Chapter 3

BACKGROUND AND BASIC INFORMATION

3.1 INTRODUCTION

Optical code division multiple access (OCDMA) has been considered as one of the most promising technologies for next generation optical access networks [33]. In an incoherent OCDMA system, each user is allocated a unique signature sequence, selected from a family of 0/1 sequences, that satisfies certain correlation properties. These signature sequences are referred to as optical orthogonal codes (OOCs) [7].

In this chapter, we introduce the basic concepts of the thesis and discuss different types of multi-rate techniques in OCDMA. In Section 3.2, we discuss OCDMA systems. Section 3.3 present **o**ptical **o**rthogonal **c**ode (OOC). In Section 3.4, we discuss two different types of Optical CDMA receivers. Section 3.5 shows the analysis of Optical CDMA receivers. In Section 3.6, the need of multi-rate transmission is discussed. A general overview of the three basic types of multi-rate techniques are presented in Section 3.7. Two-dimensional optical orthogonal code called (2D OCFHC/OOC) is discussed in Section 3.8. In Section 3.9, we talk about two different random access protocols for slotted optical CDMA packet networks.

3.2 OPTICAL CODE DIVISION MULTIPLE ACCESS (OCDMA)

Optical fibers offer a large bandwidth in the order of tera-hertz, making it the best candidate for current and future communication and computer networks.

In optical CDMA techniques, a user is normally given a signature code that satisfies good auto and cross correlation properties [8] to help in its data transmission and identifying itself.

Fig. 3.1 shows a typical structure of a fiber-optic CDMA network. Each information source provides an information bit for a laser based optical On Off Keying (OOK) modulator every T second. Pulses generated by an optical OOK modulator have duration $T_c = T/L$ where L is OCDMA code length or processing gain of the system. In an optical CDMA encoder, energy of pulses generated by data modulator splits into w (Code Weight) equal parts. Each part undergoes a pre-specified delay and then recombine in such a way to form the CDMA code pattern at the output of a CDMA encoder. This process is usually performed using optical couplers and optical tapped delay lines. OOC codes with minimum auto and cross correlation $C_{OOC} = \{a_1, a_2, \cdots, a_{|C|}\}$ is assigned to each users encoder.
Where $|C|$ is called the cardinality of OOCs which means total number of codes in the system.
N is the number of active users of the network and by N_{max} the maximum number of allowed users, i.e., N_{max} is the size of the star coupler. Under conditions of minimum auto and cross correlations, N_{max} is limited to $(L-1)/w(w-1)$ [7].

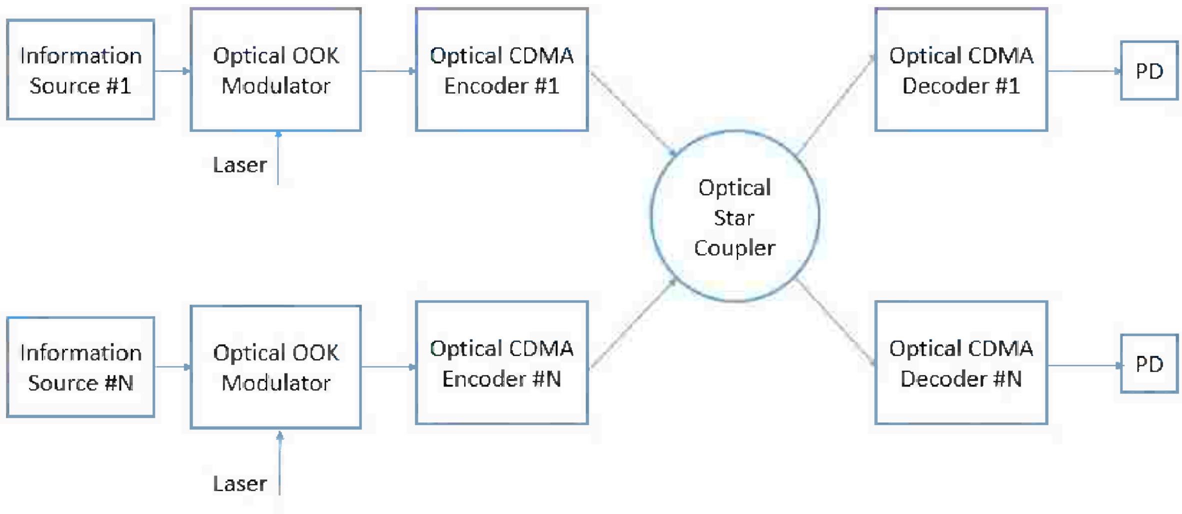

FIGURE 3.1 Structure of an optical CDMA network [34].

3.3 OPTICAL ORTHOGONAL CODES (OOCs)

An **o**ptical **o**rthogonal **c**ode (OOC) is a family of (0, 1) sequences with good auto and cross correlation properties, i.e., the autocorrelation of each sequence exhibits the "thumb-tack" shape and the cross correlation between any two sequences remains low throughout. The use of OOCs enables a large number of asynchronous users to transmit information efficiently and reliably. The lack of a network synchronization requirement enhances the flexibility of the system. The thumbtack shape of the autocorrelation facilitates the detection of the desired signal, and the low cross correlation reduces the interference from unwanted signals in the network.

An $(L, w, \lambda_a, \lambda_c)$ optical orthogonal code C is a family of (0, 1) sequences of length L and weight w which satisfy the following two properties.

- The Autocorrelation Property:

$$\sum_{t=0}^{L-1} x_t x_{t+\tau} \leq \lambda_a \tag{3.1}$$

- The Cross-Correlation Property:

$$\sum_{t=0}^{L-1} x_t y_{t+\tau} \leq \lambda_c \tag{3.2}$$

for any $x \neq y \in C$ and any integer τ.
The (0, 1) sequences of an optical orthogonal code are called its codewords. The size of an optical orthogonal code, denoted by $|C|$, is the number of codewords in it [8]. The cardinality of an OOC depends on the code length L , the code weight w, and the out-of-phase autocorrelation and cross correlation constraints λ_a, λ_c, respectively. For the case of $\lambda_a = \lambda_c = 1$, we have [3]

$$|C| = \left\lfloor \frac{L-1}{w(w-1)} \right\rfloor \tag{3.3}$$

where $\lfloor x \rfloor$ denotes the largest integer not greater than x. This constraint $(\lambda_a = \lambda_c = 1)$ on the code correlations guarantees minimal interference between the users at the expense of limiting the maximum number of codewords (subscribers).

3.4 VARIOUS OPTICAL CDMA RECEIVERS

In this section, Different receiver structures will be considered where they are proposed for optical fiber CDMA and discuss their major strengths and drawbacks. those receiver structures introduced and studied here are with minimum electronic processing. The main electronic functions used in these structures are integration and comparison versus a threshold value. These are the simplest electronic functions that can be implemented with relatively high speeds. Other receiver structures can be introduced which widely benefit from electronic signal processing. Those receivers can use as a pattern recognition or multi-user detection techniques to improve performance of the systems. But the intensive electronic processing required is not desirable for high-speed optical CDMA signal processing due to its complexity [34, 35].

3.4.1 Correlation Receivers

Salehi was the first scientist that studied Optical CDMA correlation receiver [7]. Simply, this receiver serves as an optical matched filter that collects the spread optical power from mark positions and compares it to a certain threshold.

1. Passive Correlation Receivers
   In this receiver, the received signal will be compared versus the transmitter signature sequence, fig. 3.2. The whole receiver act as a matched filter to the input signal. Incoming signal will be divided into w equal parts each suffering a time delay complement to one of the delay elements of the CDMA encoder, to form a filter inversely matched to the transmitted signature sequence. For example, if $L = 32$ and transmitter sequence is (1, 4, 13, 30), then delay elements will be designed to generate delays $(31T_c, 28T_c, 19T_c, 2T_c)$. The output of these delay lines will be combined and after photodetection and integration, the output voltage will be sampled at the end of each bit interval. If the transmitted bit is '1', an optical pulse will appear at the sampling chip time with a power that is w times the power of each received chip pulse.
   The main strength of this design is its passive optical correlator. However, this

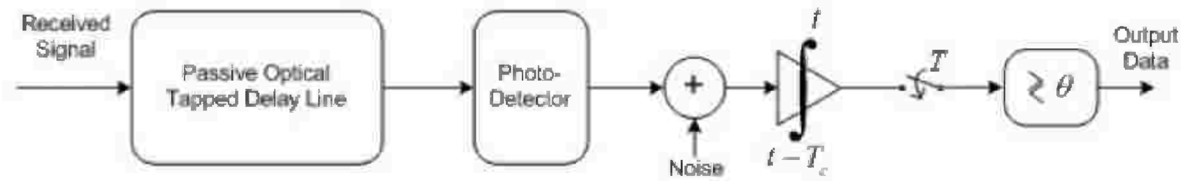

FIGURE 3.2 Passive correlator structure [35].

   receiver needs a very high-speed electronic circuitry which should operate at a chip-rate speed and thus limits this structure, and other similar structures using passive correlator, only to relatively low speed applications. Another shortcoming of this system is the strong power loss in optical splitters. The original pulse will split to w parts at the encoder and then each pulse will be divided to N_{max} parts at the star coupler and again to w parts at the optical decoder. Therefore, the energy of the original transmitter encoded laser pulse, will be divided to $N_{max}.w^2$ and forms the energy of each chip pulse at the receiver.
   Therefore, the transmitter should produce strong enough pulses so that the decision variable has enough energy for reliable decision. The sampled value, which is the output voltage of an integrator, will be compared against a threshold level θ and an estimation of the transmitted bit will be given [34, 35].

