneously in a single fiber to indicate different channels. Thus, the transmitter and the receiver are designed to tune in at a particular wavelength by utilizing a tunable optical wavelength converter (TOWC). Control and signaling information can be transmitted concurrently in the networks. The total transmission rate can accumulate up to a few terabits per second (Aljunid, 2005). Timing is not a critical concern in a WDM system. Multiple signals are transmitted in a single fiber via different wavelengths. A WDM system operates at the third window because of the lowest attenuation level. Channel spacing and the number of channels determine WDM classifications, including broad WDM, coarse WDM, dense WDM, and ultra-dense WDM (Mukherjee, 2000) as shown in Figure 1.3.

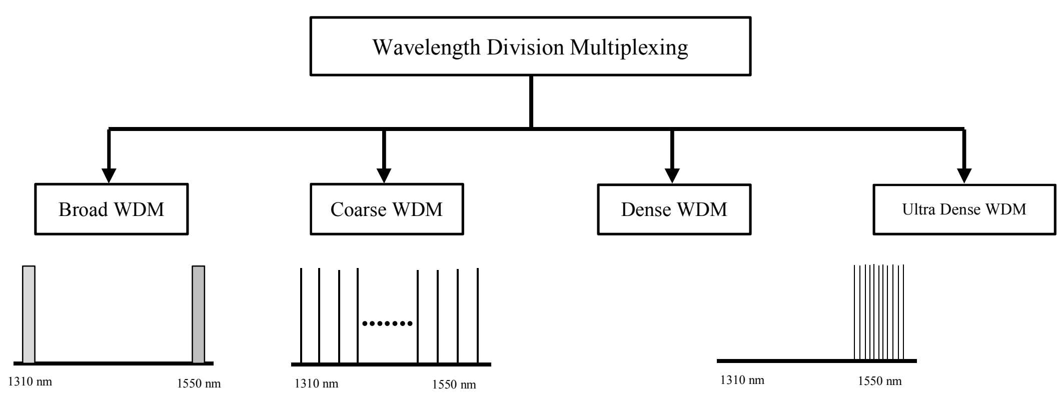

Figure 1.3: The classifications of wavelength division multiplexing techniques.

However, this technique induces several impairments, including the requirement of a predefined channel, crosstalk, non-linearity, and dispersion. In addition, installing a light source in the third window is costly. The dispersion effect is mainly attributed to variations in propagation time by different wavelengths in a single fiber, which degrades signal quality. A dynamic wavelength range is also required to support additional users. In a WDM system as shown in Figure 1.4, wavelength assignment and traffic management are required to schedule data traffic to minimize the collision of packets transmitted at same wavelength from different outbound links.

Graph theory and colouring are required for traffic scheduling which increases the complexity of switching and routing architecture. A number of FDLs may also be needed for a queuing mechanism. Moreover, a TOWC must operate at a rate that is greater than that of the incoming traffic. Thus, some packets need to be stored and retrieved. This process is difficult to achieve in an optical domain. The dimension of FDLs may also increase the switch size (Mukherjee, 2000). During wavelength contention, only one packet can be transmitted on the channel, whereas others must be stored for queuing.

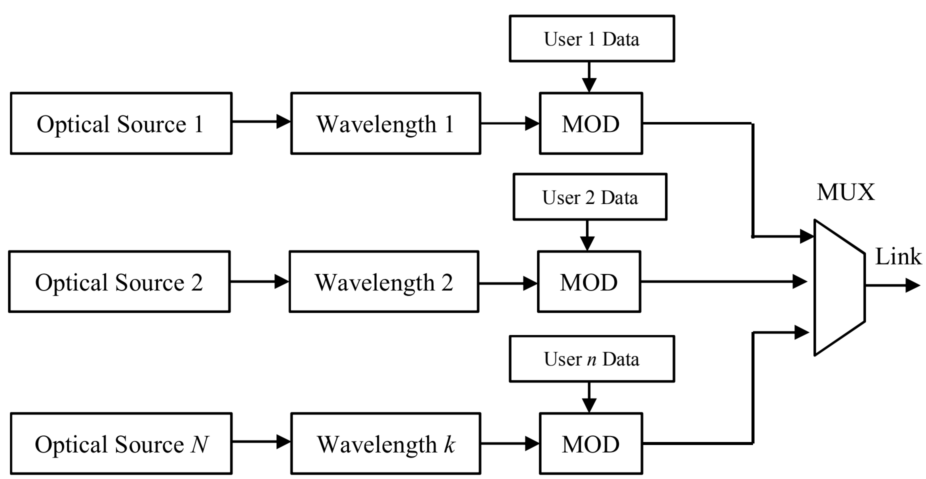

Figure 1.4: Implementation of multiple wavelengths in a WDM system.

Optical packets transmitted at the same wavelengths and preferred outbound links will contend for a wavelength channel to maintain wavelength continuation. In a packet switching network, each packet has to go through a number of switches before arriving at its destination. Contention occurs when two or more packets attempt to leave the switch from the same output port at the same wavelength (Mukherjee, 2000). MAC protocols are required to provide traffic management and monitoring in a WDM system to ensure fair medium access among multiple users. The limitations in conventional approaches cause a new paradigm to emerge, that is, OCDMA.

1.2.4 Code Division Multiple Access (CDMA)

In an OCDMA network, users are identified and distinguished by different codes. OCDMA offers enormous bandwidths with considerable channel numbers, and multiplies network capacity compared with traditional TDMA or WDMA techniques. The tremendous demand of bandwidths for real-time delivery cannot be satisfied by a conventional system as previously mentioned. Meanwhile, the probabilities of packet contention and collision are relatively low in an OCDMA system. Packet contention and collision contribute to packet dropping and packet loss, which degrade network throughput. OCDMA technique can also be applied in MPLS enabled system via optical label along transmission links with a low delay as shown in Figure 1.5 (Kamath, 2004).

