CHAPTER 2

OPTICAL CODE DIVISION MULTIPLE ACCESS TECHNIQUE

This chapter reviews the optical code division multiple access technique from the following aspects:

2.1 Characteristics, Properties and Merits of OCDMA

OCDMA supports a higher number of channels via the utilization of a single carrier frequency, allowing multiple access capability, eliminating rigid network timing synchronization and traffic management, supporting random asynchronous traffic, possessing soft capacity, and providing satisfactory levels of security via a high chipping rate of encryption. The services and application of OCDMA varies from Mbps to Gbps, and ranges from point-to-point transmission to multiple access system. OCDMA simplifies the management of large numbers of users. Unlike TDM and WDM, OCDMA does not require large amounts of fiber delay lines for the queuing of data and tunable optical wavelength converter (TOWC) to support more users. The OCDMA system requires minimal network control and reconfiguration, thereby reducing the number and types of network equipment and MAC management.

Ideally, all-optical networks can transmit signals in the optical domain without optical-to-electrical conversion. In this way, the system throughput is enhanced and the network transmission delay is minimized. Moreover, the unnecessary conversion of O/E and E/O, which increases the amplified spontaneous emission (ASE) noise, is minimized as well. The scarcities in the dynamic range of wavelength allocation and orthogonal frequency requirement of conventional TDM, FDM, and WDM networks accelerate the OCDMA technique in supporting future high-speed networks. The simplicity of the network architecture, considerable size of the code set, transparent packet format, and protocol further contribute to the growth of the OCDMA technique. Based on the increase in the number of users, the code set can be expanded without the need to install additional equipment, and can provide encryption capability via a unique chipping pattern.

OCDMA improves the network by connecting large numbers of asynchronous users with low latency and jitter. OCDMA is commonly used in access and metropolitan area networks spanning from 25 km to 100 km, and supports both wide and narrow bandwidth applications in the network. In the OCDMA network, users are identified and distinguished via different codes. The binary data signal, $b(t)$ can be expressed by equation (2.1) where P_T is the rectangular pulse of duration T, and the binary sequence is b_l. Each transmitter with zero mean stationary Gaussian process, $V_k(t)$ has autocorrelation function as expressed by equation (2.2). Thus, the OCDMA receiver is designed to recognize the corresponding code, $r(t) = \sum_{k=1}^{k} s_k(t)V_k(t)$ where $s(t)$ is the binary data signal sequence with k number of transmitted signals (Salehi, 1989).

$$b(t) = \sum_{l=-\infty}^{\infty} b_l P_T(t - lT) \tag{2.1}$$

$$R_V(\tau) = \begin{Bmatrix} (T_c)^{-1}(T_c - |\tau|), & |\tau| \leq T_c \\ 0, & |\tau| \geq T_c \end{Bmatrix} \tag{2.2}$$

OCDMA offers an enormous bandwidth with greater channel capacity that multiplies network capacity, compared with the traditional multiple access techniques of TDMA, FDMA, and WDMA technique. The conventional system cannot satisfy the tremendous demand for real time delivery of bandwidth. The chances of packet contention and collision are relatively high when traffic in the conventional network is not managed well. Packet contention contributes to packet dropping, which degrades the network throughput and system performance, and offers a multiple access network that allows N number of users to share a common transmission medium concurrently. The transmission capacity can be increased dramatically without installation of new fibers. The OCDMA technique promises low processing latency, which guarantees a higher quality of service (QoS). However, OCDMA can hardly be decoded without having matched code at the correlators because of the encryption mechanism applied.

The OCDMA system adopts an optical label that can be swapped along the transmission links with low delay. OCDMA also increases the security of the system by utilizing random signals for code set generation, offers dynamic and flexible logical network topologies, and equalizes the access of shared resources among users. The implementation of OCDMA is one step closer to the realization of the future router, which features bufferless, transparent data rates and formats that eliminate the process of O/E and E/O conversion. OCDMA supports the all-optical label swapping (AOLS) fast-forwarding technique, which can be incorporated with the multi-protocol label switching (MPLS)-based signaling and traffic engineering capabilities. OCDMA realizes the non-buffered based contention resolution that supports label processing via the development of AOLS forwarding protocol policies (Kamath, 2004).

2.2 Spread-Spectrum Techniques

CDMA is known as the spreading spectrum technique because the transmitted information is spread across the available RF spectrum. Efficient spectrum utilization and robustness to multipath interference are the reasons behind the success of CDMA. Thus, the synchronization issue is not extremely crucial. Moreover, CDMA has superb signal security; each user is assigned a unique pseudo-noise or pseudo-random code sequence. CDMA is divided into two major categories: frequency hopping and direct sequence (Salehi, 1989). The optical CDMA has drawn the attention of the communication sector over two decades ago because of the success of CDMA. However, the imitation was unsuccessful because of signal characteristic differences and transmission properties of the medium (e.g., carrier, spreading method, encoding and decoding technique, interference reduction approach, and propagation issues).

2.2.1 Direct Sequences Spread-Spectrum

The pseudo-random stream encodes user-generated data in the direct sequences spreading spectrum network. The direct sequences spreading spectrum technique is achieved in a time domain where a series of pulse sequences encodes every bit transmitted depending on chipping pattern. The output is then used to modulate the carrier that the laser source generates, and the spreading ratio between the chipping rate and user data speed is determined. These sequences are copied to each channel. However, only the matched code at the correlators is decoded by using the on-off keying technique at the transmitter. For the level of bits received at the decision circuit, the thresholding technique is used at the receiver. The mode-locked laser can provide the minimum level of synchronization and coherent source that this system requires, but the laser can be relatively costly (Dexter, 2010).

2.2.2 Frequency Hopping Spread-Spectrum

The frequency-hopping spreading spectrum technique is achieved in the frequency domain. Information is modulated via a carrier component with a frequency that varies over a wide range. The variation pattern and spectral separation are defined by pseudo-random code sequences. Thus, the transmitted signal consists of a series of components that hop around the frequency spectrum. The carrier frequency varies based on the frequency hopping code of the encoder. A selective, narrowband filter is required to be tuned at the frequency range corresponding to the transmitter. Conversely, a broadband spectrum of user input data in the frequency-encoded spreading spectrum system is encoded into a number of frequency components. Both techniques are in contrast to the direct sequences technique achieved in the time domain.

2.3 OCDMA Architecture and Equipment

The OCDMA system is developed by several optical fibers connected to a passive star coupler and split among several users. As every user broadcasts to all other users, OCDMA can be applied in a multi-wavelength WDM network by assigning different wavelengths to different users (Salehi, 1989). OCDMA techniques could possibly support up to gigabit data rates for a number of users without integrating with the WDM system. The switching function of OCDMA networks is performed by the distribution of codes, which reduces the cost and complexity of coordinating and switching multiple wavelengths with the TOWC in WDM. Figure 2.1 illustrates how the connection among several nodes is developed using different codes that use encoders and decoders. Optical sources are characterized by coherent time. After data encoding, the multiplexed signals of *n* active users are linearly superimposed at the optical channel.