2. Active Correlation Receivers
   This receiver executes the same operation as the passive correlation receiver, but an active multiplier that can be implemented for example using an acousto-optic modulator will perform code multiplication, fig. 3.3. Therefore, the integration time after

the photodetector should be extended to T (bit duration) seconds and this receiver has a lower speed electronic design comparing with passive correlation receiver, but it uses a more complicated optical technology. Although longer integration times makes the electronic circuits more feasible, it increases the contribution of collected noise in decision variable.

Using an active multiplier, only pulses at mark positions will enter the receiver and

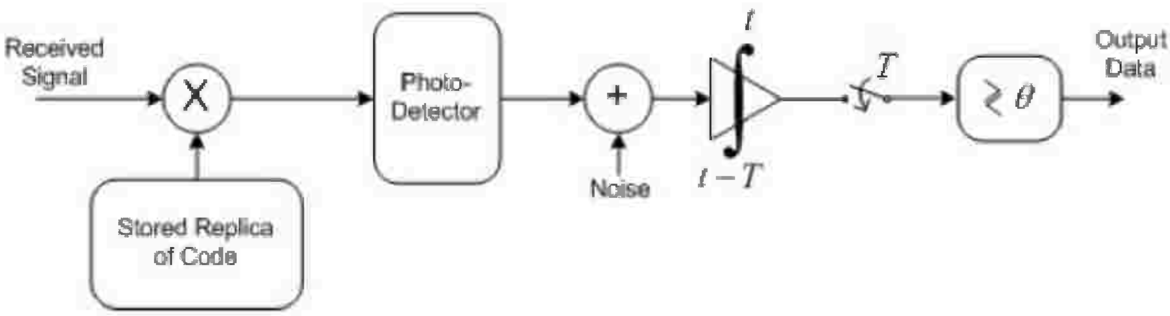

FIGURE 3.3 Active correlator structure [35].

then the integration should be performed over the entire bit duration. Therefore, this receiver needs electronic circuitry in bit-rate speed, not chip-rate speed, which is more feasible than electronic circuit in passive correlation structure. This structure is also more efficient the regarding required power and does not split the received power as in passive correlator. However, the receiver needs an optical multiplier which itself has speed limitations and is a costly device [34, 35].

3. Correlation Receivers with Optical Hard-Limiters
   This structure removes many interference patterns using an optical hard-limiter placed before the correlation receiver [7]. The characteristics of an optical hard-limiter are represented in Fig. 3.4, where we have plotted the relation between output power and input power P_{out} and P_{in} , respectively.

The transfer function of an ideal optical hard-limiter can be written as [36]:

$$g(x) = \begin{cases} u & if\ x \geq v' \\ 0 & otherwise \end{cases} \tag{3.4}$$

where x denotes the input power, $g(x)$ is the output power, v' is the threshold level of the optical hard-limiter and u is a constant. The function of an optical hard-limiter at the input of the correlator is to limit the energy of input pulses to the equivalent of one pulse. Therefore, if a transmitted bit is $'0'$ and there are several interfering pulses at a specified mark position, the optical hard-limiter, limits the incoming optical energy to the energy of just one pulse. Therefore, the number of input pulses to the correlator is limited to one pulse at each chip time position, thus considerably reduces the possibility of detecting $'1'$ when $'0'$ has been transmitted. For example, if $w = 4$ and a transmitted bit is $'0'$, assuming that the number of

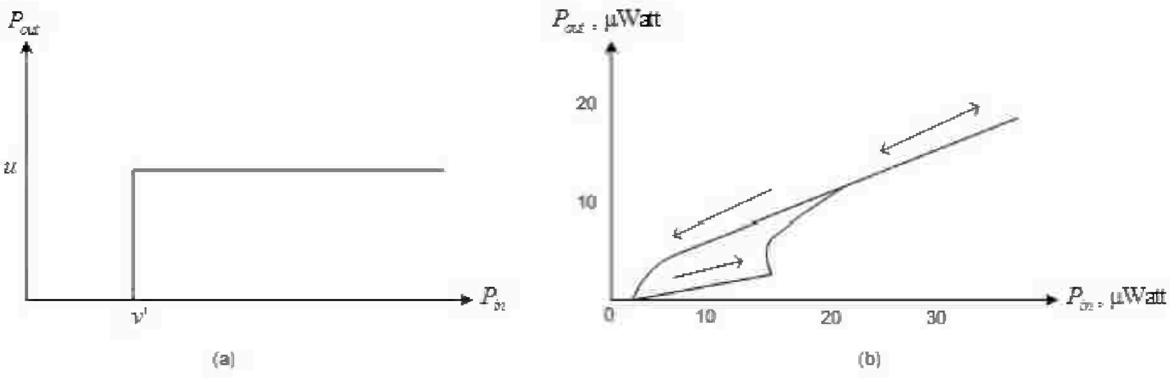

FIGURE 3.4 Optical hard-limiters characteristics: (a) An ideal optical hard-limiter, (b) A practical optical hard-limiter [36].

received pulses at four positions are $(3, 2, 0, 0)$. A correlation receiver adds these numbers, compares the result with the code weight, and erroneously decides that data bit $'1'$ is transmitted. However, a hard-limiter converts the interference pattern to $(1, 1, 0, 0)$ allowing the correlator a sufficient margin to make a correct decision about the transmitted bit.
To improve the performance of the correlation receiver with single hard-limiter, Ohtsuki [5] proposed an optical CDMA correlation receiver with double optical hard-limiters. Double optical hard-limiter structure removes many interference patterns, which will pass through a simple optical hard-limiter. The first hard limiter clips the energy of incoming pulses, but the second hard-limiter removes the stray pulses produced by passive optical correlator (delay lines) not contributing to the decision criteria. Both types of correlation receivers with hard-limiters are shown in fig. 3.5.

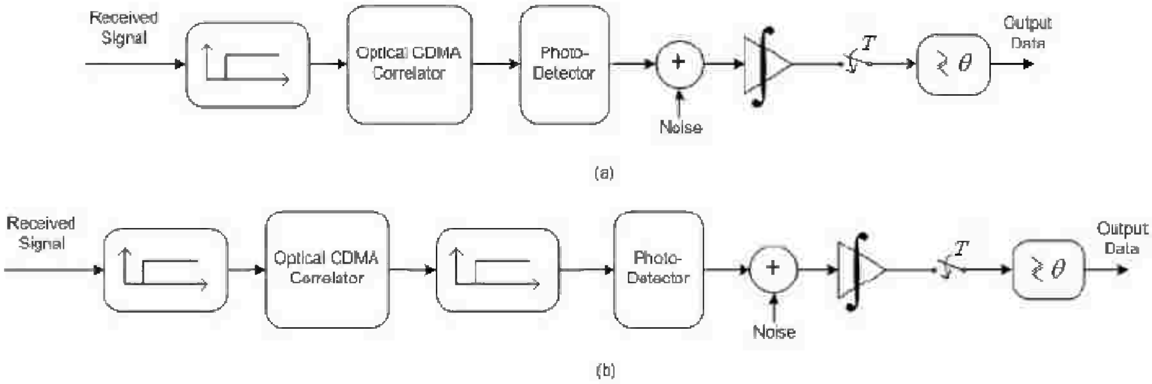

FIGURE 3.5 (a) Optical correlation receiver with hard-limiter, (b) Optical correlation receiver with double hard-limiters [35].

Correlation receivers with hard-limiters may be implemented either in a passive or an active structure [34, 35].

3.4.2 Chip-Level Receivers

In [6], Shalaby proposed a new optical CDMA receiver, called the chip-level receiver. Both On-Off Keying (OOK) and pulse-position modulation (PPM) schemes, that utilize this receiver, were investigated. The main difference between chip-level and other receivers is that the chip-level receiver decision rule depends on the photon counts in each mark position, i.e., to decide data bit '1' the photon count in each mark position should exceed a certain threshold. Results revealed that significant improvement in the performance is gained when using the chip-level receiver in place of the correlation one. Nevertheless, the complexity of this receiver is independent of the number of users, and therefore, it is much more practical than the optimum receiver [35].