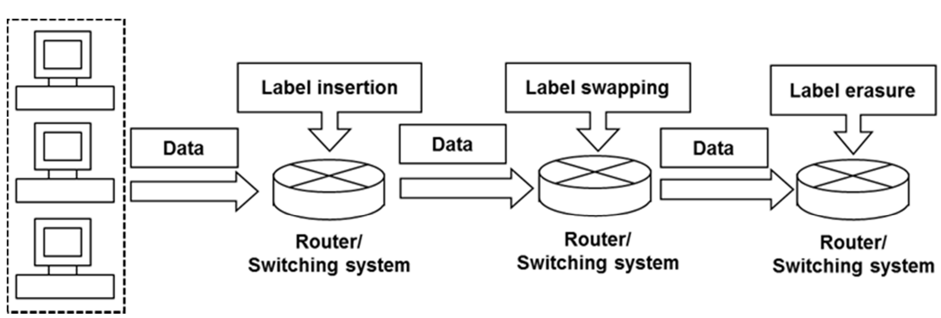

Figure 1.5: Optical labels used in a MPLS enabled OCDMA system.

Transmission capacity can be increased significantly without installing new fibers with an appropriate code set design. This technique promises low processing latency with guaranteed QoS and increases the security of a system because of the use of random and pseudo random signals to generate code sets. Given the encryption mechanism offered in OCDMA, data transmitted can hardly be decrypted. OCDMA also offers dynamic and flexible logical network topologies and introduces fairness among users in accessing shared resources. The flexibility of the code set design allows the switch node to operate in an asynchronous manner. Thus, OCDMA is one of the promising techniques for accommodating data traffic, which supports future high-speed networks. Essential elements used in an OCDMA system include a laser source, a modulator, an encoder, a polarizer, correlators, a matched filter, and MUI reduction devices as shown in Figure 1.6. This system allows multiple-user access in an asynchronous manner with a minimum delay level and traffic scheduling mechanism. However, several impairments are highlighted and discussed in section 1.3.

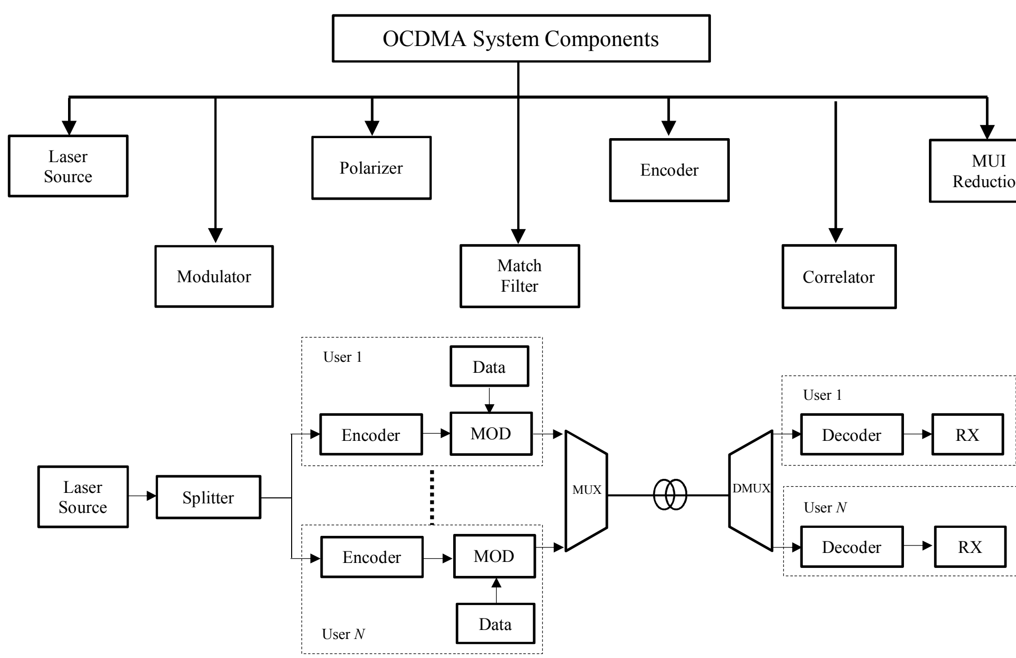

Figure 1.6: The key components used in an OCDMA system.

1.3 Problem Statements

OCDMA cannot be realized successfully by imitating wireless CDMA because of the inherent natures of the signal, carrier frequency, spreading process, and code generation. In addition, the encoding scheme, transmission medium, dispersion level, linearity, interference suppression approach, and propagation manner are different. Conversion of O/E and E/O may induce unnecessary noises in the signal. The speed of a system may be limited because of electronic or optoelectronic speed constraint. This issue may not be significant in all-optical network (AON). Thus, the architecture of the transmitter and the receiver as shown in Figure 1.7, the MUI reduction approach, as well as transmission medium design and considerations must be carefully developed to achieve optimization in system performance.