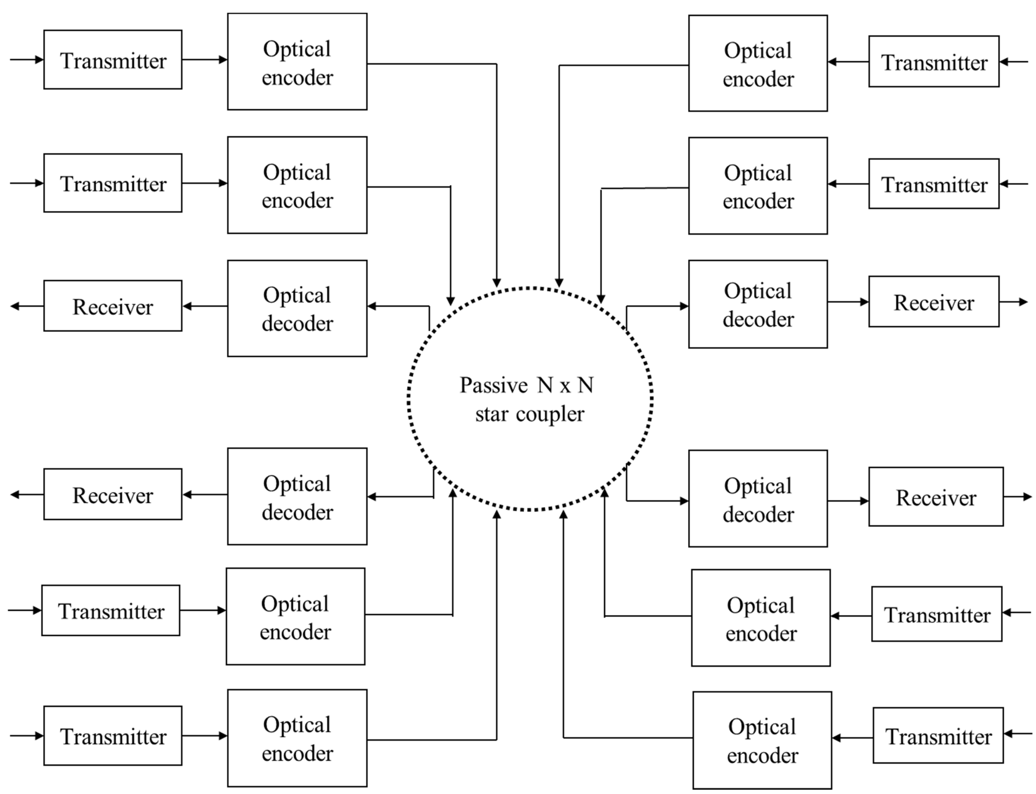

Figure 2.1: Connections in OCDMA system by using star topology.

The receiver model consists of coupler, decoders, and differential detector as shown in Figure 2.2. In a coherent OCDMA system, bipolar codes can be used via a phase coding technique known as bipolar phase shift keying. The signal is assumed to be orthogonal where the bipolar encoder and decoder are used. Thus, each transmitter operates at a wavelength and an optical code, which is unique to the corresponding transmitter (Salehi, 1989), whereas each receiver is tuned to a wavelength and an optical code that is also unique to the receiver. Each node is relatively equipped with a transmitter and a receiver. In the optical packet switched network, each input packet is stamped with a signature that corresponds to the intended output port.

Each output port has a certain number of assigned signatures. A given output port can address more than one packet simultaneously. The stamped packets are combined in a common medium, and these combined streams of packets are sent to every output port (Kamath, 2004). At each output port, standard CDMA decoding techniques are used so that only the appropriate packet leaves each port. A buffering mechanism is required to accommodate the simultaneous exits at a given output port. In the OCDMA system, OC_{ij} represents the optical codes j on the wavelength λ_i. If node 1 uses two different optical codes on the same wavelength λ_1, then the node can be represented by OC_{11} and OC_{12}.

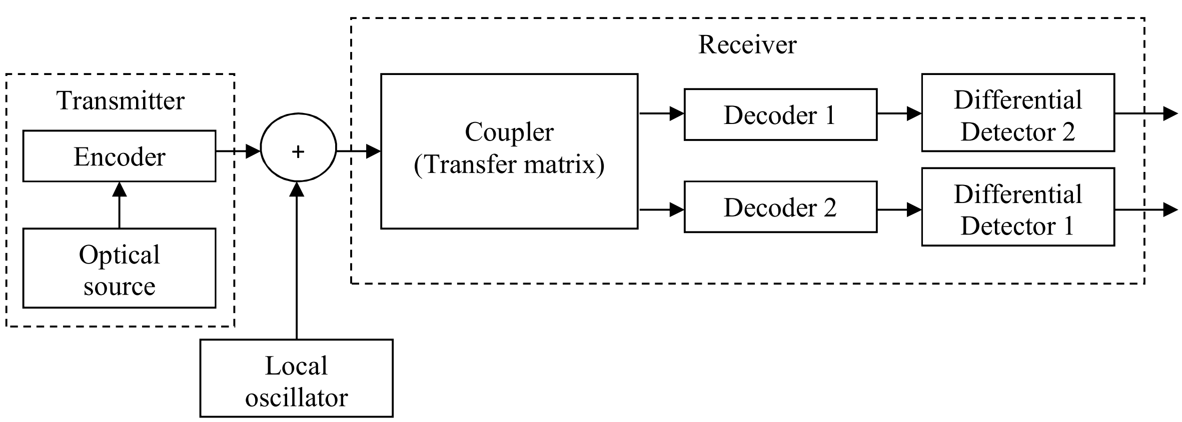

Figure 2.2: Encoder (transmitter) and decoder (receiver) models in an OCDMA system.

If the receiver node of node 1 is tuned to the same optical code on two different wavelengths λ_5 and λ_7, then the receiver node can be represented by OC_{51} and OC_{71}. In a packet-slotted OCDMA network with *N* nodes and *C* codes (N > C), the node set is defined as {1, 2,…, *N*} where the code set is {1, 2,…, *C*} as shown in Figure 2.3. The requests are stored in the controller and the scheduling algorithm is implemented via slot basis (Kamath, 2004). The duration for one slot is equal to the transmission time required for each data packet. The network employs a centralized controller for code assignment and transmission scheduling. The controller involves three important stages: request, scheduling, and notification.

The nodes send access requests to the centralized controller, which are then scheduled for contention-free transmission. Scheduling is constrained by the number of codes, *C* in a packet-switching OCDMA network with a single data transmitter and receiver at each node, and limits the number of requests served to the code numbers during a slot. At the beginning of each cycle, the controller polls all request queues and develops a demand set for the current cycle. The controller notifies the nodes of the transmission timing and the code channels, and upon receipt of their assignments, the nodes immediately tune to the assigned codes for data transmission (Kamath, 2004).

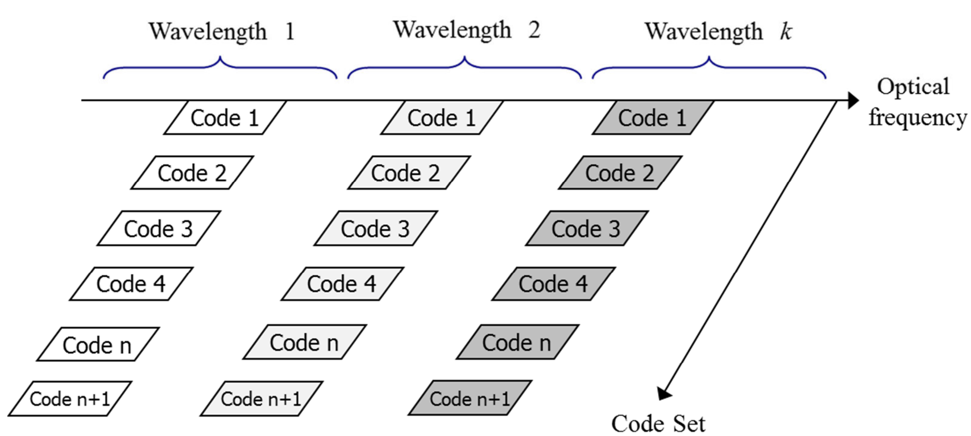

Figure 2.3: Different code sets transmit at multiple wavelengths.

The controller schedules these requests for transmission, assigning the request codes and time slots. When this batch of requests has been completely scheduled, the controller starts the next cycle. A random binary matrix specifies the scheduled requests for each cycle. Table 2.1 illustrates various codes and wavelengths assigned at different nodes. The source-destination pair is represented by (s, d) as shown in Figure 2.4. The random variable is assumed to be independent and identically distributed with probability. The algorithm randomly selects a request from the matrix for arbitration and the process continues until all requests are granted or all codes are used (Kamath, 2004). An available code is selected from the code pool when a request is made. Basically, the optical switch consists of several important functional blocks and stages (i.e., label processing, scheduling, switching, routing, and buffering). Label processing is performed electronically and optically (Kamath, 2004). Ideally, optical label processing via the optical label processor reduces the unnecessary conversion of the signal domain from optical to electrical and vice versa. However, the conversion of E/O/E degrades the signal quality, and introduces unwanted noise and delay.

Table 2.1: Different codes and wavelengths used in multiple outbound and inbound links.