1. High-Speed Chip-Level Receivers
   In this receiver, fig. 3.6, decision is based on w partial decision random variables. Signal will be sampled at each chip pulse interval and a '1' bit will be detected when at least one pulse is present at all chip pulse positions and a single missed chip pulse at the designated code pulse position is sufficient to detect '0' bit. It can be shown that if no noise is present, a hard-limiter receiver performs as well as a chip-level detector. This receiver requires a fast electronic design, since the receiver needs to integrate w times the incoming signal on T_c intervals during a bit time. It has been shown that if only Poisson shot-noise is considered, the performance of this receiver rapidly approaches the performance of the ideal double hard-limiter receiver [6, 34, 35].

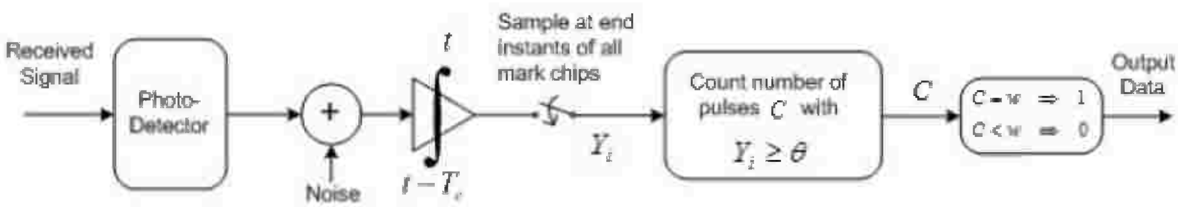

FIGURE 3.6 High-speed chip-level receiver [35].

2. All Optical Chip-Level Receivers
   To make full use of the vast bandwidth available to the optical network, an equivalent all optical chip-level receiver that requires a lower speed electronic design (shown in fig. 3.7) was also presented by Shalaby, [6]. The received optical signal is sampled optically at the correct mark chips. Each sampled signal is then photodetected and integrated over the entire bit duration ($T = LT_c$) and is further sampled electronically by the end of the bit duration. If each sampled signal is not less than θ, a data bit '1' is declared to be transmitted. Otherwise a '0' is declared.

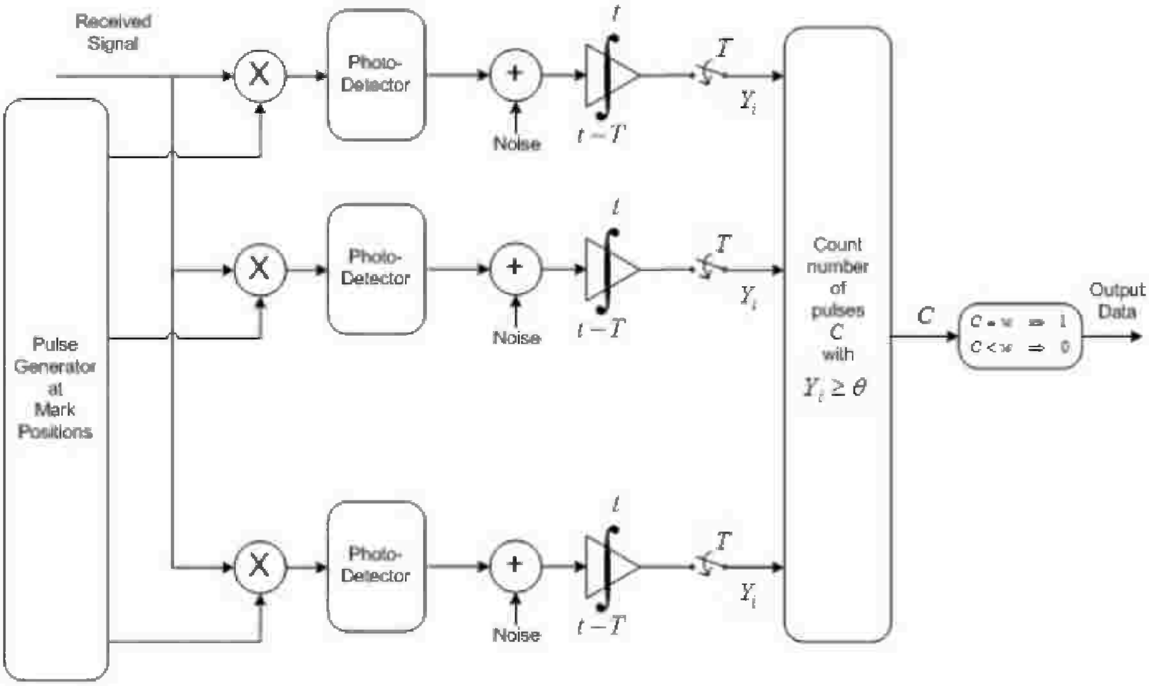

FIGURE 3.7 All optical chip-level receiver [35].

3.5 ANALYSIS OF OCDMA RECEIVERS

In this section, analysis of OCDMA receivers is discussed in terms of packet success probability. For convenience comparison, the packet success probability is evaluated for both chip-level receivers and correlation receivers without optical hard-limiters. In this analysis, shot noise and thermal noise are neglected, and focus our attention on the influence of MAI. The effect of shot and thermal noise may be added in cases where physical noise sources are expected to be of interest [37]. Optical orthogonal codes are used as the users' signature codes, with a correlation constraint of $\lambda_a = \lambda_c = 1$. That is, users of different codes interfere with each other by one chip at most. On the other hand, users of same code interfere with each other by 0, 1, or w chips. The chip synchronous case is considered which gives an upper bound of bit error probability [7].
Assuming that there are $r \in \{1, 2, \cdots, N\}$ active users in the network at a given time slot, defining $\ell \in \{0, 1, 2, \cdots r-1\}$ such that $\ell = \sum_{i=1}^{w} \ell_i$, and $m \in \{0, 1, \cdots r-1-\ell\}$ as the number of users that interfere with the desired user at exactly 1 chip and w chips, respectively; l_i denotes the number of users that interfere with the desired user at weighted chip i , $i \in \{1, 2, \cdots, w\}$.
Let p_1 and p_w denote the probability of 1 and w chip-interferences, respectively, between two users, then [3]:

$$P_1 = \frac{w^2}{L} - wP_w, \qquad P_w = \frac{1}{L} \cdot \frac{1}{|C|} = \frac{1}{L} \cdot \left\lfloor \frac{L-1}{w(w-1)} \right\rfloor^{-1} \tag{3.5}$$

3.5.1 Correlation Receivers without Hard-Limiter

Assuming equally-likely binary data bits ($Pr\{0\} = Pr\{1\} = 1/2$), the conditional bit correct probability $P_{bc}(m, \ell)$ is calculated as follows. The correlation receiver decides a data bit $'1'$ was transmitted if the total received pulses Z from all weighted chips is greater than or equal to a threshold $\theta = w$. A data bit $'0'$ is decided otherwise:

$$\begin{aligned} P_{bc}(m,\ell) &= Pr\{a \quad bit \quad success|m,\ell\} \\ &= \frac{1}{2}Pr\{a \quad bit \quad success|m,\ell,1 \quad was \quad sent\} \\ &\quad + \frac{1}{2}Pr\{a \quad bit \quad success|m,\ell,0 \quad was \quad sent\} \\ &= \frac{1}{2}Pr\{Z \geq w|m,\ell,1 \quad was \quad sent\} + \frac{1}{2}Pr\{Z < w|m,\ell,0 \quad was \quad sent\} \\ &= \frac{1}{2} + \frac{1}{2}Pr\{all \quad m \quad users \quad send \quad 0s \quad and \quad Z < w|m,\ell,0wassent\} \\ &= \frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\frac{1}{2^\ell}\sum_{i=0}^{w-1}\binom{\ell}{i} \end{aligned} \tag{3.6}$$

Considering a packet of length K bits, the conditional packet success probability for the correlation receiver is thus

$$P_s(r|m,\ell) = [P_{bc}(m,\ell)]^K = \left[\frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\frac{1}{2^\ell}\sum_{i=0}^{w-1}\binom{\ell}{i}\right]^K \tag{3.7}$$

Since the interference can be modeled as a random variable having a multinomial distribution [36], the packet success probability given r active users is

$$\begin{aligned} P_s(r) = &\sum_{l=0}^{r-1}\sum_{m=0}^{r-1-\ell}\frac{(r-1)!}{\ell!m!(r-1-m-\ell)!}\cdot p_1^\ell p_w^m \\ &\cdot (1-p_1-p_w)^{r-1-\ell-m}\cdot\left[\frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\frac{1}{2^\ell}\sum_{i=0}^{w-1}\binom{\ell}{i}\right]^K \end{aligned} \tag{3.8}$$

