Chapter 1

Introduction to Fiber-optic CDMA

The introduction to the evolution of fiber-optic CDMA (FO-CDMA) with its literature review is discussed in the following sections.

1.1 Introduction

Code division multiple access (CDMA) is a type of spread spectrum multiple access technique where the user signal is spread over a bandwidth larger than the minimum required for transmission. This is achieved by multiplying the user signal with an encoding sequence that is some kind of a random signal. In CDMA system, all the users operate using the whole system bandwidth and transmit at random timings for random durations unlike as in time division multiple access or frequency division multiple access (TDMA/FDMA). There is least coordination required in CDMA as opposed to TDMA/FDMA which require cumbersome protocols to deal with issues like synchronization, slot allocation etc.

There are many benefits of CDMA technology as listed by Feher (2004), which are given below.

1. secure communications
2. minimum interference
3. anti-jamming
4. code-division multiplexing
5. increased capacity
6. graceful performance degradation for larger number of users

CDMA earlier has been used for military applications because of its anti-jamming capabilities. But now it is a competing communication technology in areas such as satellite and mobile communication as has been discussed by Feher (2004) and Garg (2003).
Direct sequence spread spectrum (DS-SS) and frequency-hop spread spectrum (HP-SS) are the two CDMA techniques those have been in use since long for communication technology. Recently some new techniques have been proposed such as spectral amplitude coding, spectral phase coding, wavelength/time coding etc.

**Figure 1.1** On-off time-encoding using a one-dimensional code for unipolar Optical CDMA (a) data bits ‘10’ (b) transmitted coded data using a one-dimensional code ‘101000’ for bit ‘1’.

Figure 1.1 gives the concept of CDMA. The data is transmitted after being encoded by the CDMA code. A code ‘101000’ is transmitted for the bit ‘1’ and nothing is transmitted for the bit ‘0’. This is the case of on-off keying. The length of
the code is determined by the correlation constraints. The number of 1’s in the code is the weight of the code. For the 1’s in the code, optical pulses are transmitted, and no pulse is transmitted for a ‘0’ in the code as shown in the above figure.

Optical CDMA is a very useful multiple access technique due to the features like

- simultaneous network access
- soft capacity
- unique addressing of the users

The multiple access interference (for interference limited systems) determines the maximum number of users that can simultaneously access the network for a given BER. If the number of users is larger than this limit, the network still operates but with reduced performance; and if the number of simultaneous users is smaller than this limit, the performance improves.

Protocols are defined for every system in order for it to work efficiently. The existing multiple access protocols like Ethernet and token ring, could achieve a relatively low throughput. These operate satisfactorily for lower data rates and smaller traffic but the collision rate increases as the data rates and the traffic increase.

The network access protocols have been studied by Shalaby (2003) where the protocols for link layer of the packet oriented network with and without pre-transmission coordination are described. Again Shalaby (2004) describes a round-robin receiver/transmitter protocol.

The performance of optical CDMA is determined by the code correlation properties and the optical communication infrastructure which will include optical fiber and the optical components such as couplers, multiplexers, de-multiplexers, amplifiers etc. The optical fiber medium has a huge bandwidth, but the limited ability of optical-domain processing and relatively slower speed of electronics have been a practical hurdle to achieve very high data rates. But the developments in the WDM technology due to the improvements in performance of the optical components like fiber gratings, multiplexers-demultiplexers, optical switches etc., has led to higher data rates and improved spectral efficiencies. Such bottlenecks and their solutions are described by Aggarwal (2003).
Kim and Poor (2001) have described the use of channel coding for high bit-rate systems, where the turbo-coded pulse position modulation direct-detection CDMA system has been proposed for wireless indoor optical LANs.