Node n	outbound	outbound	wavelength	code	inbound	inbound	wavelength	code
Node 1	$oc_{(1, 1)}$	$oc_{(1, 2)}$	1	1,2	$oc_{(5, 1)}$	$oc_{(7, 1)}$	5,7	1
Node 2	$oc_{(2, 1)}$	$oc_{(2, 2)}$	2	1,2	$oc_{(5, 2)}$	$oc_{(7, 2)}$	5,7	2
Node 3	$oc_{(3, 1)}$	$oc_{(3, 2)}$	3	1,2	$oc_{(6, 1)}$	$oc_{(8, 1)}$	6,8	1
Node 4	$oc_{(4, 1)}$	$oc_{(4, 2)}$	4	1,2	$oc_{(6, 2)}$	$oc_{(8, 2)}$	6,8	2
Node 5	$oc_{(5, 1)}$	$oc_{(5, 2)}$	5	1,2	$oc_{(1, 1)}$	$oc_{(3, 1)}$	1,3	1
Node 6	$oc_{(6, 1)}$	$oc_{(6, 2)}$	6	1,2	$oc_{(1, 2)}$	$oc_{(3, 2)}$	1,3	2
Node 7	$oc_{(7, 1)}$	$oc_{(7, 2)}$	7	1,2	$oc_{(2, 1)}$	$oc_{(4, 1)}$	2,4	1
Node 8	$oc_{(8, 1)}$	$oc_{(8, 2)}$	8	1,2	$oc_{(2, 2)}$	$oc_{(4, 2)}$	2,4	2

Thus, the optical datagram via the optical code has attracted attention from the communication sector. The scheduling process is conducted via the field programmable gate array (FPGA), and the buffering is realized via the optical fiber delay lines. The routing table determines the designated port for the switch as shown in Figure 2.4. Label processing is performed electronically in the conventional system. However, the electronic process limits the capacity of the optical fiber link because of the use of the electronic memory access. Thus, the optical code-based header is used and analyzed optically by employing the planar light-wave circuit (PLC).

Ideally, optical correlators in an all-optical label processing network work as a label bank, where the optical codes that indicate the destination address in the routing table are stored. Label recognition is performed via parallel optical correlations between the optical codes at the input and in the label bank in the time domain (Banerjee, 2001). Correlators decode the input codes of each packet header. The signal at the correlators output indicates high and low value; the values correspond to matched and unmatched cases, respectively. The label processor controls the optical switch and provides the packet delivering information to the scheduler.

$$
\begin{array}{c c}
\text{Source node} & \\
\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} & \left\{ \begin{array}{ccccc} 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \end{array} \right\} \\
 & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
 & \text{Destination node}
\end{array}
$$

	Slot 1	Slot 2	Slot 3
Code 1	(1, 1)	(1, 3)	(1, 4)
Code 2	(1, 5)	(2, 3)	(2, 5)
Code 3	(3, 1)	(3, 2)	(3, 4)
Code 4	(4, 2)	(4, 3)	(4, 5)

Figure 2.4: Mapping of the source and destination nodes by different codes.

2.3.1 Transmitter Model

At the transmitter as shown in Figure 2.5, the optical packet generator is realized via the mode locked laser diode at the pulse rate of 10 GHz with 2 ps of pulse duration. The intensity modulator is intended to reduce the repetition rate of the pulse and to generate a label for a packet. The PLC-type encoder converts the low rate pulses to optical code labels. The pulses are modulated at the rate of 10 Gbit/s by the intensity modulator. Optical amplifiers, band pass filters, and optical fiber delay lines are used for signal conditioning. Moreover, the optical time division multiplexing (OTDM) type multiplexer converts the 10 Gb/s data stream to 40 Gbit/s output data (Wang, 2007). The essential functional blocks of an optical switching stage are shown in Figure 2.6. The label processing can be achieved in optical or electrical domain. The routing policy determines the packet routing, whereas the scheduling can be achieved by using field-programmable gate array (FPGA) technology. Some test bed demonstrated the feasibility of SOA gate switches to support 200 Gchip/s at 10 Gbps/port of transmission capacity (Wang, 2007).

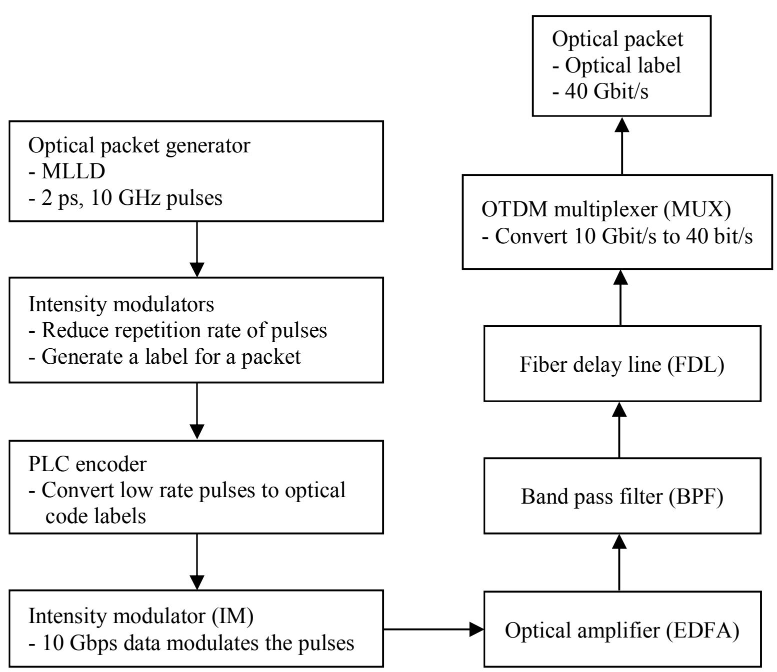

Figure 2.5: Key functional blocks in an optical packet switched network.

2.3.2 Receiver Model

At the receiver, the optical correlators, band pass filters, photo detectors, optical fiber delay lines, and gate signal generators determine the PLC decoder, which makes up the label processor (Wang, 2007). Packet labels are processed in a parallel manner and determined by the lookup table. Ideally, label processing should not involve O/E and E/O conversion. In the optical switch, the optical correlation occurs when the incoming optical code is compared with the lookup table. The decoder generates a high peak signal for the matched code, indicating the autocorrelation wave (Wang, 2007). The optical gate switch is then triggered and opened to designate the packet to the corresponding output port. The routing process occurs via the gate signal generator. The decoder generates a low peak signal for the unmatched case, indicating the cross-correlation wave. The optical gate switch is triggered and closed.

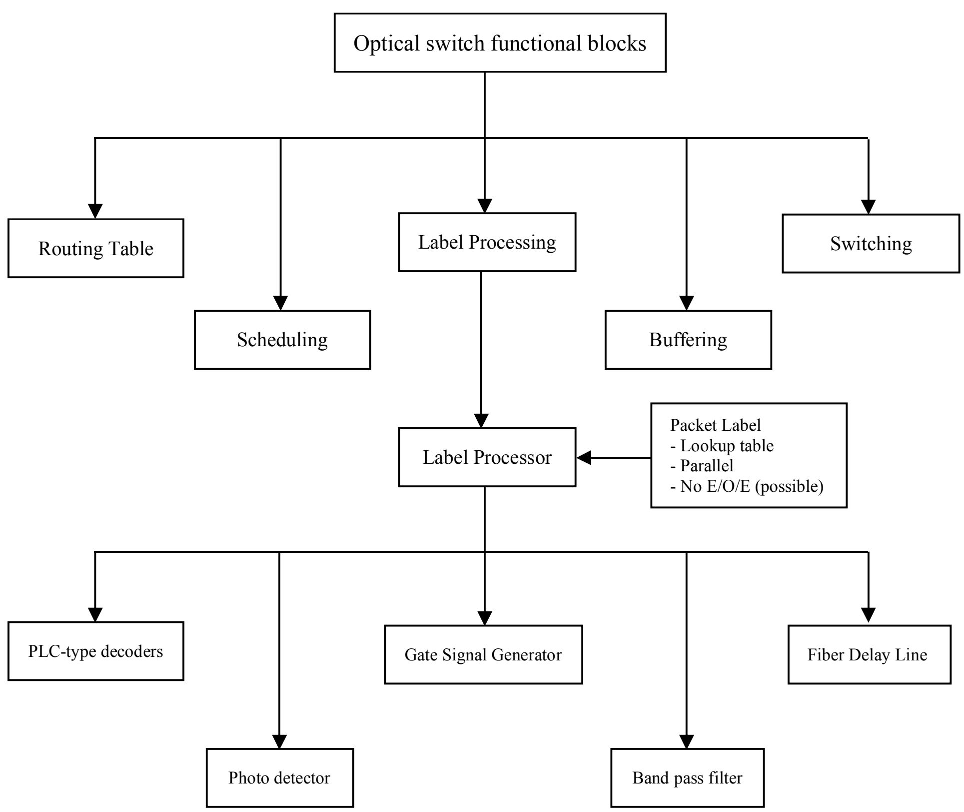

Figure 2.6: The key elements in an optical switch and label processing.