3.5.2 Chip-Level Receivers

This case differs from that of the correlation receiver in the bit decision rule [6]. In our analysis, we select $\theta = 1$ as a suboptimum threshold. Of course the obtained results form an upper bound (with respect to the bit error probability) of optimum chip-level receiver "with optimum θ". Let Z_i , $i \in x$, $x \in \{1, 2, \cdots, w\}$ be the number of received pulses per marked chip i. Since we have r active users, there are $r-1$ interfering users to the desired one. Out of these users, let m users interfere with the desired user at w chips and $\overline{\ell}$ users interfere with it at exactly 1 chip. Further, let $\overline{\ell} = (\ell_1, \ell_2, \cdots, \ell_w)$ be the interfering vector having a multinomial distribution. We evaluate the conditional bit-correct probability as follows.

$$
\begin{aligned}
P_{bc}(m,\bar{\ell}) &= Pr\{a \quad bit \quad success|m,\bar{\ell}\} \\
&= \frac{1}{2}Pr\{a \quad bit \quad success|m,\bar{\ell},1 \quad was \quad sent\} \\
&\quad + \frac{1}{2}Pr\{a \quad bit \quad success|m,\bar{\ell},0 \quad was \quad sent\} \\
&= \frac{1}{2}Pr\{Z_i \geq 1 \quad \forall i \quad \in x|m,\bar{\ell},1 \quad was \quad sent\} \\
&\quad + \frac{1}{2}Pr\{Z_i = 0, some \quad i \in x|m,\bar{\ell},0 \quad was \quad sent\} \\
&= \frac{1}{2} + \frac{1}{2}Pr\{all \quad m \quad users \quad send \quad 0s \quad and \\
&\qquad\qquad Z_i = 0 \quad some \quad i \in x|m,\bar{\ell},0 \quad was \quad sent\} \\
&= \frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\left(\sum_{i=1}^{w}\frac{1}{2^{\ell_i}} - \sum_{i=1}^{w-1}\sum_{j=i+1}^{w}\frac{1}{2^{\ell_i+\ell_j}} + \ldots + (-1)^{w-1}\frac{1}{2^{\ell}}\right)
\end{aligned}
\tag{3.9}
$$

where we have used the inclusion-exclusion property to justify the last equation. The packet success probability given r active users is thus expressed as follows:

$$
\begin{aligned}
P_s(r) = &\sum_{\ell=0}^{r-1}\sum_{m=0}^{r-1-\ell}\frac{(r-1)!}{\ell!m!(r-1-m-\ell)!}\cdot p_1^{\ell}p_w^{m}(1-p_1-p_w)^{r-1-\ell-m} \\
&\cdot \sum_{\substack{\ell_1,\ell_2,\ldots,\ell_w: \\ \ell_1+\ldots+\ell_w=\ell}}\frac{\ell!}{\ell_1!\ldots\ell_w!}\cdot\left(\frac{1}{w}\right)^{\ell} \\
&\cdot\left[\frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\left(\sum_{i=1}^{w}\frac{1}{2^{\ell_i}} - \sum_{i=1}^{w-1}\sum_{j=i+1}^{w}\frac{1}{2^{\ell_i+\ell_j}} + \ldots + (-1)^{w-1}\frac{1}{2^{\ell}}\right)\right]^{K}
\end{aligned}
\tag{3.10}
$$

3.6 THE NEED FOR MULTI-RATE TECHNIQUES

Required to support multimedia services (e.g., data, voice and video) in optical networks. Where, users with very different signaling rate and quality-of-service (QoS) requirements are expected to coexist in the same network.

3.7 MULTI-RATE TECHNIQUES

The conventional OCDMA systems can not support such sorts of data, because only one sequence code is assigned to each user and thus the bit rate of each user is fixed. In addition, optical CDMA systems require the sequence codes with long length to accommodate many users, and thus achieving high bit rate using the conventional sequence codes is not so easy. Recently, we have proposed multi-rate optical CDMA techniques to support several kinds of data with different bit rates coping with a multimedia network. Multicode, variable-length spreading, and variable processing gain techniques are the major approaches to provide multi-rate services in radio CDMA.

3.7.1 Variable Spreading Length (VSL)

Variable-length spreading CDMA employs multiple spreading factors for multiple-rate transmission and adjusts the length (i.e., spreading gain) of a users sequence, depending on its rate requirement. Orthogonal variable spreading-factor codes that preserve the orthogonality between different rates and spreading factors [22].
The OVSF (orthogonal variable spreading factor)-CDMA system offers opportunities to provide variable user data rates and flexibly support applications with different bandwidth requirements. Spectrum spreading is achieved by mapping each data bit (0 or 1) into an assigned code sequence. The length of the code sequence per data bit is called the spreading factor. The possible OVSF codes can be represented as nodes in a complete binary tree called the OVSF code tree. These variable spreading factor codes support different data rates in an OVSF–CDMA system with only one spreading code per user. The codes at each layer of the tree have different spreading factors, allowing users to transmit at different data rates [38].
In order to identify the codes in the tree without ambiguity, each code can be denoted as $C_{SF,L}$, where SF is the spreading factor and L is the code length, $1 \leq L \leq SF$. In a CDMA (code division multiple access) system, the number of chips per data symbol is called the SF (spreading factor), the lower the spreading factor the higher the data rate. The branches in each code layer are numbered sequentially form up to down, starting from 1 as shown in fig. 3.8 [38].

- Disadvantage:
  In the OVSF codes, once a particular code is used, its descendant and ancestor codes cannot be used simultaneously because their encoded sequences become indistinguishable. Any two codes of different levels are orthogonal if and only if one of two codes is not an ancestor/descendant in each other. Therefore, when an OVSF code is assigned to a user, it blocks all of its ancestor and descendant codes. For instance, the assignment of code $C_{4,2}$ shown in fig. 3.9 blocks the assignment of its ancestor codes (i.e. $C_{1,1}$ and $C_{2,1}$) and descendant codes (i.e. $C_{8,3}$ and $C_{8,4}$). This results in a major drawback of OVSF codes, called blocking property. This disadvantage of code blocking in OVSF codes leads to poor utilization of network capacity [38].

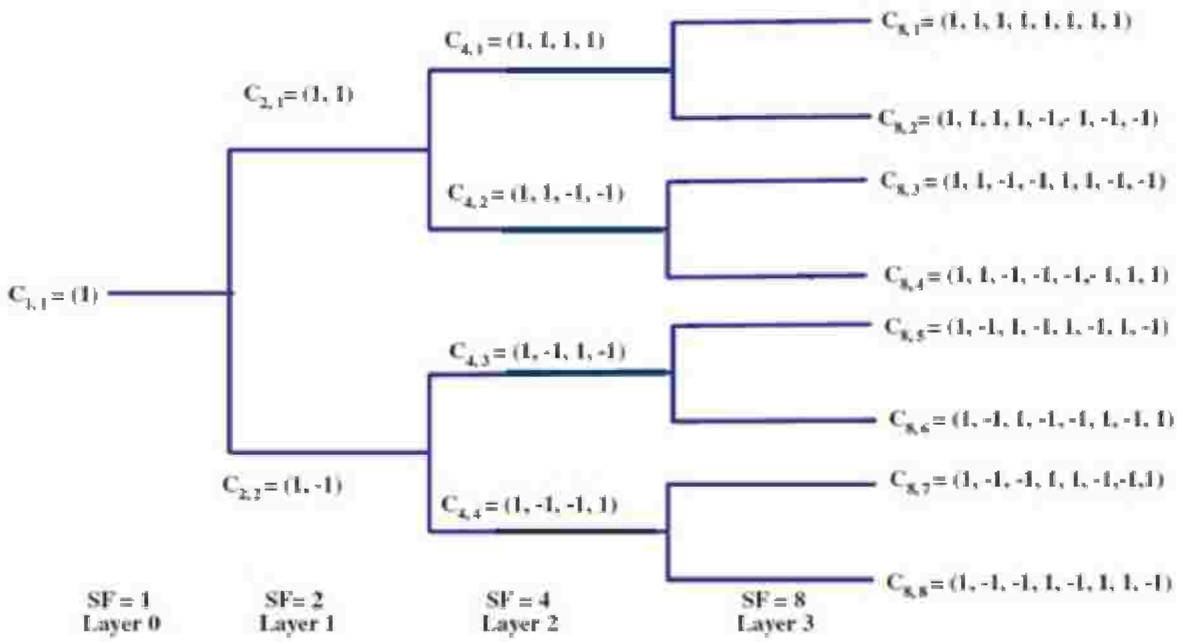

FIGURE 3.8 Orthogonal variable spreading factor (OVSF) Code tree [38].