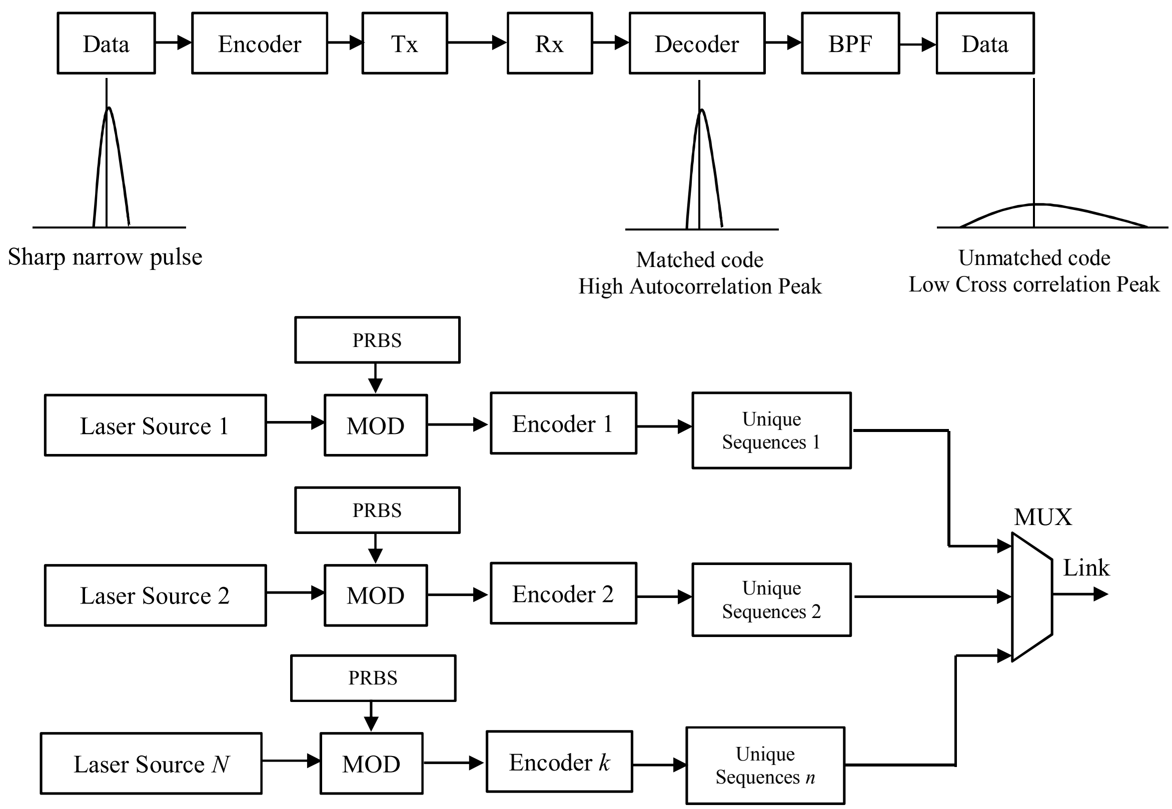

Figure 1.7: The encoder (transmitter), decoder (receiver) and the correlation process (code-matching) in an OCDMA system.

Noise source, inter-symbol interference (ISI) effect, polarization issues, detection scheme, modulation technique, and the bit error rate (BER) estimation model must also be studied. In an OCDMA system, performance deteriorates over distance because of multiple user interference and signal dispersion. To support additional simultaneous active users, a long and complex code set is required, which may lead to unnecessary conversion and processing time. A long code may require a fast signal processor. However, the speed of a processor may limit maximum code length. This condition deteriorates as the number of user increases. Numerous spreading spectrum sequences have been proposed; however, these codes have not been evaluated in an actual MAN.

1.3.1 OCDMA Impairments and Challenges

The bottleneck in OCDMA is attributed to the inherent characteristics of the signal. Impairments in OCDMA can be summarized based on the following aspects.

a) Multi-user Interference (MUI)

OCDMA allows multiple users to access common transmission facilities in an asynchronous, random, and incoherent manner. Thus, this system tends to suffer from high MUI when the code set is not properly designed. This phenomenon tends to deteriorate over long distances at increasing transmission rates. OCDMA allows multiple users to transmit at a single frequency, occupying a common time slot without rigid synchronization and FDL for queuing. However, when the number of user increases, the bursty traffic arrival pattern induces high MUI among users, thus degrading system performance. In an OCDMA system, MUI is related to phase-induced intensity noise (PIIN) because of the overlapping spectra from simultaneous users.

b) Optical Beat Noise

Optical beat noise (OBN) is induced when the detector encounters different users transmitting at the same frequencies at the receiver. The difference of the optical phase from various users induces variation levels of the optical current, thus causing variations in the intensity of the optical signal. This phenomenon deteriorates when the number of users increases, thereby degrading overall system performance, particularly in a coherent system.

c) Dispersion and Non-linear Effect

OCDMA guarantees good signal-to-noise ratio (SNR), but suffers from several phenomena while transmitting in the fiber, which is relatively dispersive compared with other transmission media. These effects are mainly attributed to the dispersion properties caused by chromatic dispersion as well as non-linearity caused by self-phase modulation, cross-phase modulation, four-wave mixing, scattering, and polarization issues.

1.3.2 Conventional Solutions

The solution for OCDMA impairments can be typically summarized as follows.

a) Code Set Design

Various approaches have been proposed in code set development, including Hadamard code, prime code, Kasami code, extended carrier-hopping prime code, modified quadratic congruence code, wavelength-time coding, modified frequency-hopping code, optical orthogonal code, multi-weight code, double-weight code, and modified prime-hop code (Aljunid, 2005). However, most of these codes have not been evaluated in an actual optical network. Most of the proposed codes set developments have only been justified theoretically (Aljunid, 2005). A long code is required to support many users, which will increase the complexity of the hardware and involve long processing time. Code generation is complicated too. Moreover, not all proposed code sets guarantee strict auto- and cross-correlation criteria. Consequently, scalability and feasibility of the system are limited, which does not favor high-speed networks. Such design can also be costly because of the complexity of code generation. System optimization cannot be achieved by depending only on code set development.

b) OCDMA Architecture

To minimize OCDMA impairments, architecture must employ additional FDL loops, a synchronization stage, a high-power laser source, complicated code generation, and a recognition device. In addition, unnecessary signal conversion, use of multi-stage amplification, complex MUI reduction methods, and incoherent light sources are also involved. However, these solutions suffer from different drawbacks in both coherent and incoherent systems. Such architecture can also be costly and difficult to integrate into existing technologies. Thus, its flexibility and compatibility are inadequate for supporting dynamic high-speed networks. The summary of section 1.3.2 is presented in Figure 1.8.