2.4 OCDMA Encoder and Decoder

The generation and recognition of the code are essential factors in determining the success of the OCDMA system. Because of the immaturity of the encoding and decoding mechanism in OCDMA, the encoding techniques evolve from the utilization of fiber delay lines (FDL) to the arrayed waveguide grating (AWG), planar light wave circuit (PLC), fiber Bragg grating (FBG) and superstructure fiber Bragg grating (Teh, 2003). In OSCDMA system, programmable optical filter, broadband light sources, TFF and free-space diffraction grating are used (Aljunid, 2005). The encoding and decoding in OCDMA system can implemented in coherent and incoherent manner. Thus, the design of the encoder and decoder varies in different encoding system. Section 2.4.1, 2.4.2 and 2.4.3 will discuss the commonly used techniques in OCDMA system.

2.4.1 Fiber Delay Lines

Waveguide-based delay lines as shown in Figure 2.7 (Teh, 2003) are used in time domain via temporal encoding and in the frequency domain via spectral encoding using an array of discrete delay lines. Several fibers with length variations are coupled via fiber couplers. However, storing the data in an optical fiber and retrieving the data at the right timing are difficult. Moreover, the fiber length dimensions determine the accuracy of the encoding process. Large amounts of fiber spans increase the complexity of the system architecture and make the system bulky (Teh, 2003). The pulse needs to be placed at a different delay in accordance with the code pattern, and be combined via a passive optical coupler. Since the delay line is employed, the decision circuit at the receiver may require extra synchronization stages, which may lead to higher complexity of data extraction; such configuration is not compatible with high-speed networks.

2.4.2 Arrayed Waveguide Grating and Planar Light-wave Circuit

The planar light-wave circuit (PLC) is used via the tunable taps, phase shifters, and combiner. The installation of PLC is temperature-controlled to minimize the environmental fluctuations in order to achieve good system stability. PLC-based encoder able to achieves bipolar encoding with phase shift of 0º and 180º. The arrayed waveguide grating (AWG) is another technique achieved via PLC technology (Teh, 2003). However, the fabrication and utilization of PLC technology is not cost effective. Another type of encoding is the utilization of diffractive free space optics which requires diffraction grating pair and phase mask to separate and recombine the frequency components of a short pulse. Besides, programmable (liquid crystal modulator) phase mask with mode locked loop laser can be used in time-spreading OCDMA system (Aljunid, 2005).

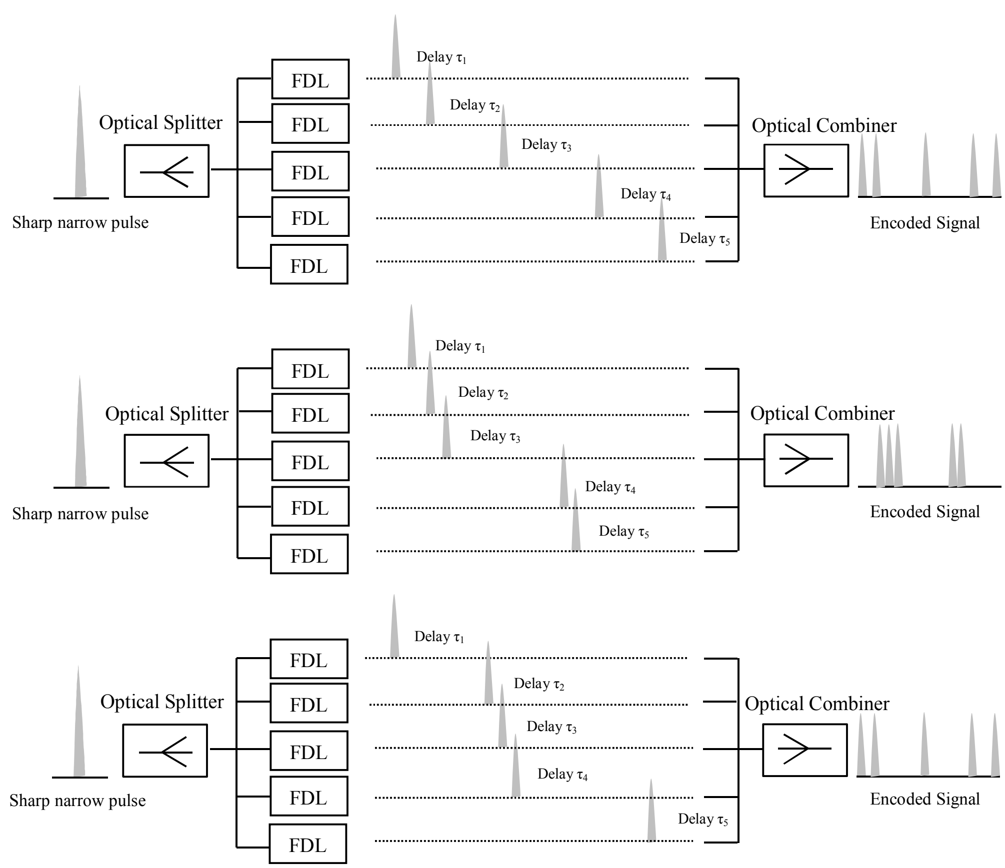

Figure 2.7: The encoded signals in a direct-sequence OCDMA by using FDLs.

2.4.3 Super-structured Fiber Bragg Grating

The FBG is used as the encoder by changing the refractive index modulation at the grating along the fiber. The dimensions of FBG length, spacing, reflectivity, and grating profile are configured based on the code sequences used, and are imprinted on the core of the fiber. This technique applies both unipolar and bipolar encoding (Teh, 2003). Moreover, different design parameters of optical code sequences at different chip lengths and code weights can be applied via a SSFBG because of the reconfigurable ability of FBG. The size of this encoder is relatively smaller depending on the grating configurations. This encoder can also be integrated via a coherent light source where only a single-frequency carrier is used to support multiple users. Such a configuration eliminates the use of the TOWC and reduces ASE noise. Phase coding can be adopted via this encoder; the phase is inverted between 0º and 180º with a uniform refractive index modulation, which provides a relatively lower cross talk and improves spectral efficiency. There are other FBG structures: uniform grating, chirped grating and apodized grating, etc.

2.5 OCDMA Encoding and Decoding Techniques

The encoding and decoding of OCDMA is done in all-optical form or partly optical form, and data signals are in either optical or electrical form, which involves O/E and E/O conversion. The encoding and decoding of OCDMA is done in a coherent and incoherent way (Dexter, 2010). Normally, the all-optical CDMA system is done using an incoherent approach. In coherent OCDMA systems, the complex form of the optical field is manipulated in terms of amplitude or phase. Phase shift is one of the key elements of code set design as well as the encoding mechanism. Coherent and incoherent systems exhibit the differences in term of the employment of encoding approach and equipment.

2.5.1 Coherent Coding

Optical delay lines and phase shifters are used in coherent OCDMA, which can be conducted in partly optical or all-optical form. In a partly optical system, the chip sequence used to modulate the optical carrier is generated electronically. These types of coherent OCDMA systems are delayed line-based coherent direct sequence OCDMA and time spread OCDMA (Dexter, 2010). In the delayed line based coherent direct sequence OCDMA, each pulse is modulated and split into sub-pulses and combined using a passive coupler into a single fiber. The position of the pulse and the length of the fiber are important design parameters determined by code sequences. The time spread OCDMA uses a mode locked loop laser (MLL) using on-off keying modulation. This technique involves the utilization of Bragg grating and programmable liquid crystal modular phase mask where the phase shift is conducted.