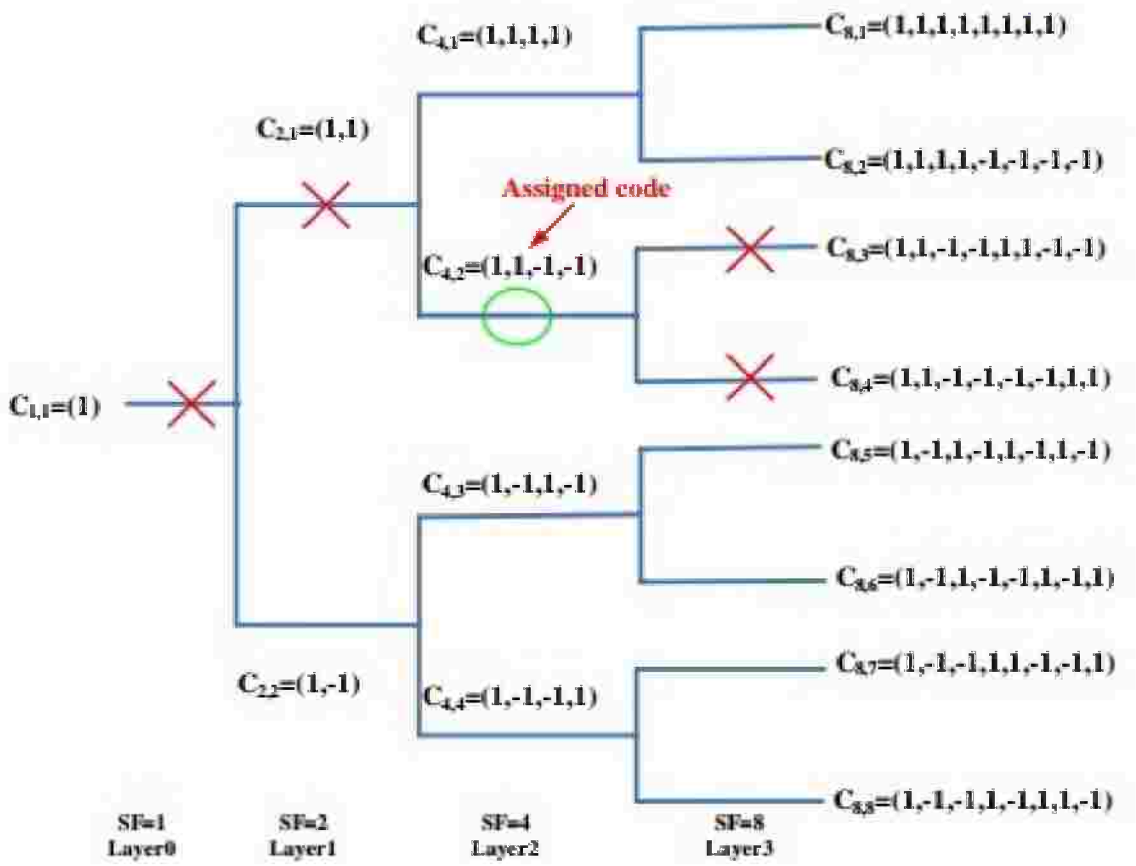

FIGURE 3.9 Orthogonal variable spreading factor (OVSF) blocking property [38].

3.7.2 Variable Processing Gain (VPG)

Assume a fixed packet time duration of $T_P = KT_n = KGT_c$ where K is the nominal packet length, T_c is the chip intervals, T_n is the nominal bit duration, and G is the processing gain. In this system, the variable transmission rate is accomplished by varying the processing gain in such a way that increasing the transmission rate by a factor of $\alpha \geq 1$ allows the reduction of spreading factor by the same amount. The corresponding nominal rate is $R_n = 1/T_n = 1/GT_c$. The variable processing gain G_V is:

$$G_V = \frac{G}{\alpha} \tag{3.11}$$

The bit rate in this case is given by

$$R_s = \alpha R_n \quad (bits/sec) \tag{3.12}$$

In a packet network, $x_b^{(V)} = \lfloor \alpha K \rfloor$ bits are allocated in a time slot instead of K as shown in fig. 3.10, where $\lfloor x \rfloor$ is the highest integer less than x. Then, the new transmission rate becomes

$$R_s = \frac{x_b^{(V)}}{K} R_n \quad (bits/sec) \tag{3.13}$$

In Fig. 3.10 a), we present a case study where $G = 5$ and $K = 2$ which means the nominal

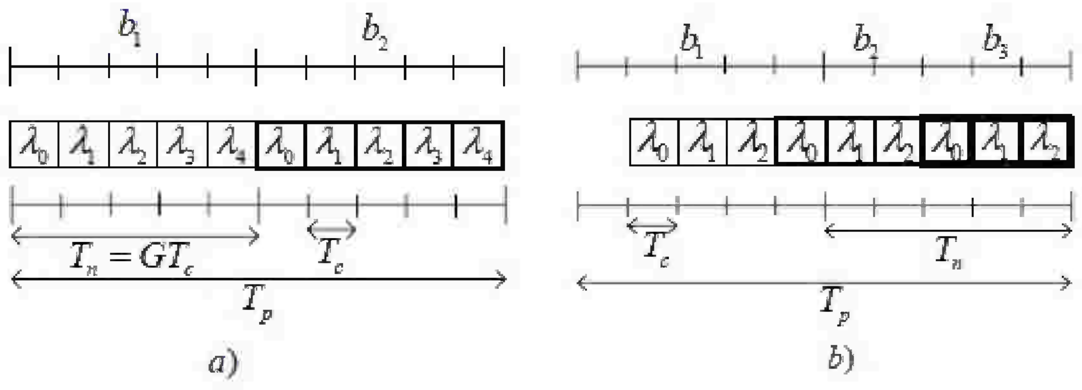

FIGURE 3.10 Variable Processing Gain (VPG) OCDMA concept [39].

rate is two bits per packet. On the other hand, in Fig. 3.10 b), we have decreased the PG to $G_V = 3$ (which means $\alpha = 5/3$) in order to increase the transmission rate to three bits per packet.

- Disadvantage:
  Due to the fact that the bit error probability is equal for every bit in the packet, the probability of successfully receiving a packet for r simultaneous active terminals

using a simple On-Off Keying (OOK) modulation is [39]

$$P_c(k) = [1 - P_b(i)]^{x_b^{(V)}} \tag{3.14}$$

where P_b is the bit error probability. When the transmission rate becomes very high, the PG becomes very small. This in turn drastically decreases the packet correct probability.

3.7.3 Multi-coding (MC)

Multi-code CDMA allocates multiple codes to high-rate services and each user employs multiple sequences for transmission. To avoid the occurrence of self interference to a user in the multi-code CDMA systems (i.e., providing mutual orthogonality among the users), a subcode concatenation scheme was proposed to generate the multiple sequences for the user [40]. Where in multi-code direct-detection optical CDMA systems support several kinds of data with different traffic requirements coping with a multimedia network. Where each user is assigned a set of time-shifted versions of OOCs.
Defining a minimum distance between 1s among all the codes as the minimum distance of OOCs d_{min}. The sequence codes of each user are obtained by right rotated $d_{min} - 1$ times, so that $d_{min} - 1$ new sequence codes can be generated from a seed. I assume the number of sequence codes required for the desired user is r': $r' \leq dmin$. The number of sequence codes used by each user is decided according to the data. An information bit stream is directly converted into OOK pulse sequence through an OOK encoder. According to the consecutive r outputs of an OOK encoder, the laser is pulsed on or not over consecutive r chips from the 0th chip to the $r - l$th chip. The output laser pulses are converted into the signature sequence codes through a sequence encoder comprising a set of tapped optical delay lines. The output of each sequence encoder is asynchronously multiplexed and transmitted over fiber to the desired destinations as shown in fig. 3.11. At the receiver, the received signal is split into d_{min} branches. In the optical correlator for i shifted sequence code the length of each optical delay line is i unit length shorter than that for the signature sequence code used as a seed as shown in fig. 3.12. Finally, through the parallel-series converter data are recovered [12].