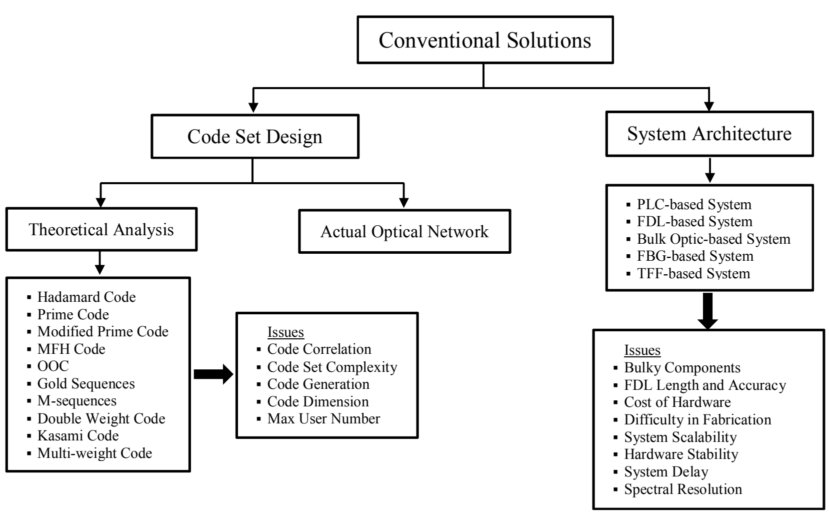

Figure 1.8: The conventional solutions, design issues and system limitations in OCDMA.

1.3.3 Deficiencies of Existing Work

The deficiencies of the existing work can be investigated from several perspectives.

a) Encoding Scheme

First, OCDMA encoding mechanism can be achieved by time spreading, frequency hopping, frequency encoding, spectral amplitude, wavelength-hoping time spreading, as well as temporal- and spectral-phase coding (Teh, 2003). Coherent direct sequence encoding can be achieved by delayed lines. Time spreading encoding can be achieved by using a programmable phase mask, whereas incoherent spectral intensity encoding can be realized by diffraction grating and using an amplitude mask. Spectral encoding can be accomplished by employing a programmable optical filter and a broadband light source.

b) Encoder Types

Different disadvantages are exhibited in FDL- and planar light-wave circuit (PLC)-based encoders used in direct-sequence encoding systems, bulk optic-based encoders used in frequency encoding systems, and FBG array-based encoders used in frequency-hopping encoding systems. The problems include length, accuracy, and delay issues in FDL-based mechanism (Teh, 2003).

For PLC-based mechanism, the issues include phase variation, temperature control, stability, fabrication, and cost. In bulk optic-based mechanism, the issues include compactness of the device, resolution of the design parameters, and cost. Frequency hopping-based mechanism needs an incoherent light source and a tunable laser, which are costly and inflexible (Teh, 2003).

In FDL-based, coherent, direct-sequence systems, the length needs to be carefully set to allocate pulses from a coupler according to the code pattern. Moreover, a synchronization stage is required in such configuration, which also involves high precision and expensive decoding devices at the receiver. The aforementioned configurations are unfavorable to high-speed networks. In the time spreading-based encoding system, the bulk optics used induces splitting and insertion losses. Such ultra-fast pulse-shaping mechanism is highly dispersive and requires an additional dispersion compensating device that complicates overall system design (Teh, 2003).

In the incoherent spectral intensity encoding system, synchronization and FDL are not required. However, orthogonality from different users and spectrum reshaping facilities are required to minimize the MUI effect. In optical spectral encoding systems, incoherent light sources and programmable optical filters are required. However, such configurations are not suitable for coherent networks.

c) MUI Reduction Method

MUI reduction can be achieved by time gating and thresholding methods (Dexter, 2010). Time gating methods can be implemented through non-linear optical loop mirrors. However, such mechanism exhibits several problems, including high optical power requirement, fiber dispersion, fiber dimension, and stability issues because of environmental fluctuations. Optical thresholding do not need a clock pulse for optical gating. In fiber-based thresholding, non-linear fiber, Holey fiber, and dispersion-flattened fibers are used. This method employs the non-linear effect of the fiber to compensate for MUI. However, such mechanism requires special types of fibers with special characteristics, as mentioned previously (Dexter, 2010).

d) Modulation Technique

The modulation technique is essential, particularly in a MAN design over long distances. The parameters of the carrier, including the amplitude and phase, can vary according to the input signal. This process can be achieved by using direct and external modulations. In a direct detection system, optical power varies according to the modulating signal. Such mechanism depends on signal intensity at the receiver. Variations in optical signal intensity characteristic are inefficient for long-distance transmissions, particularly for a MAN. Such mechanism requires high laser power and amplification stage, and induces high amplified spontaneous emission noise in the system, which can be scale up in a cascaded network. Moreover, tolerance to crosstalk and the non-linear effect are low, which is unfavorable for data rate and long distance optimization design. In a conventional phase shift keying system, a reference signal is required for phase comparison. This system needs to operate in a coherent manner, wherein one symbol is represented by one bit. Such requirement is inefficient for high-speed networks. This system also requires complex carrier recovery devices to ensure the accuracy of the phase as a reference signal. Such configuration increases the complexity and cost of the overall system.