2.5.1.1 Temporal Phase Coding

Temporal phase coding is similar to the temporal spread technique in which the bit duration is segmented into several slots; the number of slots depends on the number of chips and the total chip number is the chip length. Sharp, narrow optical pulses are used, with each phase shifted based on the code sequences, typically between 0º and 180º (Dexter, 2010). Unlike intensity-modulated signals in direct detection, such a technique does not solely rely on the position of the pulse. Sometimes the inappropriate allocation of the position of the pulse may deteriorate the bit error rate (BER), which may not be a significant issue in temporal phase coding. The temporal phase coding technique has been employed in OCDMA and OCDMA/WDM systems at different bit rates via different lengths of chipping pattern using FBG.

Several encoding techniques are adopted for a coherent light source system, including the coherent time with direct reception and envelope detection, coherent time with heterodyne or homodyne reception, and coherent frequency coding with direct reception and envelope detection.

2.5.1.2 Spectral Phase Coding

Spectral phase coding uses short pulses that are generated by the mode-locked laser because of its coherence; the spectral of the pulse is segmented into several discrete spectral, with a particular phase shift between 0º and 180º normally applied to it (Dexter, 2010). The decoder requires a spectral phase mask and diffraction grating to decode the data. Several test beds have been developed, and the nonlinear device for thresholding performs the multi-user interference (MUI) reduction. In the spectral phase coding, time gating and AWG are used for detection and spectral coding, respectively.

2.5.2 Incoherent Coding

The incoherent optical CDMA has attracted the attention of the communication sector because of its ease of implementation. The en/decoding depend on the optical power levels. Normally, the detection is conducted using direct detection. Incoherent coding, such as incoherent spectral intensity encoded OCDMA and optical spectral OCDMA, use an incoherent broadband light source (Dexter, 2010). Possible coding used for non-coherent light sources consists of non-coherent time addressing unipolar sequences, non-coherent time addressing bipolar sequences, spectral encoding with unipolar or bipolar sequences, quasi-coherent phase addressing ternary sequences, quasi-coherent time addressing ternary sequences, and quasi-coherent phase addressing differential detection.

2.5.2.1 Temporal Spreading Coding

In the temporal spreading coding system, each bit duration is segmented into several small time intervals depending on the number of chips used in the code sequences. The total number of the chips multiplied by chip duration is the total length of the code sequences. Such a technique depends on the placement of the pulse at different positions according to code sequence patterns. The code weight determines the number of symbol one in the code word (Dexter, 2010). The temporal spreading coding system is dependent on the intensity of the pulse at the receiver. Thus, the minimum power received has to be estimated to achieve a certain BER. The matched code generates a high peak of the autocorrelation wave and a low peak of the cross-correlation wave for the unmatched code. This technique has certain tradeoffs even with its relative ease of implementation. Longer code lengths may be needed to support more users and maintain lower MUI.

2.5.2.2 Spectral Intensity Coding

In spectral intensity coding system, the encoding mechanism is carried out in wavelength domain instead of time domain. The code length is independent of the date rate (Dexter, 2010). Oppositely, in time domain encoding system, the code length depends on the allowable date rate. In Spectral intensity coding uses a broadband source to pass through an amplitude mask and encode the input signal in accordance with the code sequences in the wavelength domain. The longer the code sequences are, the higher is the number of frequency bins needed to modulate the amplitude of each frequency component (Dexter, 2010). This technique may have to use diffraction grating and lens to disperse the frequency components of the signal. Spectral amplitude masking is used to modulate the frequency-dispersed signal and the spectrum is recombined using diffraction grating.

2.6 OCDMA Codes

In an OCDMA system, each user is distinguished and identified using different signature sequences or code words. Each bit of information data is encoded by the signature sequence. The signature sequences are a series of chips that depend on the chipping pattern. Any sequence sent represents the unique signature of the user who sent the information. All users sharing the transmission medium use different unique sequences from different optical code sets combined and sent over the channel. Several coding schemes and mechanisms have been developed, such as optical orthogonal codes, prime sequence codes, modified prime codes, modified frequency hopping codes, Hadmard codes, double weight codes, and modified double weight codes (Aljunid, 2005).

Each signature sequence and code word has different lengths, weights, properties, merits, and demerits. The ultimate objective is to allow multiple users to access the network asynchronously and simultaneously. Another goal is to reduce the MUI. Thus, testing the code sequences using suitable encoders and encoding techniques is important, as well as examining the code sequences in a practical optical network, such as an access and metropolitan area network under different user number and bit rate considering all possible noise sources, MUI effect, and design parameters. For all else, the competency still remains unknown.

2.6.1 Prime Codes

Prime codes use total length $l = P^2$, where P is the prime power. The prime sequences are obtained using the Galois field GF(P) with the code size and code weight of P (Aljunid, 2005). The number of users and code weight can be any prime number, P. If the GF(P) of the prime code is expressed as (0, 1, 2,…., P - 1), then a prime sequence of $S_y = (S_{y0,} S_{y1,\ldots,} S_{y(p-1)})$ can be constructed. Prime codes are generated using a prime number. The prime number that indicates the number 1 in the code is the prime number, P. The code length is P^2 with the peak autocorrelation of P because the code length is determined by the square of the prime power. A longer code with a larger prime value is required to support more users.

2.6.2 Maximal Length Sequences

Maximal length sequences are generated by linear feedback shift register with the linear polynomial $y(x)$ of degree, n which can be expressed by: $y(x) = y_n a^n + y_{n-1} a^{n-1} + y_{n-2} a^{n-2} + \cdots + y_1 a + y_0$ where $a^n = y_{n-1} a^{n-1} + y_{n-2} a^{n-2} + y_{n-3} a^{n-3} + \ldots + y_1 a + y_0$. The maximum number of non-zero states is estimated via $2^n - 1$, where the states of the shift register are changed based on the recurrence conditions. This code has periodic autocorrelation and aperiodic autocorrelation, depending on the synchronization window used. Any code in these sequences has the $2^n - 1$ of symbol one and $2^{n-1} - 1$ of symbol zero, which is suitable for code synchronization. However, larger cross-correlation may occur among some of the codes.

2.6.3 Walsh-Hadamard Codes

Walsh-Hadamard codes are commonly used in CDMA because of the low cross-correlation properties of the codes when synchronization is applied. These codes are derived from the basic matrix containing all the rows of one (Aljunid, 2005). The other rows have equal numbers of one and a negative one. The interchange of row and column, or the sign in the row or column, does not affect the orthogonality in the code matrix.

The characteristic can be expressed by $HH^T = nI_n$ and $HH^T = H^TH$, where n is the Hadamard matrix, with the dimension of n, H^T is the transpose of H, and I is the identity matrix. If synchronization among the users is not achieved, then the cross-correlation may not be zero. Generating such a code is conducted through a recursive procedure using the basic matrix for a size matrix of 4 which can be expressed by:

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

2.7 OCDMA Detection Techniques

Coherent and incoherent detection techniques are used in an OCDMA system. Coherent detection refers to the detection of information signals on the phase of the carrier, whereas incoherent detection does not consider the phase of the carrier. Conventionally, the incoherent system utilizes unipolar code sequences, whereas the coherent system utilizes bipolar code sequences. The advantages of the incoherent system are the simplicity of the design and the absence of the strict synchronization stage because the phase shift is not the main concern. Conversely, the coherent system employs a more complex design architecture and synchronization stages are needed in certain cases. Figure 2.8 illustrates a delayed line based coherent direct sequences OCDMA system (Aljunid, 2005).

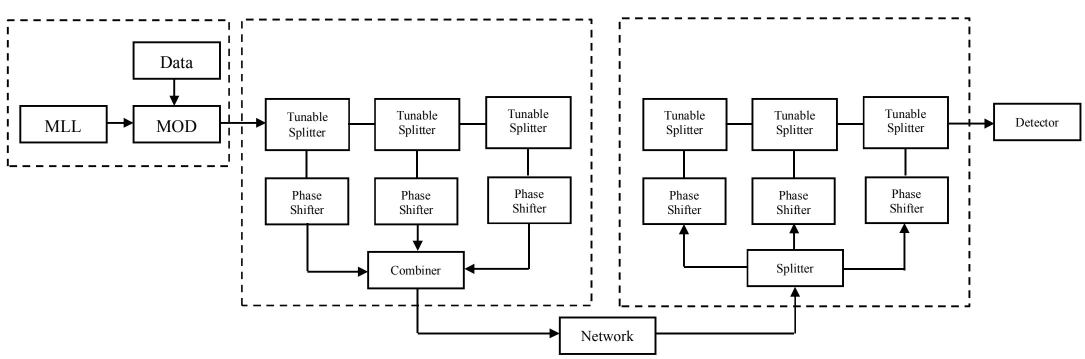

Figure 2.8: FDL-based coherent, direct-sequence OCDMA system.