3.8 TWO DIMENSION ONE CONCIDENCE FREQUENCY HOP CODE/ OPTICAL ORTHOGONAL CODE (2-D OCFHC/OOC)

To overcome the shortcoming of one-dimensional optical orthogonal code (1-D OOC) where the number of codewords is very small, two-dimensional optical orthogonal code (2-D OOC), which extends the cardinality while still possessing good auto-and-cross correlation properties, is proposed by introducing another dimension (wavelength) based on

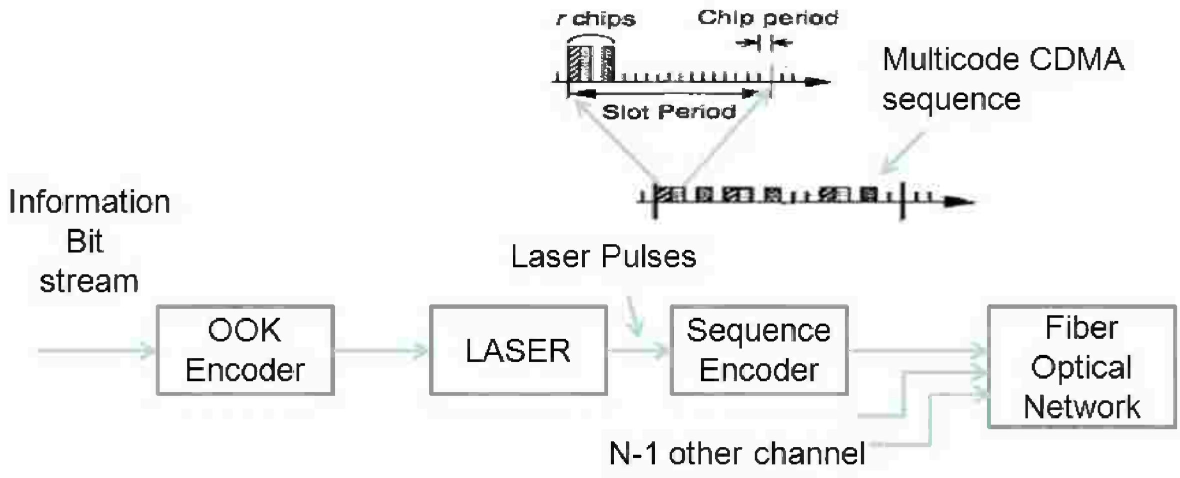

FIGURE 3.11 The transmitter block diagram of multi-code direct detection optical CDMA system [12].

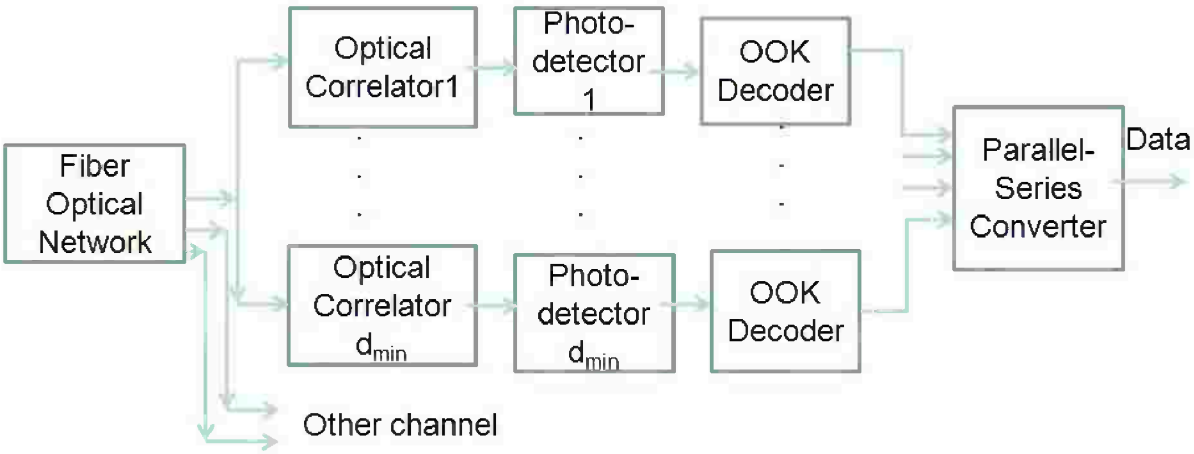

FIGURE 3.12 The receiver block diagram of multi-code direct detection optical CDMA system [12].

1-D OOC. A 2-D OOC codeword is represented by a $M_1 \times M_2$ matrix consisting of 0 and 1, where M_1 is the number of wavelengths used, and M_2 is the code length (i.e., the number of time slots used). Several 2-D OOCs have been constructed by employing different wavelength-hopping and time-spreading patterns [14].

3.8.1 Construction of OCFHC

Frequency hop code (FHC) is a collection of codewords to determine how to place different carrier frequencies (i.e., wavelengths) in different time slots. There are four parameters with regard to FHCs design; they are number of available frequencies Q_f, code length L, code cardinality Φ, and the maximum value of correlation between any two codewords from the code H_{max}. Assuming that S is an FHC of code length L, S could be expressed as:

$$S = \{S_0, S_1, \cdots, S_{\Phi-1}\} \tag{3.15}$$

When each frequency appears in each codeword only once and H_{max} of the code equals 1, this code is called OCFHC, which satisfies the following property:

$$N \leq \frac{Q_f(Q_f - 1)}{L} \tag{3.16}$$

OCFHC is optimal; in other words, the number of codewords of OCFHC is maximum when equation 3.16 is an equal.
We term an OCFHC with Q_f available frequencies, length of L and maximum correlation value $H_{max}(L, Q_f, H_{max})$ OCFHC. As in table 3.1 gives the $(2^3, 7, 1)$ OCFHC, where $p = 2$, $k = 3$, $L = 2^3 - 1 = 7$, $Q_f = 2^3$, $N = 2^3$. Utilizing arbitrary OCFHC and OOC as hopping and spreading patterns, respectively, a new 2-D OOC could be constructed [14].

TABLE 3.1 $(2^3, 7, 1)$ OCFHC [14].

i	S_i						
0	1	2	4	3	6	7	5
1	0	3	5	2	7	6	4
2	3	0	6	1	4	5	7
3	5	6	0	7	2	3	1
4	2	1	7	0	5	4	6
5	7	4	2	5	0	1	3
6	6	5	3	4	1	0	2
7	4	7	1	6	3	2	0

w=3

w=5

3.8.2 Construction of OCFHC/OOC

An OCFHC/OOC codeword is represented by a $p^k \times N_{ooc}$ matrix consisting of 0 and 1, p is a prime number, k is a positive integer, p^k is the number of available wavelengths, and N_{ooc} is the OOC code length. When code weight is w, the side lobes of auto correlation between arbitrary two codewords are at most λ_a, and if the maximum value of the cross correlation is λ_c, the code is termed $(p^k \times N_{ooc}, w, \lambda_a, \lambda_c)$ OCFHC/OOC. In our thesis, OCFHC/OOC exhibits ideal correlation properties ($\lambda_a = \lambda_c = 1$), and we will denote it

$(p^k \times N_{ooc}, w)$ OCFHC/OOC for short [14].
An OCFHC/OOC C is composed of three parts: C_0, C_1, and C_2. C_0 employs OCFHC and OOC as hopping and spreading patterns, respectively, C_1 employs OOC as spreading patterns and uses one wavelength (i.e., all 1s are in the same row), and C_2 employs OOC as hopping patterns and uses one time slot (i.e., all 1s are in the same column).

- Example:
  $(2^3 \times 7, 3)$ OCFHC/OOC is shown in table 3.2, utilizing (7, 3, 1, 1) OOC, which contains one codeword (1101000) and (8, 3, 1, 1) OOC that contains one codeword (11010000).

TABLE 3.2 $(2^3 \times 7, 3)$ OCFHC/OOC [14].

C_0				C_1	C_2
i=0	i=1	...	i=7		
$\lambda_1\lambda_2 0\lambda_4 000$	$\lambda_0\lambda_3 0\lambda_5 000$	⋯	$\lambda_4\lambda_7 0\lambda_1 000$	$\lambda_0\lambda_0 0\lambda_0 000$	$(\lambda_0\lambda_1\lambda_3)000000$
$\lambda_2\lambda_4 0\lambda_3 000$	$\lambda_3\lambda_5 0\lambda_2 000$	⋯	$\lambda_7\lambda_1 0\lambda_6 000$	$\lambda_1\lambda_1 0\lambda_1 000$	$(\lambda_1\lambda_2\lambda_4)000000$
$\lambda_4\lambda_3 0\lambda_6 000$	$\lambda_5\lambda_2 0\lambda_7 000$	⋯	$\lambda_1\lambda_6 0\lambda_3 000$	$\lambda_2\lambda_2 0\lambda_2 000$	$(\lambda_2\lambda_3\lambda_5)000000$
$\lambda_3\lambda_6 0\lambda_7 000$	$\lambda_2\lambda_7 0\lambda_6 000$	⋯	$\lambda_6\lambda_3 0\lambda_2 000$	$\lambda_3\lambda_3 0\lambda_3 000$	$(\lambda_3\lambda_4\lambda_6)000000$
$\lambda_6\lambda_7 0\lambda_5 000$	$\lambda_7\lambda_6 0\lambda_4 000$	⋯	$\lambda_3\lambda_2 0\lambda_0 000$	$\lambda_4\lambda_4 0\lambda_4 000$	$(\lambda_4\lambda_5\lambda_7)000000$
$\lambda_7\lambda_5 0\lambda_1 000$	$\lambda_6\lambda_4 0\lambda_0 000$	⋯	$\lambda_2\lambda_0 0\lambda_4 000$	$\lambda_5\lambda_5 0\lambda_5 000$	$(\lambda_5\lambda_6\lambda_0)000000$
$\lambda_5\lambda_1 0\lambda_2 000$	$\lambda_4\lambda_0 0\lambda_3 000$	⋯	$\lambda_0\lambda_4 0\lambda_7 000$	$\lambda_6\lambda_6 0\lambda_6 000$	$(\lambda_6\lambda_7\lambda_1)000000$
				$\lambda_7\lambda_7 0\lambda_7 000$	$(\lambda_7\lambda_0\lambda_2)000000$