In summary, optimization issues need to be addressed in the design of a MAN. Achieving overall system optimization is impossible when only code set development or complicated system architecture is considered. The alternative solution is to propose an integrated formulation that can be tackled from three important aspects, namely, encoding, modulation, and MUI reduction. The motivations and objectives of the work are discussed in section 1.4. Moreover, the integrated optimization solution is presented in Figure 1.6. This is followed by the contribution of the work which is elaborated in section 1.5. Finally, the comparative study is carried out in section 1.6 and summarized in Table 1.1.

1.4 Motivations and Objectives of the Work

Numerous approaches have been employed on code development as stated in section 1.3.2 to address the problems as presented in section 1.3.1. However, code sets do not promise zero cross-correlation, or they are extra-long, thus leading to high complexity of the system and a long processing period, which defeats the inherent objective of this technique. Moreover, spreading spectrum sequences have not been tested in an actual optical system over long distances, particularly in a MAN by considering various noise sources and multi-user interferences. Thus, feasibility, compatibility, and reliability of these sequences have not been verified with absolute certainty. Meanwhile, conventional encoding and decoding mechanisms are complex, expensive, bulky, and not configurable. The motivations of the work are summarized as below:

- To identify the merits, impairments and challenges in OCDMA systems.
- To develop an optimized OCDMA system and to identify the optimal design configurations and requirements.
- To identify the characteristics and properties of spreading spectrum techniques and to design optimal encoding schemes.
- To develop optimal MUI reduction approach to optimize a metropolitan area network (MAN).
- To evaluate the system performance via different modulation techniques, noise sources and dispersion effects.
- To evaluate the performance in MAN at different transmission distances by using different modulation and detection techniques.
- To justify the performance enhancements by measurable performance parameters which include BER and SNR, etc.
- To investigate the sustainability of the optimal solution under different aggregated traffic capacity and active users.
- To carry out comparative study by using different OC models and encoding schemes in MAN.

Thus, the present work aims to develop optimal grating configurations for encoding and decoding mechanisms via super-structured FBG (SSFBG) for numerous optical spreading sequences at different numbers of chips, code weights, and chip spacing. System performance is evaluated under different numbers of simultaneous users transmitting at standard OCDMA transmission rate, laser power, amplifier gain, and distance, which will be analyzed through the BER, an eye diagram, the optical spectrum, and SNR. A comprehensive and comparative analysis of various encoding schemes is conducted. Practicability of the solution is examined through advanced modulation techniques, including DPSK and DQPSK over traditional binary modulation techniques. Testing is conducted on up to 12 users over 40 Gbps at 100 km of single mode fiber in a MAN. The integrated optimization formulation is presented in Figure 1.9. The objectives of this work are summarized as below:

Objective 1

Investigation on OCDMA system impairments and the conventional solutions.

- To identify the deficiencies of the existing approach.

Objective 2

Development of optical code (OC) models for system optimization.

- To configure FBG as encoder for phase encoding.
- To investigate different types of FBG and grating profiles for encoding.
- To design optimal grating configurations based on the code sets properties and orthogonality.
- To develop optimal encoding and decoding scheme by using FBG.
- To examine the system performance under different configurations which include the chip lengths, code weights and grating spacing, etc.

Objective 3

Development of OCDMA system for system optimization.

- To evaluate the OCDMA system by using different modulation techniques including IM-DD, external modulation, NRZ-DPSK and NRZ-DQPSK.
- To investigate the system performance under various noise sources and nonlinear effects as well as the multiple user interference.
- To examine the feasibility of the work to support higher number of active users, aggregated traffic capacity and MAN transmission distance.
- To evaluate the optimal system performance to maintain error free transmission by using BER, SNR and eye diagram, etc.

Objective 4

Formulation of integrated optimal solution which includes optimal encoding, modulation technique and MUI reduction for MAN optimization.

- To evaluate the system performance by using traditional and advance modulation techniques in order to outline the optimal solution for MAN.
- To develop the optimal MUI reduction approach for MAN.
- To investigate the effect of different design parameters to performance parameters for optimization in MAN.

Objective 5

Justification on the enhancements achieved in this work under different scenarios.

- To verify the improvements of the integrated optimization formulation through different comparative studies by using BER, SNR and eye diagram, etc.