One useful feature of optical CDMA is that it can minimize the delay in accessing the network since it allows the users to transmit asynchronously without waiting for their turn or for finding the free channels before transmitting as required in TDMA/FDMA. Also unlike other multiple access schemes where the system operates with a variety of protocols to find out the free channel and to communicate the destination address, the FO-CDMA system transmits destination address as the information by modulating the data with it. This increases the throughput and hence the system efficiency. Other benefits of FO-CDMA systems are

- Minimum network control
- Simultaneous access

The encoding/decoding operations are very simple for asynchronous systems since the receiver clock is not required. The optical filters or gratings along with delay lines make a cost-effective passive implementation of encoder/decoder for the asynchronous FO-CDMA systems.

Optical CDMA can also be classified into synchronous and asynchronous categories. According to Kwong et al. (1991), the synchronous systems accommodate many more users compared to the asynchronous case, whereas the asynchronous systems are less complex because no synchronization is required between the different users.

### 1.2 A Generalized Fiber-optic CDMA system

Shivaleela (2006) gives a generalized model of a transmitter/receiver in a star-connected optical CDMA network. Figure 1.2 shows such a scheme of optical CDMA network. The user data is fed to the electric-to-optic converter in the transmitter. It then is encoded in a tunable encoder which uses a spreading sequence for that purpose. The encoded data is further transmitted to the network where it
combines with similar transmissions from the other users. Each receiver is tuned to a unique address code.

On the receiver side, the matched decoder receives the data correctly by despreading the signal intended for it because it was coded by the same code in the transmitter. The multiple access interference form other users is left spread. The decoder output is threshold-detected and the desired data is recovered after optical-to-electrical conversion.

Figure 1.2  A Generalized Star Connected Fiber-Optic CDMA System [Shivaleela (2006)].
The coding can be implemented by many different schemes discussed in the next section. Optical CDMA is based on assigning unique codes to all the users for an error-free operation. Many parameters affect the performance of the optical CDMA system in addition to the properties of the codes. The code used should have the following desired properties.

1. The code should be distinguishable from the shifted version of itself
2. Maximum peak auto-correlation and minimum cross-correlation.
3. Ability of faster synchronization at the receiver

### 1.3 Classification of Encoding Techniques for FO-CDMA

Ever since its introduction by Davies and Shaar (1983), many approaches for the design and implementation of fiber-optic CDMA (FO-CDMA) have been considered. According to Yim (2002), FO-CDMA has been classified into the following categories where direct or differential detection can be used.

- Incoherent amplitude encoding
- Spectral encoding
- Coherent phase encoding
- Spatial encoding
- Matrix encoding

The other classifications are coherent/non-coherent and synchronous/asynchronous systems, which will be discussed in a later section.

#### 1.3.1 Incoherent Amplitude Encoding

The incoherent amplitude encoding is very economical as only the power of the signal is detected and any phase information of the signal is not considered. The performance of such a system depends on the cross-correlation properties of the code i.e. the interference among the codes. Obviously, sparsely spaced and longer-length
codes (for low cross-correlation) are used for coding such as prime sequences constructed by Shaar and Davies (1983).

Optical codes have also been proposed by many other authors; for example, the optical orthogonal codes by Chung et al. (1989). Prucnal et al. (1986) show that the capacity of LAN can be increased by increasing the number of chips in the code. They construct the prime codes and use these to study the optical CDMA system. Salehi (1989) has used the scheme of Figure 1.3 to generate the one-dimensional (1-D) optical orthogonal codes. Salehi and Brakett (1989) give the performance evaluation of the codes proposed by Salehi (1989) using various parameters like data rate, code length, code weight, number of users and the receiver threshold. They also show that ideal optical hard-limiter improves the system performance by reducing the multiple access interference. Kwong et al. (1991) uses optical delay lines and encodes the optical signals beyond their coherence length as shown in Figure 1.3.

**Figure 1.3** Optical Tapped Delay Line Encoder.
Chung and Kumar (1990) have proposed a family of optical codes with cross-correlation of 2. They also give the upper bound on the size of the code set. Maric et al. (1993) have constructed quadratic congruence codes. There are \( p-1 \) generated codes where \( p \) is a prime number. As MAI is the dominant source of noise in broadcast networks, the performance is studied considering the MAI only while the receiver noises are neglected.