3.8.3 Correlation Properties

Obviously, the value of autocorrelation of any codeword in C is at most 1, according to the autocorrelation property of OOC. Assume C' consists of C1 and C2. For any two different codewords of C', if they employ the same spreading pattern, the maximum value of the cross correlation between them is 1, due to the properties of OCFHC that each wavelength appears only once in each OCFHC codeword and the maximum value of the cross correlation between any two OCFHC codewords is 1. Otherwise, if the two codewords employ different spreading patterns, the value of the cross correlation between them is at most 1 according to OOCs cross correlation property.
When it comes to C2, the cross correlation of two different codewords from it is at most 1 because of OOCs cross correlation property. By virtue of the fact that C2 employs one time slot, the value of the cross correlation of two codewords from C2 and C', respectively, is at most 1 as given in [14].

3.8.4 Cardinality of OCFHC/OOC

Suppose Φ_{C_0}, Φ_{C_1}, Φ_{C_2}, and Φ_C are the cardinality of C_0, C_1, C_2, and C, respectively. We can derive from the construction process of OCFHC/OOC that

$$\Phi_{c_0} = p^k(p^k - 1) \cdot \frac{N_{ooc} - 1}{w(w-1)} \tag{3.17}$$

$$\Phi_{c_1} = p^k \cdot \frac{N_{ooc} - 1}{w(w-1)} \tag{3.18}$$

$$\Phi_{c_2} = p^k \cdot \frac{p^k - 1}{w(w-1)} \tag{3.19}$$

$$\Phi_c = \Phi_{c_0} + \Phi_{c_1} + \Phi_{c_2} = \frac{p^{2k} \cdot N_{ooc} - p^k}{w(w-1)} \tag{3.20}$$

The upper bound of 2-D OOCs cardinality with ideal correlation properties is

$$\Phi_{2-Dooc} \leq \frac{1}{M_2} \cdot \frac{M_1 M_2 (M_1 M_2 - 1)}{w(w-1)} = \frac{M_1(M_1 M_2 - 1)}{w(w-1)} \tag{3.21}$$

Comparing equations(3.20) with (3.21), it is clear that OCFHC/OOC is optimal; namely, the cardinality of OCFHC/OOC achieves the upper bound theoretically [14].

3.8.5 OCFHC/OOC Hit probability

Denoting q_i as the average number of hits between a codeword from C_i and another codeword from C, we can derive that

$$\begin{aligned} q_0 &= \frac{\frac{w}{2N_{ooc}} \cdot wt_1 + \frac{1}{2N_{ooc}}[w^2(p^k-1)t_1 - w] + \frac{1}{2N_{ooc}} \cdot w^2 t_2}{\Phi_c - 1} \\ &= \frac{\frac{w^2}{2N_{ooc}}(p^k t_1 + t_2) - \frac{w}{2N_{ooc}}}{\Phi_c - 1} \end{aligned} \tag{3.22}$$

$$\begin{aligned} q_1 &= \frac{\frac{w^2}{2N_{ooc}} \cdot (t_1 - 1) + \frac{w}{2N_{ooc}} \cdot w(p^k-1)t_1 + \frac{w}{2N_{ooc}} \cdot wt_2}{\Phi_c - 1} \\ &= \frac{\frac{w^2}{2N_{ooc}}(p^k t_1 + t_2 - 1)}{\Phi_c - 1} \end{aligned} \tag{3.23}$$

$$\begin{aligned} q_2 &= \frac{\frac{1}{2N_{ooc}}(w^2 t_2 - w) + \frac{w}{2N_{ooc}} \cdot wt_1 + \frac{1}{2N_{ooc}} \cdot w^2(p^k-1)t_1}{\Phi_c - 1} \\ &= \frac{\frac{w^2}{2N_{ooc}}(p^k t_1 + t_2) - \frac{w}{2N_{ooc}}}{\Phi_c - 1} \end{aligned} \tag{3.24}$$

where t_1 and t_2 are the cardinality of $(N_{ooc}, w, 1, 1)$ OOC and $(p^k, w, 1, 1)$ OOC, respectively, and $t_1 = \lfloor (N_{ooc} - 1)/w(w-1) \rfloor$, $t_2 = \lfloor (p^k - 1)/w(w-1) \rfloor$. Denoting q as the average number of hits between arbitrary two codewords from C, q could be expressed as

$$q = \frac{\Phi_{c_0}}{\Phi_c} \cdot q_0 + \frac{\Phi_{c_1}}{\Phi_c} \cdot q_1 + \frac{\Phi_{c_2}}{\Phi_c} \cdot q_2 \qquad (3.25)$$

3.9 OPTICAL CDMA RANDOM ACCESS PROTOCOLS

Optical fibers have a vast transmission capacity. On the other hand optical technology is still in its start, and conversions between electrical and optical environment are relatively slow compared to the transmission capacity. Thus, in optical networks the processing power, instead of bandwidth, is the limiting factor. Therefore, the requirements for the media access control (MAC) protocol are different in the optical network than in the traditional electronic network. We start by giving a quick review for the different MAC protocols that were proposed in literature [3], [41], and [42]. The link layer of an optical direct detection CDMA packet network is then considered. We present the previous work concerning optical CDMA networks and analyze several random access protocols. In [3], they were proposed two different protocols (Pro 1 and Pro 2), that need pretransmission coordination. A variation of the second protocol, that does not need pretransmission coordination, is also discussed. These protocols are concerned with different techniques for assigning spreading codes to users. Whereas the effect of multi-rate, connection establishment and corrupted packets havent been taken into account.
The MAC layer exists above the physical layer in the Open Systems Interconnection (OSI) model and the IEEE 802 reference model. It is designed to ensure orderly and fair access to a shared medium. It manages the division of access capacity among the different stations on the network. A good MAC protocol should be:

- Efficient: There should be high data throughput and packets should not face large transfer delays.
- Fair: Each station should have equal access to the medium.
- Simple: The implementation of the MAC protocol should not be so complex that it requires powerful hardware or long processing times that weaken performance.

Because optical environment differs from traditional electronic environment, the requirements for MAC protocols are also different. The main difference is that in electronic networks the limiting factor is the bandwidth, while in optical networks there is enough bandwidth and the processing power is the scarce source. Thus, in optical environment the packets compete rather for processing time in the nodes than for the transmission channels. The most important factors of the performance of the MAC protocols in optical networks are:

- Throughput
- Delay
- Fairness
- Buffer requirements
- Number and cost of components needed

3.9.1 Traditional Random Access Protocols

The original single channel random access protocol is the ALOHA protocol, where transmission is done with no regard to other nodes. If two messages from different nodes overlap in time, both are corrupted. Systems in which multiple users share a common channel in a way that can lead to conflicts are widely known as contention systems. Several protocols are more or less pure improvements of the ALOHA protocol, e.g., Slotted ALOHA, CSMA (Carrier-Sense Multiple-Access), and CSMA/CD (CSMA with Collision Detection). Common to the random access protocols is that they do not perform well at high traffic loads owing to the increased probability of collision.

1. **Pure ALOHA**
   This is the conventional form of access in networks, there is no explicit media access protocol. The stations are transmitting their messages asynchronously without any observation of the channel traffic. There will be collisions of course and faulty packets must be retransmitted until error free reception. Retransmissions occur after the stations wait a random amount of time to avoid repeated collisions.

2. **Slotted ALOHA**
   In slotted ALOHA, all nodes are synchronized and transmissions are allowed to be started only at the beginning of a time slot. The vulnerable period will be reduced from twice the packet length for the case of pure ALOHA to exactly the packet length. In this way, the probability of collision is reduced and the throughput is doubled at the expense of system complexity.