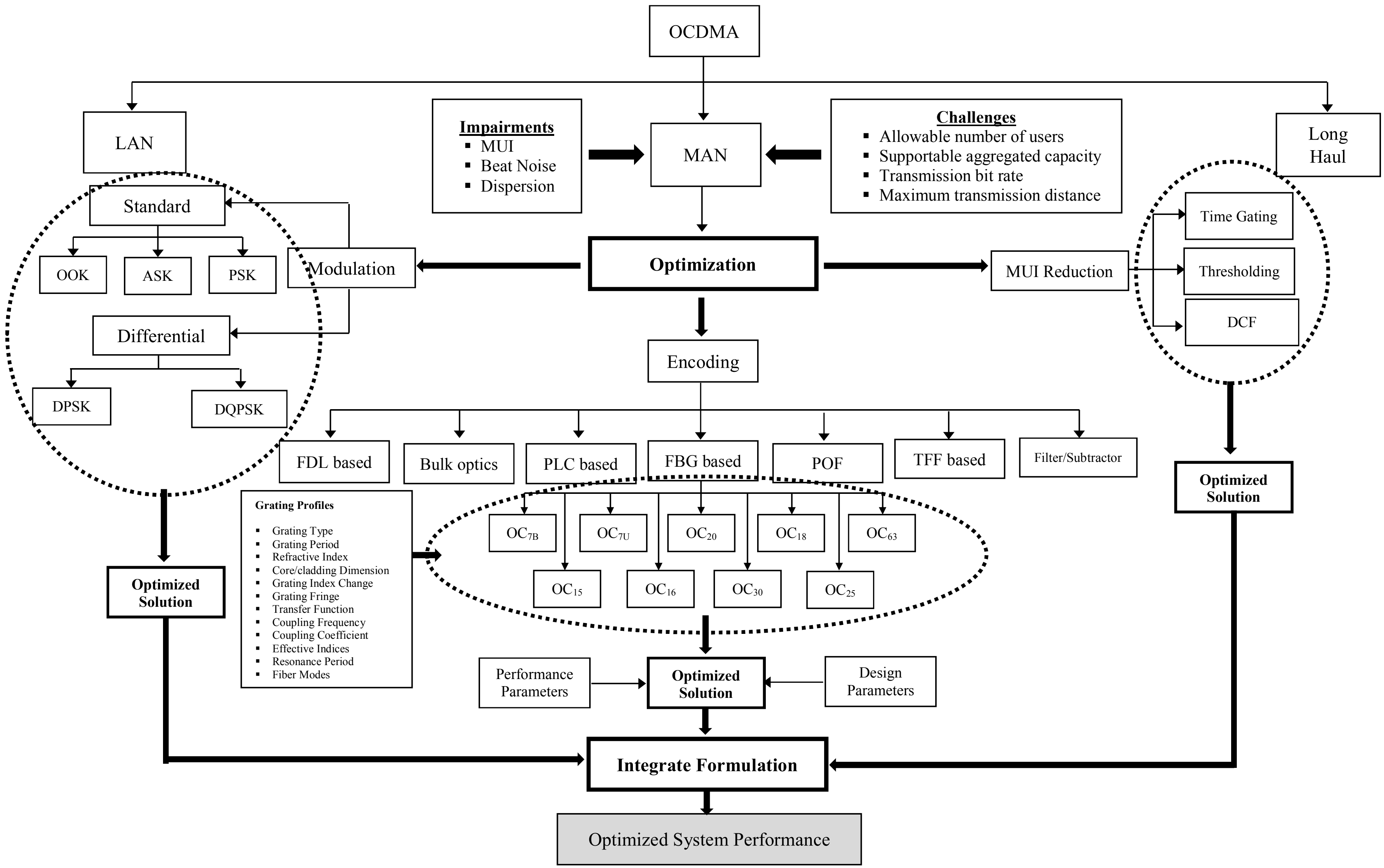

Figure 1.9: The motivations, objectives and scope of work for MAN optimization.

1.5 Contributions

The objectives of this work are outlined according to observations on OCDMA impairments, review on conventional solutions, and investigations on the deficiencies of the existing work. The main contributions of this study can be summarized as follows.

a) Configuration of FBG

FBG is configured as an encoder and a decoder to achieve bipolar phase encoding. Phase encoding allows high cross- and auto-correlations with high spectral efficiency. FBG can be used as a reflective type of filter which is stable and exhibits low loss. It provides a stable reflective spectrum and can be integrated into other optical components.

b) Development of OC models

OC models are developed to be imprinted on the fiber core to generate unique sequences based on code patterns. Code patterns are selected based on code set and correlation properties, including auto-correlation and cross- correlation. The encoder/decoder parameters consist of grating type, grating period, refractive index, core and cladding dimensions, grating index change, grating fringe, transfer function, coupling frequency, coupling coefficient, effective indices, resonance period, and fiber modes.

c) Investigation on the Optimal OC Model

The optical code models of OC_7 (7-chips), OC_{25} (25-chips), OC_{20} (20-chips), OC_{18} (18-chips), OC_{15} (15-chips), OC_{16} (16-chips), OC_{31} (31-chips) and OC_{63} (63-chips) are assessed via the design parameters of code weight as well as chip length and spacing, and the performance parameters of BER and SNR, etc.

A four-channel system is developed to examine the encoded and decoded signals and the optical spectrum. The required received and input powers to obtain an error transmission are examined. A two-channel system is developed to investigate the optimal and trade-off BERs by using different numbers of chips. Two-channel and four-channel systems are developed for back-to-back evaluation. The effects of the design parameters to system performance are examined. These parameters include code set parameters (code weight and chip length) and system parameters (gain control amplifier, laser power, and pulse type). The maximum allowable MAN transmission distance and transmission bit rate for error-free transmission are also examined. The key contributions on the assessment of intensity modulated, direct detection system are summarized in section 4.9.

d) Development of OCDMA Architecture

OCDMA architecture includes the presented transmitter and receivers, namely, IM-DD, external modulation (NRZ-MZM), NRZ-DPSK, and NRZ-DQPSK. Noise source and interference consideration in the design include ISI, PIIN, OBN, shot noise, thermal noise, and the MUI effect. The optical code model is integrated into the system at the encoder and decoder stages. MUI reduction and amplification are applied to the system.

e) Formulation on Integrated System Optimization

The optimal models are integrated to achieve overall system optimization and to be evaluated in a MAN.

f) Application on MAN

A four-channel system is developed and evaluated by NRZ-MZM, NRZ-DPSK, and NRZ-DQPSK to examine BER over MAN transmission distance and BER over SNR.