Gamiero (2000) studied the sequences based on Gold codes for use in Quasi-synchronous CDMA (QS-CDMA). The codes are shown to be more tolerant to the timing jitter in the user’s clock.

### 1.3.2 Spectral Encoding

Spectral encoding can use modulation of amplitude or phase of the spectral components in the signal to embed the information. Zaccarin and Kavehrad (1993) and Kavehrad and Zaccarin (1995) reported the spectral encoding scheme using a low-cost broadband optical source which is shown in Figure 1.4. The two types of spectral encoding are discussed below.

![Spectral Encoder](image-url)

**Figure 1.4** Spectral Encoder.
1.3.2.1 Spectral Amplitude Encoding

Nguyen et al. (1997) have demonstrated experimentally the non-uniform spectral amplitude encoding to compensate for the uneven spectral shape of the laser source. Non-uniform spectral encoding improves orthogonality between the coded waveforms of the multiple users.

For spectral amplitude encoding, an amplitude mask is used in the encoder and a complementary mask in the decoder but such integrated structures lead to significant insertion losses as shown by Fathallah et al. (1999). A grating separates the various spectral components which are focused by a lens at the amplitude mask imprinted with the desired code.

Pfeiffer et al. (1999) have studied the operational stability of spectral coded optical CDMA. The system can achieve a BER of $<10^{-9}$ with poor quality filters and loosely specified optical transmitters. This dictates that optical transmitter filters do not need to be actively temperature controlled over a wide temperature range. Boffi et al. (2000) have implemented spectral CDMA system using fiber Bragg grating arrays and broadband incoherent source. They have used piezo-electric elements to tune the gratings independently in order to obtain a flexible structure. A new code family for spectral amplitude encoding has been proposed by Wei et al. (2001). Djordjevic and Vasic (2004) have proposed the construction of optical orthogonal codes for spectral amplitude coded optical CDMA systems using combinatorial methods. Djordjevic et al. (2004) have also designed multi-weight codes to be used for multimedia applications.

Park et al. (2004) have used differential detection with spectral coding to reduce multiple access interference. Pham et al. (2005) have used a heterodyne detection receiver in their work on demonstration of spectral-amplitude-encoding optical CDMA system. Chang et al. (2006) have demonstrated spectral encoding using modified pseudo-random noise codes and bipolar encoding. The experiment shows that the transmissions can be done over 80 km with a very small penalty using spectral encoding.

Wen et al. (2006) have employed perfect difference codes (PDC) in spectral optical CDMA. Though the PDCs are not useful for asynchronous systems because of their poor correlation properties in the time domain, they have used these for
asynchronous spectral amplitude coded optical CDMA by employing an interference cancellation scheme. Non-uniform spectral phase encoding has been proposed by Du et al. (2006) to compensate for the non-ideal uneven spectra of optical sources. The scheme improves the orthogonality of the encoded waveforms between the multiple users. The authors have considered only the synchronous systems and mode-locked lasers.

1.3.2.2 Spectral Phase Encoding

In spectral phase encoding, a phase mask with a pseudo-random spatial phase pattern is inserted between two lenses similar to the scheme for spectral encoding. Weiner et al. (1986) have used a grating pulse compressor to carry out the spectral masking. Salehi et al. (1990) have proposed a spectral phase coding optical CDMA system in which the user addresses are generated by spectral phase coding of the source. The first lens separates the different spectral components spatially. The phase mask is placed at mid-point between the lenses where the spatial distance between the different spectral components is maximum. It introduces the pseudo-random phase shifts into the spectral components. The second lens will collect the phase shifted spectral components and gives out a composite spectral phase coded signal. This introduces phase shifts among different spectral components of the transmitted signal. A conjugate phase mask is used to extract the signal at the desired receiver which removes the phase shifts. An unmatched decoder further re-spreads the signal. Puntsri et al. (2008) have investigated the steady state system throughput and average system packet delay time analysis is carried out using random access protocol proposed in Shalaby (2003) and Shalaby (2004).