2.7.1 Coherent Detection

Coherent detection typically uses higher receiver sensitivity by maintaining relatively lower noise levels at certain SNR, which is performed via a high-power local oscillator and a high quantum efficient detector. However, this condition leads to system complexity and requires precision in coherence and frequency selectivity, which can be costly. Moreover, the addition polarizer has to be used to ensure the polarization of the transmitter signal in accordance with the local oscillator receiver signal. Phase coherency has to be achieved along with the transmission.

2.7.2 Direct Detection

Direct detection normally uses the intensity modulator or the input signal directly modulates the optical source. Several intensity-modulated signals are coupled and sent via the optical fiber. The receiver uses a photodiode, which may involve O/E conversion; this process can be conducted in a lower cost system with greater simplicity. The amplification stage and a higher power laser source may be required to support longer transmission distances because detection depends on the power level received. The thresholding technique used is for the detection of the minimum level of signal power to determine the symbol one or zero at the decision circuit (Aljunid, 2005). Thus, to be reconstructed correctly, the signal that reaches the receiver must maintain the minimum level of receiver sensitivity. Along with the transmission, various noise sources and ISI are added into the intended signal, making the detection and differentiation between the real signal and the noise more difficult. This issue is resolved via line coding, which involves changing the form of the signal representation or the adding extra bits into the signal.

2.8 Codes Correlations Properties

The ultimate goal of optical CDMA is to extract data with the desired address codes in the presence of all users. Orthogonality plays a significant role in the optical CDMA system. The design of the code set consists of two significant properties: auto correlation and cross correlation functions. Auto correlations and cross correlations are important processes in the OCDMA system. Multiple access interference is insignificant compared with the energy contained in the received information. If both autocorrelation and cross-correlation are large, then the multiple access interference is significant as the number of users increases. The length of code words increases as the number of users increases (Chung, 1989).

2.8.1 Cross Correlation

The cross correlation measures the similarity of two signals and is used to find features in an unknown signal through comparison with a known one. The cross-correlation represents the degree of mutual interference between two code sequences. An OCDMA code can be represented by (N, W, λ_c). N is the code length of the code sequence, and the weight of each code sequence, W is the number 1 inside the code sequence (Salehi, 1989). λ_c denotes the maximum cross-correlation value between any two code sequences and indicates the number of spectral overlapping in the sequence. The cross correlation of $R_x(t_1, t_2)$ and $R_y(t_1, t_2)$ are defined in equation (2.3) and (2.4).

$$R_{xy}(t_1, t_2) = E\{x_1 y_2^*\} = \iint x_1 y_2^* p(x_1, y_2) dx_1 dy_2 \tag{2.3}$$

$$R_{yx}(t_1, t_2) = E\{y_1 x_2^*\} = \iint y_1 x_2^* p(y_1, x_2) dy_1 dx_2 \tag{2.4}$$

λ_c denotes the maximum cross-correlation value between any two code sequences and indicates the number of spectral overlapping in the sequence. The cross correlation, λ_c between any pair of code sequences must be small, which ensures that each code sequence is easily distinguished from every other address sequence. For code sequences, $X = (x_1, x_2, \dots, x_N)$ and $Y = (y_1, y_2, \dots, y_N)$, the cross-correlation is given by: $\lambda_c = \sum_{i=1}^{N} x_i y_i$ (Prucnal, 1986). Codes with ideal in-phase cross correlation, $\lambda_c \leq 1$ are required in OCDMA systems because these codes minimize MUI and suppress the effect of phase-induced intensity noise (PIIN). MUI can be eliminated if the cross-correlation is less than 1.

2.8.2 Auto Correlation

For signal analysis purposes, the auto correlation measures how well a signal matches the time-shift version of itself as a function of the amount of time shift, and the cross correlation of a signal with itself is always at a peak with a zero lag. The continuous autocorrelation, $R(\tau)$ for a signal is defined as the continuous cross-correlation integral of the signal with itself at lag, τ which is expressed in equation (2.5). The auto-correlation function determines how well the intended receiver detects a code sequence in the presence of mutual interference. For any code sequence, the non-shifted autocorrelation, λ_a is equal to the weight of the code sequence; thus, the autocorrelation should be as large as possible (Salehi, 1989). This condition ensures that the received signal is significantly larger than the background noise in the system. For the code sequences, $X = (x_1, x_2, \dots, x_N)$, the non-shifted autocorrelation is given by $\lambda_a = \sum_{i=1}^{N} x_i x_i$.

$$R_x(\tau) = \iint x_t x_{t-\tau}^* p(x_t, x_{t-\tau}) dx_t dx_{t-\tau} \quad (2.5)$$

$$R_x(t_1, t_2) = \iint x_1 x_2 p(x_1, x_2) dx_1 dx_2 \quad (2.6)$$

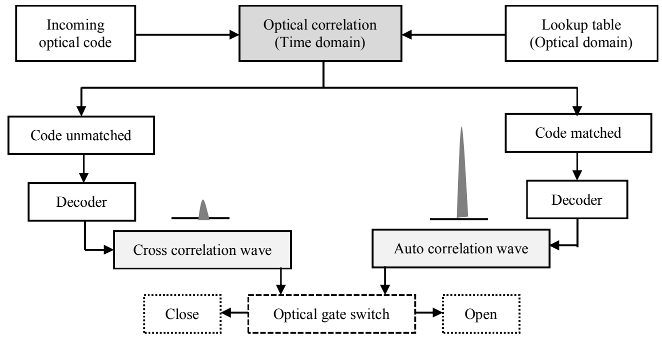

Figure 2.9: Optical correlations for matched and unmatched codes at the receiver.

The autocorrelation function for a random process is defined in equation (2.6), where x_1, x_2, …, x_n are random variables of $x(t)$, and the samples are chosen at t_1, t_2, …, t_n with probability density function of $p(x_1, \ldots, x_n)$. Two random process $x(t)$ and $y(t)$ have the autocorrelation of $R_x = (t_1, t_2)$ and $R_y = (t_1, t_2)$. Figure 2.9 illustrates the correlation processes for the matched and unmatched codes at the correlators in an optical switch. The autocorrelation and cross correlation waves are used to control the optical gate switch.

2.9 Multi-User Interference Reduction Techniques

MUI is a phenomenon that cannot be avoided in an OCDMA system. The effect of MUI deteriorates with the increase in the number of simultaneous users. This condition is minimized using a dispersion compensating device, longer code lengths, or orthogonal unique sequences. Several approaches have been introduced, including time gating and thresholding. MUI reduction is conducted more effectively in the optical domain than in the electrical domain. Thus, most MUI approaches are performed in the optical domain. Optical time gating can be realized via nonlinear optical loop mirror (NOLM) and terahertz optical asymmetric demultiplexer (TOAD) whereas optical thresholding can be carried out via NOLM thresholding, TOAD thresholding and fiber-based thresholding (Dexter, 2010). Section 2.9.1 and section 2.9.2 will further elaborate these techniques.

2.9.1 Time Gating

Both NOLM and TOAD techniques have to be conducted in a synchronized system where the autocorrelation peak is detected within a predefined time slot. The optical clock controls the time gate. Normally, clock pulses, fiber loops, isolators, 50:50 couplers, and band pass filters are required in the nonlinear loop mirror approach. This technique is employed in temporal phase OCDMA system. However, this technique has certain constraints, such as the bulkiness of the fiber loops and the high optical power requirement of such configurations. An alternative method to time gating is TOAD, which is a type of interferometer. TOAD requires the additional semiconductor optical amplifier to manipulate the gain and phase as well as control the time gate.

2.9.2 Thresholding

This technique depends on the non-linear power-transfer response of the optical devices to minimize the MUI. (Dexter, 2010). Several studies have demonstrated the optical thresholding approach to achieve the MUI reduction via the implementation of holey fiber, which has a relatively high nonlinearity and short length at 8.7 m, incorporating a band pass filter at 1555.5 nm, 1 nm of full-width at half-maximum (FWHM), Erbium-doped fiber amplifier, and super-structured FBG (Teh, 2003). Optical thresholding is also achieved via the NOLM thresholding, TOAD thresholding, and fiber-based thresholding using highly nonlinear fiber, Holey fiber, and dispersion-flattened fiber via self-phase modulation because of its nonlinearity (Dexter, 2010). MUI and OBN limit the maximum number of users which can be supported by an OCDMA system. Current resolutions for the above mentioned issues exhibit several limitations including synchronization and the need of long fiber span as well the requirement of special type of fiber (Dexter, 2010).