Investigations on other physical layer parameters of noise power density and chromatic dispersions are examined via eye diagram, BER, and SNR. The effects of the modulation technique, transmission bit rate, and transmission distance are also investigated. The key contributions on the application in OCDMA MAN are presented in section 5.9

g) Evaluation on System Sustainability

Four-user, eight-user, and twelve-user systems have been developed by using NRZ-ASK, NRZ-DPSK, and NRZ-DQPSK to examine the sustainability of the system. The investigations include different aggregated traffic capacities, SNRs, transmission rates and distances, and numbers of active users. The keys contributions on the evaluation of sustainability and feasibility in multiple users MAN are summarized in section 6.5.

h) Performance Comparison

The performance of the system is compared with the conventional approach in terms of BER, SNR, eye diagram, and transmission distance. Comparative studies on hybrid schemes and multi-wavelength systems are also conducted. Comparative studies on the assessment of intensity modulated, direct detection system are summarized in Tables 4.3, 4.4, 4.5 and 4.6 in section 4.11. The comparative studies on the application in OCDMA MAN are summarized in Tables 5.1, 5.2, 5.3 and 5.4 in section 5.11. The comparative study on the evaluation of sustainability and feasibility in multiple user MAN is summarized in Tables 6.1, 6.2, 6.3 and 6.4 in section 6.7. The overall comparative studies are summarized in Table 7.2.

i) Performance Enhancement

Performance enhancements are justified via the MUI reduction method, optical code design, types of encoding schemes, modulation, and transmission distance numerically by BER and SNR, and graphically by eye diagram and optical spectrum. The enhancements achieved in the assessment of intensity modulated direct detection system are outlined in Tables 4.1 and 4.2 as described in section 4.10. The enhancements of the integrated formulation in the application of OCDMA MAN are highlighted in section 5.10 whereas the enhancements achieved on the evaluation of sustainability and feasibility in multiple user MAN are outlined in section 6.6. The overall performance enhancements are summarized in Table 7.2.

1.6 Scope of Work and Comparative Study

The scope of work and comparative study are presented in Table 1.1 including encoding scheme, code set, modulation and detection technique, MUI reduction, MAN evaluation, user number, transmission rate, system level, main design and performance parameters from various works. The materials referred are presented in Bibliography.

Table 1.1: Scope of work and comparative study as well as key design issues in OCDMA network.

	Proposed Work	Aljunid (UPM)	P. C. Teh (SOTON)	X. Wang (Heriot-Watt)	Ken-ichi (Osaka), Naoya (Tokyo)	Lin Lu (PRC)	B. R. Borja (Madrid)	T. Srinivas (India)
Encoding Scheme	Phase, Intensity	Spectrum/ spectral	Phase, Intensity	Spectral Phase	Phase	Phase	Intensity	2D, W/T
Encoder Type	SSFBG	AND, complementary	SSFBG	FBG	SSFBG	SSFBG	Standard	Standard
Optical Code Sequences	7, 25, 20, 18, 15, 16, 31, 63	18	7, 8, 16, 63, 255	16	511	63	Not specified	Not specified
Modulation Technique	Direct, External (OOK, ASK, DPSK, DQPSK)	Direct External	Standard	DPSK	Intensity Modulator	External	Standard	Standard
Detection Technique	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct
MUI Reduction	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Multi-level Encoding	Yes	No	Yes	Yes	No	No	No	No

Metropolitan Area Network Evaluation	Yes	Yes	No	No	No	No	No	Yes
Distance	10 km - 100 km	10 km - 100 km	25 km, 44 km, 50 km	34 km	Not specified	60 km	20 km - 25 km	100 km
Number of Active Users	2, 4, 8, 12	4	1, 2, 16* *(hybrid)	Not specified	Not specified	Not specified	4	4
Transmission Rate	10 Gbps - 40 Gbps	155 M - 10 Gbps	311 - 622 Mbps	2.5 Gbps	622 Mbps - 10 Gbps	2.5 Gbps	1.25 Gbps	10 Gbps
Remarks	Simulation, Industrial Software	Simulation, Academic Software	Experiment	Experiment	Experiment	Experiment	Simulation, Industrial Software	Simulation, Academic Software
Level	System	System	Device, System	System	System	System	System	System
Main Design/ Performance Parameters	Power, distance, SNR, BER, Optical Spectrum, Eye Diagram	Power, distance, BER, Optical Spectrum, Eye Diagram	Reflectivity, BER, Optical Spectrum, Eye Diagram	Optical Spectrum, Cross/Auto Correlation, BER, Power	BER, Power, Correlation	Power, BER, Eye Diagram	Power, Optical Spectrum, Eye Diagram, BER	BER, Eye Diagram

1.7 Thesis Organization

Chapter 1 reviews and introduces OCDMA technique; provides the history and evolution of OCDMA technology; discusses the demands and trends of current communication engineering; and identifies the merits and impairments of OCDMA technology. Moreover, Chapter 1 discusses several multiple access techniques including TDMA, FDMA, WDMA, and CDMA, as well as the problems encountered in current OCDMA and the need to upgrade the conventional approach to support future high-speed networks. The motivations and objectives of this work are discussed. Thesis organization is also presented.

Chapter 2 identifies the characteristics, properties, and merits of OCDMA technique; elaborates related spreading spectrum techniques, including the direct sequence spread spectrum and the frequency hopping spread spectrum. OCDMA architecture and equipment, including the transmitter and receiver model, are presented. The types of OCDMA encoder and decoder, including arrayed waveguide grating (AWG), PLC, and SSFBG are also presented. OCDMA encoding and decoding techniques, including coherent coding (temporal-phase and spectral-phase coding) and incoherent coding (temporal spreading and spectral intensity coding), are investigated. Chapter 2 also discusses several OCDMA codes, including the prime code, maximal length sequences, and Walsh code. OCDMA detection techniques are studied, including coherent detection and direct detection. This chapter also outlines correlation properties (cross-correlation and auto-correlation), and reviews multi-user interference reduction techniques, including the time gating and thresholding methods. The last section of this chapter studies OCDMA network and topology, including access networks and MANs.