1.3.3 Coherent Phase Encoding

Phase modulated narrow optical pulses are generated using electro-optic modulators. Pulses are then encoded by using tapped optical delay lines introducing different delays and phase-shifts in the different branches. Griffin et al. (1992) have studied the optical phase coding and employed differential detection to reduce multiple access interference. They use a ‘master’ encoder to provide a reference for the system. Zaccarin and Kavehrad (1994) give the evaluation of phase coded optical CDMA system using two different sequences and establish the feasibility of the
scheme. Huang et al. (2000) describe the coherent optical CDMA systems and give their performance comparison with the OTDMA system. They also propose a hybrid OCDMA/WDMA system for better performance.

1.3.4 Spatial Encoding

Spatial encoding systems use multiple fibers as space channels for encoding in optical CDMA systems. Many implementations of such system have been proposed like two-dimensional optical codes by Kitayama (1994), Yang and Kwong (1996) and the spatial optical CDMA by Hui (1985). Park et al. (1992) have proposed Temporal/Spatial codes. The performance of the temporal/spatial codes is better than temporal codes as these allow for smaller bit times. The correlation values are also improved. Hassan et al. (1995) have used random coding and synchronous scheme for their study.

Lin et al. (2005) have proposed non-coherent spatial/spectral codes, named 2-D perfect difference codes.

1.3.5 Matrix Encoding

Zhang and Pichhi (1993a) have proposed a tunable encoder/decoder using splitter, combiner, switches and fiber delay lines. A wavelength-time encoder using super-structured fiber Bragg grating (SSFBG) is shown in Figure 1.5.

The broadband light pulse is used with a SSFBG so that the Bragg wavelengths of the gratings are reflected back so as to appear at the output of the encoder as the coded signal. The different spectral components are time-shifted due to the positions of the gratings in the fiber. A conjugate of the SSFBG is used at the decoder to recover the signal. Fathallah et al. (1999) have used identical gratings which can be strain-tuned to different wavelengths.

Kim (2000) have proposed a cyclic encoder/decoder using arrayed waveguide grating. Arrayed waveguide gratings (AWG) along with metal reflection delay lines have been used to carry out wavelength/time encoding/decoding by Yu et al. (2000). Chen et al. (2000) have used chirped moire gratings for encoding/decoding with four users and a bit rate of OC-12. A uniform FBG is reported in Mokhtar et al. (2002), which can be tuned by heating locally through resistive wires.
Kwong and Yang (2003) have reported the use of arrayed waveguide grating for constructing programmable wavelength-time optical CDMA coders. The design is based on the phenomena of wavelength periodicity of the AWG’s. Kwong et al. (2005) have used the programmable AWG’s to design encoder/decoder structure for the class of codes they have designed. The wavelength hopping uses unipolar version of the bipolar codes while the unipolar codes are used for time spreading. To overcome bandwidth expansion in FO-CDMA systems, low rate super orthogonal channel coding has been proposed by Azmi et al. (2001).
1.4 Codes for FO-CDMA Systems

The direct detection receivers compare the decoded signal with a threshold (equal to the weight of the code) and the decision on the bit value is made. So, in order to improve the bit error rate, a larger threshold (i.e. a larger code weight) is used. This condition reduces the generated codes in the code set when the peak cross-correlation is kept unchanged or the code size is required to be increased. To reduce code-spread in one dimension, 2-D/3-D codes have been proposed. The codes are classified here according to the code dimensions: One-dimensional codes, two/three-dimensional codes. In one-dimensional (1-D) codes, the code length increases with the increase in the required number of users and it also increases with the increase in the code weight in order to satisfy the cross-correlation constraints. This longer code length either limits the transmission bit rate or increases the chip rate. Codes with additional dimensions reduce the wavelength and/or time spread as well as meeting the correlation constraints. Many such codes families of codes with two-dimensions (2-D) and three dimensions (3-D) have been proposed. These are briefly reviewed below.