2.10 OCDMA Network and Topology

Conventionally, the optical network is categorized into local, access, metropolitan, and long-haul transmission. The OCDMA network spans point-to-point from the access network to the metropolitan area network. The access network normally covers up to 25 km and the metropolitan area network covers 10 km to 100 km. Long-haul transmissions span from 100 km and more.

2.10.1 Access Network

The access network is the first and last point that connects the users to the network as shown in Figure 2.10. The traditional copper twisted pair network has to be upgraded to support a greater data rate in the presence of multiple user access. However, installing optical fiber can be costly. The problems are more complicated in urban areas where the users are scattered. Hybrid techniques, such as the hybrid fiber coax, are used before the optical network gradually replaces the conventional system (Dexter, 2010). The fiber-to-the-home (FTTH) implementation demonstrates a higher data rate than the twisted pair network. Direct modulation, incoherent detection, lower power laser, and simpler code design (distances from 5 km to 20 km) are sufficient to maintain adequate performance.

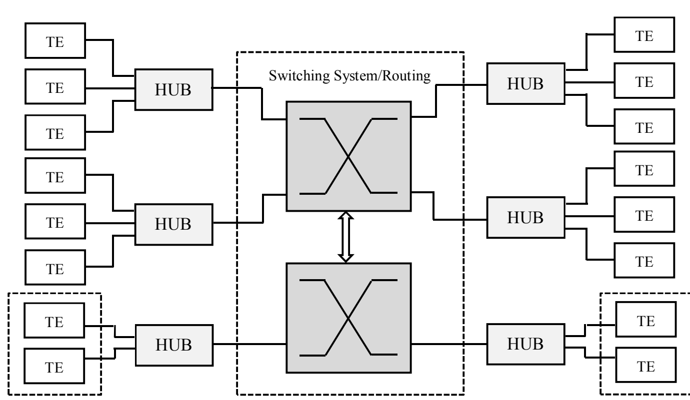

Figure 2.10: The connections of terminal equipment in a local area network.

2.10.2 Metropolitan Area Network

MAN interconnects with the access network and the long-haul network as shown in Figure 2.11. Thus, MAN must provide a sufficient transmission rate that is reliable, compatible, and flexible over long distances to support multiple users. For shorter range transmission with fewer users, the design consideration is less challenging; lower laser power, direct modulation, lower code length, and shorter chipping patterns are used to maintain error-free transmission. However, to support more users at a longer distance, various issues may emerge, such as increased dispersion, MUI, ISI, power penalty of the required power received, and complications in the code set design. Additional synchronization and polarization stages may be required depending on the encoding, modulation, and detection technique. Optimal code set designs, advanced modulation techniques, and MUI reduction techniques have to be formulated for optimized system performance to support long-distance transmission. Multilevel amplification stages are also required. However, these conditions might lead to issues of ASE noise and beat noise.

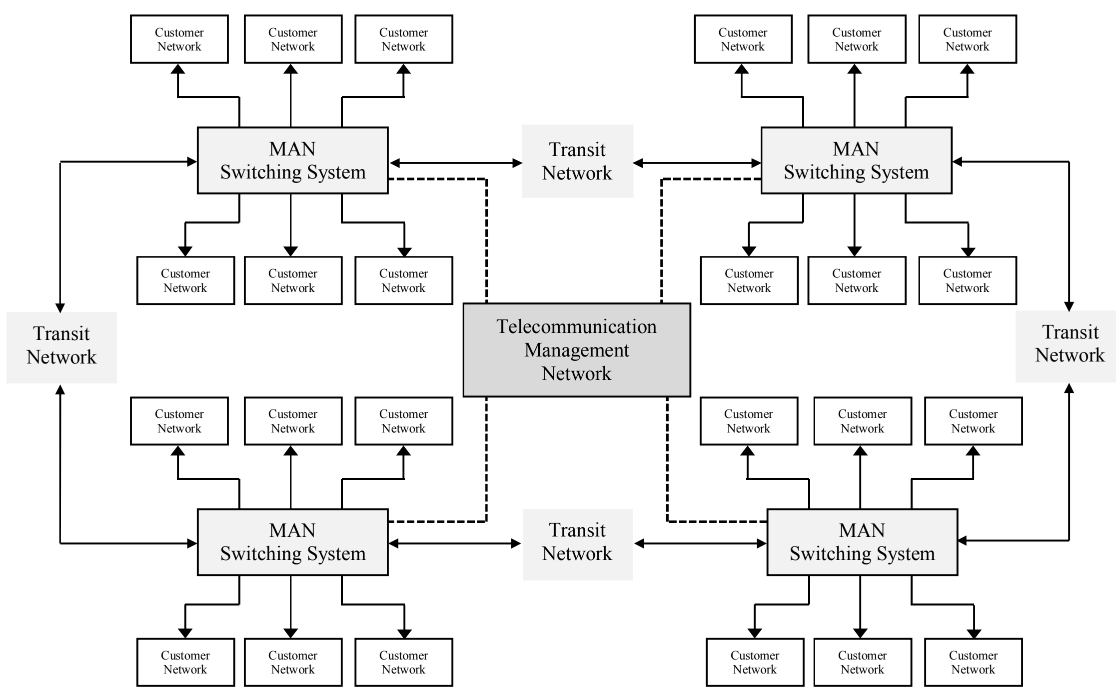

Figure 2.11: Architectural model of a metropolitan area network.

2.11 Packet Switched Network

In the packet switched network, packet arrivals are generalized through a Binomial process. Figure 2.12 illustrates the modes of traffic and the arrival rate in a packet switched network. The packet arrival is assumed to be uniformly distributed to all ports at the switch; this assumption is valid for high-speed optical packet switched network at line rate of 10 Gbps. However, real time traffic is bursty and unpredictable because of the services and applications of the users. The numbers of packets that arrive at the outbound fiber link during a particular time slot are assumed to be symmetrical (Banerjee, 2001). However, packet destinations that are non-uniformly distributed vary dynamically. Thus, the bursty model requires an on-off arrival process modulated by a two-state Markov chain. The probability density function of a random variable, X by $p(x)$ can be expressed by equation (2.7).

$$p(x) = dP(X \leq x)/dx = \sum_{i=1}^{n} P(x)\delta(x - x_i) = \int_{-\infty}^{\infty} p(x, y)dy \tag{2.7}$$

$$\rho_A = \frac{\lambda_T(1/\mu)}{Nk} \tag{2.8}$$

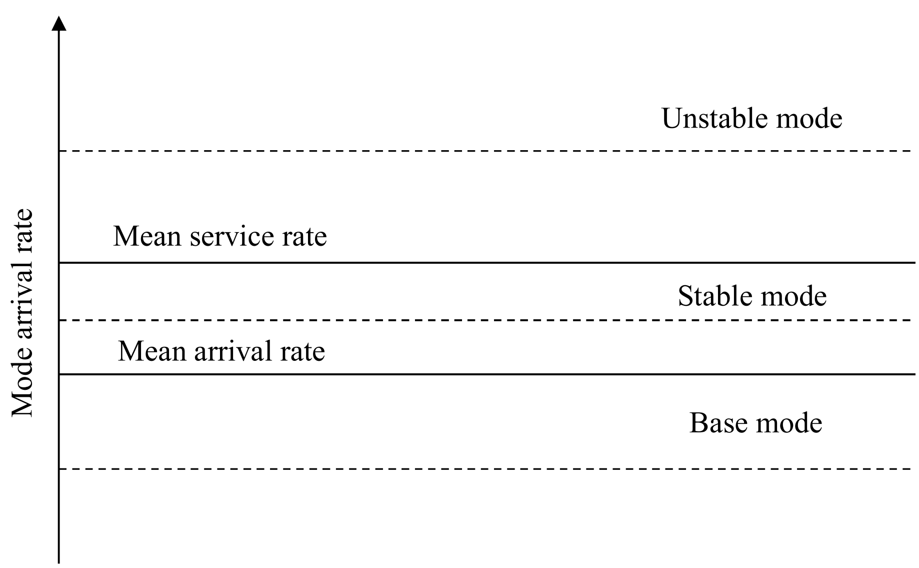

Figure 2.12: Modes of traffic and arrival rates in a packet-switched network.