Chapter 3 demonstrates system development, configurations, and design considerations; elaborates the scope of the work and its tree diagram; presents the model description and component characterizations of OCDMA systems, including transmitter architecture, dispersion compensation device, encoder and decoder, as well as the receiver architecture; identifies design configurations and considerations, including the design parameters (MAN transmission distance, transmission bit rate, number of active users, laser source power, and gain-controlled amplifier) and code set parameters (code weight, and chip length and spacing). Performance parameters, including BER, received power, eye diagram, dispersion value, noise power density, and SNR, are then discussed. Moreover, noise sources and interferences considerations are justified, including ISI, PIIN, shot noise, thermal noise, and MUI. This chapter also reveals the development of the FBG grating profile and the encoding scheme, including the 7-chips, 25-chips, 20-chips, 18-chips, 15-chips, 16-chips, 31-chips, and 63-chips models. This chapter studies the code orthogonality and correlation properties that will be used as encoding schemes, including unipolar- and bipolar-phase encodings, and multi-level phase-shift encoding.

Chapter 4 demonstrates the assessment of the proposed work in an intensity-modulated direct detection system; presents the evaluation of encoding and decoding in a four-channel system via 25-chips, 20-chips, 18-chips, 15-chips, 16-chips, and 31-chips models. The encoded and decoded signals, optical spectrum, and eye diagrams are examined. The demonstration of the two-channel 16-chips system, in which MUI reduction is conducted via dispersion compensating fiber, is presented based on the best and trade-off BERs. Chapter 4 also investigates back-to-back system performance, and demonstrates the two-channel 7-chips system, in which MUI reduction is performed via dispersion compensating fiber, is presented based on best and trade-off BERs. Evaluation of system performance over the received power is also conducted.

A comprehensive analysis of the design parameters on system performance, including code weight, chip length, gain-controlled amplifier, laser source power, MAN transmission distance, and transmission bit rate, is performed. This chapter also reveals the enhancement of system performance, and outlines the comparative study of various encoding schemes.

Chapter 5 investigates the application of the proposed work in an OCDMA MAN. A four-channel system with bipolar phase shift encoding is developed by using external modulation (NRZ-MZM) to investigate BER over MAN transmission distance, BER at a measured SNR, and BER improvement via MUI reduction (dispersion compensating fiber, encoding/decoding, multi-level phase shift by analyzing and improving the eye diagram). This chapter also developed a four-channel system with precoding and bipolar phase shift encoding by DPSK. This system evaluates BER over MAN transmission distance, BER at a measured SNR, and BER improvement via MUI reduction (NRZ precoding, dispersion compensating fiber, encoding/decoding, and multi-level phase shift) by analyzing the eye diagram. A four-channel system is developed with precoding and bipolar phase shift encoding by DQPSK. This system aims to examine BER over MAN transmission distance, BER at a measured SNR, and BER improvement via MUI reduction (NRZ precoding, dispersion compensating device, encoding/decoding, and multi-level phase shift) by analyzing the eye diagram: I-channel and Q-channel. Performance evaluation of the hybrid scheme is also conducted. This chapter also studies the effects of other physical layer parameters, including noise power density and chromatic dispersion, on system performance. Finally, this chapter elaborates code mismatch and inconsistency of user performance through BER over MAN transmission distance, BER at a measured SNR, and analysis of the eye diagram.

Chapter 6 performs the evaluation of the sustainability and feasibility of the proposed work in a MAN with multiple users. This chapter demonstrates implementation in a four-user system by employing NRZ-MZM, NRZ-DPSK, and NRZ-DQPSK modulation techniques. This chapter aims to investigate system optimization to support different aggregated traffic capacities by BER and eye diagram analysis. Chapter 6 also demonstrates implementation in an eight-user system by employing ASK modulation technique, NRZ-DPSK, and NRZ-DQPSK to support different aggregated traffic capacities by BER and eye diagram analysis. Finally, implementation in a 12-user system is demonstrated via ASK modulation technique, NRZ-DPSK, and NRZ-DQPSK, over different aggregated traffic capacities via BER and eye diagram analysis. BER enhancement is explained by using MUI reduction via dispersion compensating fiber, bipolar phase shift encoding/decoding, and the advance modulation technique (NRZ precoding and a differential approach).

Chapter 7 provides the conclusion of this work, which covers its visions and possible features and enhancements that can be integrated into this work, including OCDMA-based label swapping, all optical networks, and optical router issues. The last chapter also outlines trends and requirements of future optical terabit and petabit networks.

In the appendices, the mathematical analyses of the OCDMA system design and performance parameters are presented, including likelihood ratio, SNR, and probability of bit error estimations by considering the effect of pulse width, transmission rate, network size, code weight, code length, bit duration, chip duration, and FBG length. The probability of bit error resulting from ISI is examined by considering the effect of the type of received pulse, physical layer parameters, bit duration, chip duration, transmission rate, network size, code weight, code length, and FBG length.

1.8 Summary

This chapter reviews the history and evolution of OCDMA technology. An overview on various multiple access techniques, including TDMA, FDMA, WDMA, and CDMA, are described. OCDMA impairments and challenges, including MUI, optical beat noise, dispersion, and non-linear effects are highlighted. Conventional solutions for impairment, including code set design and OCDMA architecture, are examined. The deficiencies of the existing work, including encoding scheme, encoder types, the MUI reduction method, and modulation technique are investigated. The motivations and objectives of the work are presented. The scope of the work is summarized, and a comparative study is conducted. The contributions of the work, including characterizing FBG, developing grating configurations, investigating optimal model, developing OCDMA architecture, formulating integrated system optimization, applying in MAN, evaluating system sustainability, as well as comparing and enhancing performances, are outlined. The thesis organization is also described. **Objective 1** as described in section 1.4 is achieved. The materials referred in this chapter are listed in Bibliography. Chapter 2 will discuss on the optical code division multiple access technique from various perspectives: characteristics, spread-spectrum techniques, architecture, encoding schemes, code sets, detection techniques, MUI reduction and OCDMA networks, etc.