1.4.1 One-Dimensional (1-D) Codes

Shaar and Davies (1983) have proposed one-dimensional prime codes for FO-CDMA systems based on the elements of Galois field $GF(P)$ where $P$ is a prime number. The codes have a cross-correlation of at most two and out-of-phase auto-correlation of $(P-1)$. Gold encoding along with matched electronic filters has been proposed by Tamura et al (1985). Hui (1985) has suggested the use of tapped delay lines for matched correlator. He also suggests the use of hard-limiter for improving the system performance. Prucnal et al. (1986) have proposed a time-delay line (TDL) structure for correlation of optical CDMA. Many families of 1-D codes have been proposed. Salehi (1989) has proposed ‘Optical orthogonal codes’ (OOC) which have both out-of-phase auto-correlation and cross-correlation of unity. The properties of optical orthogonal code have also been verified experimentally.

Salehi and Brakett (1989) have analyzed the performance of fiber-optic network using optical orthogonal codes. They have shown that the probability of error is upper bounded for the chip synchronous case and that it is lower bounded for fully chip asynchronous case. The error performance is analyzed using the hard-
limiter which acts as a threshold device to reduce the multiple access interference. Chung et al. (1989) have presented different techniques for generating OOCs. Chung and Kumar (1990) have presented the improved bounds on error probability. Kwong et al. (1991) show that the number of users supported with synchronous optical CDMA is larger than with asynchronous optical CDMA. They use prime sequences for the comparative study of the two cases. Maric et al. (1993) have presented the construction of ‘Quadratic sequences’ by algebraic method and have shown that for Quadratic sequences unlike the prime codes, the auto-correlation and cross-correlation properties are independent of the weight of the code. These quadratic sequences have better auto-correlation properties but poor cross-correlation properties than the prime codes. Maric (1993) designed the improved ‘extended quadratic sequences’ by increasing the length of the quadratic sequences. These extended sequences have ‘unity’ autocorrelation and a peak cross-correlation of ‘two’ respectively. Weng and Wu (2001) have proposed OOCs with relaxed cross-correlation. They have used relaxed cross-correlation in order to get a larger code set. Gu and Wu (2005a) have proposed variable weight OOCs, which are useful for variable quality of service applications. Hara and Miao (2000) have presented code constructions of OOCs with weight greater than three using cyclic packings.

Zhang and Picchi (1993) have proposed asymmetric error correction coding for improving the performance of fiber-optic networks. They have studied the technique using OOCs and prime codes. Zhang (1994) has shown that the BER performance and hence the number of simultaneous users can be greatly increased with the use of asymmetric error correction coding. It is shown that asymmetric error correction coding is more efficient than the symmetric error correction coding. Zhang et al. (1997) have proposed the $2^n$ modified prime codes by padding $(P-1)$ zeroes in each subsequence of the codewords in the $2^n$ prime code, where $P$ is a prime number. The resulting $2^n$ modified prime codes have a peak cross-correlation of unity which is better than that for the $2^n$ prime codes. Zhang et al. (2000) have studied the performance of modified prime codes for optical CDMA systems. It is shown that as opposed to the prime codes, the modified prime codes can maintain a fixed weight for any number of users $N$, whereas for the prime codes, the code weight is equal to $N$. 
1.4.2 Two-/Three-Dimensional (2-D/3-D) codes

The 1-D codes suffer from the drawback that the required code lengths become very large if the number of users is to be increased while keeping the cross-correlation and out-of-phase auto-correlation low. This limits the bit rate or the chip rate increases for the same bit rate. Use of 2-D codes provides another degree of freedom so there is additional flexibility in code design. The code length reduces as well. The 2-D codes are wavelength-time or space-time codes. Figure 1.6 shows a 2-D wavelength-time code with $W$ wavelengths (from $\lambda_1$ to $\lambda_4$) and $T$ time-slots (or time-chips) each of duration $T_c$.