Each node is in one of two states: bursty or resting, where P and q are the transition possibilities, respectively. In the bursty state, a packet that arrives at any time slot has an average length of $1/p$. In the resting or idle state, no packet arrives. λ_T represents the total arrival density, considering the arrival intensity at every inbound link. The average traffic load, ρ_A is defined by equation (2.8). A random variable, X has a continuous cumulative distribution function, which can be defined via the probability density function.

2.11.1 Random Process

Due to the randomness of spreading spectrum system, the detection mechanism can be defined via the Gaussian process. A real random variable, y defined over the interval, $-\infty < y < \infty$ having the probability density function as expressed in equation (2.9) is a Gaussian random variable where m_y and σ_y are the mean and variance respectively. The probability distribution function can be defined by equation (2.10) where $p(z) = \frac{1}{(2\pi)^{1/2}} exp\left[-\frac{z^2}{2}\right]$ and $z = \frac{(y-m_y)}{\sigma_y}$. If two zero-mean random variable y_1 and y_2 are Gaussian distributed where σ_{y1} and σ_{y2} are the variance for y_1 and y_2 respectively, the equivalent distribution function can be expressed by equation (2.11).

$$p(y) = \frac{1}{(2\pi)^{1/2}\sigma_y} exp\left[-\frac{{(y-m_{y})}^2}{2\sigma_y^2}\right] \tag{2.9}$$

$$P(z \leq a) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{a} exp\left[-\frac{z^2}{2}\right] dz \tag{2.10}$$

$$p(y_1,\ y_2) = \frac{1}{2\pi\sqrt{\sigma_{y1}^2\sigma_{y2}^2-\sigma_{y1y2}^2}} exp\left[\frac{-\sigma_{y2}^2 y_1^2+2\sigma_{y1y2}y_1y_2-\sigma_{y1}^2 y_2^2}{2(\sigma_{y1}^2\sigma_{y2}^2-\sigma_{y1y2}^2)}\right] \tag{2.11}$$

2.11.2 Traffic Arrival

The probability P[X(x)] that x packets arrived and addressed to the output line k as shown in Figure 2.13, the Binomial probabilities can be defined by equation (2.12) for $N \geq x$. The Poisson possibility is defined in equation (2.13), for m = np where n is the Bernoulli trails and p is the probability of success. If S_0 indicates the data is 0 and S_1 indicates the data is 1, the Poisson probabilities are defined in equations (2.14), (2.15) and (2.16) where $\sum_{k=0}^{\infty} P_r(k|H_0) = \sum_{k=0}^{\infty} P_r(k|H_1)$.

$$P[X(x)] = \binom{N}{x}\left(\frac{p}{N}\right)^x\left(1-\frac{p}{N}\right)^{N-x} = \frac{N!}{x!(N-x)!}\left(\frac{p}{N}\right)^x\left(1-\frac{p}{N}\right)^{N-x} \tag{2.12}$$

$$P(k) = \sum_{k=0}^{\infty}\frac{m^k e^{-m}}{k!} \tag{2.13}$$

$$P_r(k|H_1) = \frac{\lambda_1^k}{k!}e^{-\lambda 1} = P(x|1) = \frac{\left(N\frac{p}{N}\right)^x}{x!}\ e^{-N\frac{p}{N}} = \frac{p_1^x}{x!}e^{-p_1} \tag{2.14}$$

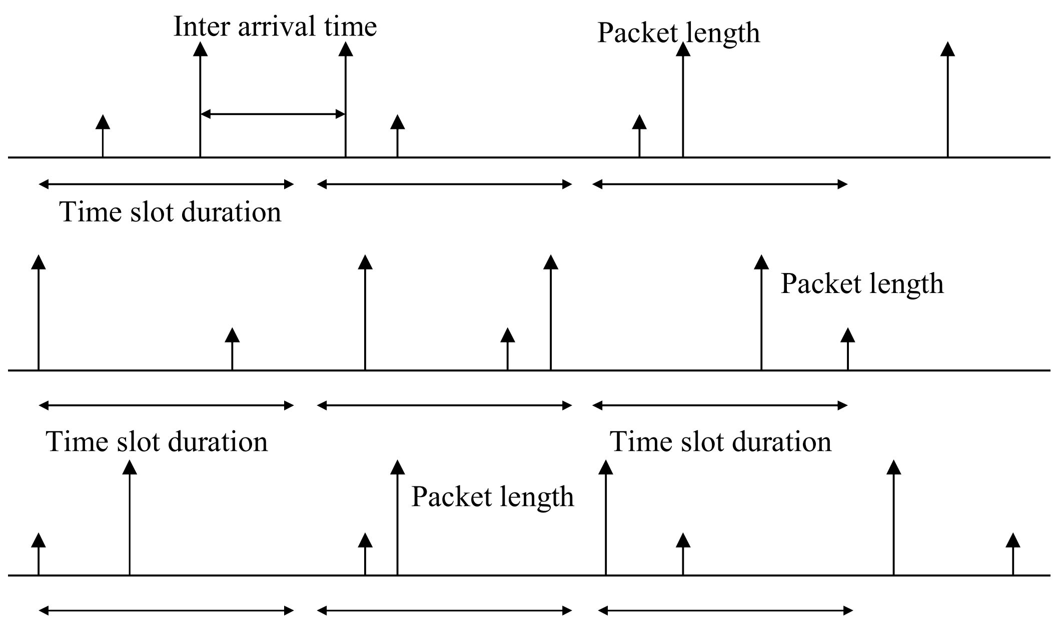

Figure 2.13: Traffic patterns in an optical packet-switched network.

$\sum_{k=0}^{\infty} P_r(k|H_0)$

$$= P(0|0) + P(1|0) + P(2|0) + P(3|0) + P(4|0) + P(5|0) + P(6|0) + P(7|0) +$$
$$P(8|0) + P(9|0) + P(10|0) + \cdots + P(100|0) + \cdots + P(1000|0) + \cdots + P(\infty|0) \quad (2.15)$$
$$= \frac{1}{e^{p_0}} + p_0^1 P(0|0) + \cdots + \frac{p_0^9}{10!} P(1|0) + \cdots + \frac{p_0^{40}}{50!-10!} P(10|0) + \cdots + \frac{p_0^{50}}{100!-50!} P(50|0)$$
$$+ \cdots + \frac{p_0^{\infty}}{\infty!} e^{-p_0}$$

$\sum_{k=0}^{\infty} P_r(k|H_1)$

$$= P(0|1) + P(1|1) + P(2|1) + P(3|1) + P(4|1) + P(5|1) + P(6|1) + P(7|1) +$$
$$P(8|1) + P(9|1) + P(10|1) + \cdots + P(100|1) + \cdots + P(1000|1) + \cdots + P(\infty|1) \quad (2.16)$$
$$= \frac{1}{e^{p_1}} + p_1^1 P(0|1) + \cdots + \frac{p_1^9}{10!} P(1|1) + \cdots + \frac{p_1^{40}}{50!-10!} P(10|1) + \cdots + \frac{p_1^{50}}{100!-50!} P(50|1)$$
$$+ \cdots + \frac{p_1^{\infty}}{\infty!} e^{-p_1}$$

2.12 Summary

This chapter reviews the characteristics, properties, and merits of the OCDMA technique. Several spreading spectrum techniques are studied, including the direct sequence spreading spectrum and frequency-hopping spreading spectrum technique. This chapter describes the standard OCDMA architecture and the equipment used (i.e., the transmitter and the receiver model). The OCDMA encoder and decoder types are explored (i.e., FDL, AWG, PLC, and SSFBG). OCDMA encoding and decoding techniques are outlined (i.e., coherent coding and incoherent coding). Several OCDMA code sets are examined, and detection techniques are studied (i.e., coherent detection and direct detection). The code correlation properties are reviewed and the MUI reduction techniques are investigated. This chapter also investigates the OCDMA network and topology, as well as the application in packet-switched networks. The materials referred are listed in Bibliography.