3. **CSMA and CSMA/CD**
   In both pure and slotted ALOHA, a node's decision to transmit is made independently of the activity of the other nodes attached to the broadcast channel. In particular, a node neither pays attention to whether another node happens to be transmitting when it begins to transmit, nor stops transmitting if another node begins to interfere with its transmission. In CSMA, the transmission medium is sensed before transmission starts, if the channel load is below a certain threshold the transmission starts with different (persistent) strategies [43]. Otherwise, the transmitter waits until the load falls below the threshold. If a collision occurs, the medium is busy for the whole duration of the corrupted transmissions. This is avoided in the CSMA/CD protocol, where a collision can be detected during transmission. If

a collision is detected by two nodes, both nodes stop and wait for a random time before trying again, beginning with the carrier sense mechanism. Many variations on CSMA and CSMA/CD have been proposed, with the difference being primarily in the manner in which nodes perform back-off. It is obvious that with this coordination, CSMA and CSMA/CD can achieve a much better utilization than ALOHA systems.

3.9.2 Optical CDMA Protocols with and without Pretransmission Coordination

The two next protocols require pretransmission coordination. Indeed the transmitter should first broadcast a control message (or packet) to all receivers informing them about its address, the destination address, and the code to be used for data transmission. The control packet can probably be broadcast using a specific period at the head of each time slot or using another channel with different wavelength. All idle receivers are normally tuned to this control channel,listening to their addresses. The transmitter and receiver of any user should thus be tunable, i.e., (TT-TR) be able to tune to any available code. Furthermore, we present a variation of Pro 2 that does not need pretransmission coordination. Of course the implementation of this variant protocol does not require any receiver tunability, and is thus simpler.

1. First Protocol: Pro 1
   In this protocol, we assume that all codes are available in a pool. When a user wants to transmit a packet to a receiver, it is assigned a code at random. This code is then removed from the pool and is no longer available for further assignment during a slot. It is obvious that if number of users more than number of codes in a pool, there might be some active users that cannot be assigned any code. These users should try to transmit at subsequent time slots. Of course this adds to the latency in the network and limits the throughput significantly.

2. Second Protocol: Pro 2
   This protocol is similar to the one above but the codes are never removed from the pool. That is, any active user can always find a code to transmit its data. Of course more interference is possible in this case since a code can be used more than once. However, the offered traffic (at a given time slot) might be higher than the previous case. In order to reduce the probability of interference among different users, a code is randomly cyclic shifted around itself once selected.

3. Variation of Pro 2
   A variation of Pro 2 that avoids the receiver tunability, and hence does not require any pretransmission coordination, can be achieved by distributing the codes to all receivers a priori. That is, when a user logs onto the network, it is given a code randomly that might possibly be used by another user. Further, the codes are randomly cyclic shifted around themselves for interference control purpose.

3.9.2.1 Optical CDMA Protocols' Performance

OCDMA network architecture is shown in fig. 4.1. There are N users in the network. Users are connected to input and output ports of a central passive star coupler. The star coupler is the main communication medium, and it is basically a power divider which acts as a multi-access broadcast channel. A set of direct-sequence OOCs $C = \{a_1, a_2, \cdots, a_{|C|}\}$, with cardinality $|C|$ and with auto and cross correlation constraints $\lambda_a = \lambda_c = 1$ is used as the users' signature sequences.

We focus on slotted data transmission. Thus after a successful control message, a Thinking User transmit a packet with average activity $A \in [0, 1]$ at the beginning of a time slot to the destination. The length of packet is K bits and corresponds to a slot duration. An active user (one that is about to transmit a new packets) is assigned an optical-orthogonal code according to the rule given in Pro 1 or 2 depending on the protocol used. The intended receiver, once it has received a packet, transmits an acknowledgment to the sending user, indicating whether the packet is received successfully or not. If not, the transmitter enters a backlog mode which are waiting a random delay time with average d time slots before retransmitting corrupted packets. Assuming that at a given slot the number of backlogged users is $n \in \{0, 1, \cdots, N\}$, the probabilities of $i \in \{0, 1, \cdots, n\}$ backlogged users and $j \in \{0, 1, \cdots, N - n\}$ thinking users are

$$\begin{aligned} P_{bl}(i|n) &= \begin{pmatrix} n \\ i \end{pmatrix} (\frac{1}{d})^i (1 - \frac{1}{d})^{(n-i)} \\ P_{th}(j|N) &= \begin{pmatrix} N-n \\ j \end{pmatrix} (A)^j (1 - A)^{(N-n-j)} \end{aligned} \tag{3.26}$$

and system throughput is

$$\beta(n) = \begin{cases} \sum_{j=0}^{N-n} \sum_{i=0}^{n} \big((i+j) \wedge C\big) P_s((i+j) \wedge |C|) P_{bl}(i|n) P_{th}(j|n) & for Pro1 \\ \\ \sum_{j=0}^{N-n} \sum_{i=0}^{n} \big(i+j\big) P_s(i+j) P_{bl}(i|n) P_{th}(j|n) & for Pro2 \end{cases} \tag{3.27}$$

respectively [3], where $x \wedge y$ denotes the minimum of the two numbers x and y. At a given time slot and for r active users, the packet success probability $P_S(r)$ for both correlation receivers and chip-level receivers are given by equations (3.8) and (3.10), respectively.

3.9.2.2 The Effect of MAI

Since we are using OOCs with correlation constraints equal 1, users of different codes (Pro 1 and Pro 2) interfere with each other by one chip at most. On the other hand, users of same code (Pro 2) interfere with each other by 0, 1, or w chips. Assuming chip-synchronous interference model among users, the probabilities P_1 and P_w of one chip and w chips interferences, respectively. P_1, P_w can be expressed as follows [3]:

$$P_1 = \begin{cases} \frac{w^2}{L} & forPro1 \\ \frac{w^2}{L} \cdot \frac{|C|-1}{|C|} + \frac{w(w-1)}{L} \cdot \frac{1}{|C|} & forPro2 \end{cases} \tag{3.28}$$

and

$$P_w = \begin{cases} 0 & forPro1 \\ \frac{1}{L} \cdot \frac{1}{|C|} & forPro2 \end{cases} \tag{3.29}$$

3.9.2.3 Performance Metrics

To obtain the steady state system throughput and the average packet delay, the above system can be described by a discrete Markov chain composed of $N+1$ states depending on the number of backlogged users $n \in \{0, 1, \cdots, N\}$. The transition between any two states occurs on a slot-by-slot basis. The transition probabilities between any two states and the stationary probabilities Π_n for both systems with Pro 1 and Pro 2 can be obtained as in [3].

$$\sum_{n=0}^{N_i} \pi_n = 1 \qquad (\forall m \in \{0, 1, \ldots, N_i\}), \qquad \sum_{n=0}^{N_i} \pi_n P_{nm} = \pi_m \tag{3.30}$$

where P_{nm} is the transition probability of backlogged users from state n to state m as in[3], where $n, m \in \{0, 1, \ldots, N_i\}$, and P_{nm} for Pro 1:

$$\begin{aligned} P_{nm} = \sum_{l=0\vee(n-m)}^{n_i} \sum_{k=0\vee(m-n)}^{(N_i-n_i)\wedge(|C|+m-n)} P_{bl}(l|n_i)P_{th}(k|n_i) \cdot \binom{(k+l)\wedge|C|}{k-m+n} \\ \cdot P_s^{k-m+n}((k+l)\wedge|C|) \cdot [1 - P_s((k+l)\wedge|C|)]^{((k+l)\wedge|C|)-k+m-n} \end{aligned} \tag{3.31}$$

For Pro 2:

$$\begin{aligned} P_{nm} = \sum_{l=0\vee(n-m)}^{n_i} \sum_{k=0\vee(m-n)}^{N_i-n_i} P_{bl}(l|n_i)P_{th}(k|n_i) \cdot \binom{k+l}{k-m+n} \\ \cdot P_s^{k-m+n}(k+l) \cdot [1 - P_s(k+l)]^{l+m-n} \end{aligned} \tag{3.32}$$

Finally, the steady state system throughput β, and the average packet delay D can be computed from the following relations.

$$\beta = \sum_{n=o}^{N} \beta(n)\Pi_n \qquad and \qquad D = 1 + \frac{1}{\beta}\sum_{n=0}^{N} n\Pi_n \tag{3.33}$$

3.10 CONCLUSIONS

In this chapter, we presented the basic concept of OCDMA system with two different receiver correlation and chip-level receiver. we discussed three different types of the multi-rate techniques which are VSL, VPG, and MC. We talk about two different dimensional codes which are one dimension code represented in OOC, and two dimension code represented in OCFHC/OOC. We have proposed an optical random access CDMA protocol. A mathematical description of this protocol has been presented using a detailed state diagram. Several performance measures were considered; namely, the steady state system throughput, the thinking probability, the blocking probability, and the average packet delay.