![Diagram of a 2-D wavelength-time code with $W$ wavelengths and $T$ time-slots](image)

**Figure 1.6** Encoding using a two-dimensional wavelength-time code with $W$ wavelengths (from $\lambda_1$ to $\lambda_4$) and $T$ time-slots (or time-chips) each of duration $T_c$ [Adams and Chen (2005)].

Chen (2001) has proposed a reconfigurable fiber Bragg grating encoder/decoder for 2-D optical CDMA. The proposed system can be used for any 2-D codes including variable weight codes, multiple pulse per row and multiple pulse
per column codes. Chung et al. (2006) have proposed a tunable encoder/decoder that uses dual holographic grating (DHG), a fiber array and delay lines.

Yegnanarayanan et al. (2000) have proposed the use of spectrally broadened output by supercontinuum generation from a mode-locked laser. The wavelength-selective time delay devices are used for encoding/decoding in wavelength/time optical CDMA.

A number of methodologies have been reported in the literature for the design of 2-D codes. Some exploit mapping techniques to map 1-D sequences into 2-D and 3-D codes while the others are based on algorithms. Still others combine different 1-D sequences to construct new codes.

Tancevski and Andonovic (1994) have proposed 2-D codes by using prime codes for both wavelength and time spreading. Tancevski and Andonovic (1996) present the hybrid EQC/prime codes by using two different sequences i.e. extended quadratic codes (EQC) for spreading and prime codes for hopping. Heo et al. (2004) have designed 2-D wavelength-time codes by hybridization of pseudo-random noise codes and the prime codes. They use differential detection with on-off keying. Yeon et al. (2005) have proposed a system with modified pseudo-random noise codes for both the wavelength hopping and time spreading while the two sequences can differ in their lengths. Wan and Hu (2001) have obtained hybrid codes by crossing prime codes and optical orthogonal codes. They use differential detection with antipodal signaling.

Yu and Park (1999) have described an algorithm to generate 2-D code from 1-D prime sequence. Mendez et al. (2000) describe the technique to construct the 2-D codes from 1-D Golomb rulers. Mendez et al. (2003) and Mendez et al. (2004) construct 2-D codes from 1-D Golomb rulers. They use four Golomb ruler sequences to develop 32 codes so as to increase the number of generated codes.

Some code constructions have been based on the algorithmic designs. Gu and Wu (2005b) have described a new family of 2-D codes using a difference family which has unequal pulses per row. Yim et al. (2002) have proposed a wavelength-time code family using depth-search algorithm. Yim et al. (2003) have proposed the construction of 2-D wavelength/time codes by relaxing the cross-correlation constraints. Shivaleela et al. (1998) give single pulse per row codes using algebraic method of modulo addition. Shivaleela et al. (2005) have described the design of 2-D multi pulse per row codes using the 1-D optical orthogonal codes.
Kim et al. (2000) have proposed 3-D space/wavelength/time codes. The generated code set is larger than obtained using 2-D codes. The limitation with the use of 3-D codes is that multiple star couplers and fiber ribbons are required. They also suggested that the 2-D implementation of the 3-D codes eliminates the above-mentioned problem associated with the implementation of the 3-D code. Hence, the potential of 3-D codes with some modifications in the implementation can be probed.

McGeehan et al (2004) have designed 3-D time-wavelength-polarisation codes for optical CDMA systems. The codes have a larger code set and better performance compared to the 2-D codes. The implementation requires use of polarization maintaining fibers, polarization sensitive components such as polarizers and polarization independent components such as amplifiers. The polarization control throughout the link is complicated and this makes the implementation costly.

The interference at the desired receiver because of other users depends on the cross-correlation property of the code. The minimum cross-correlation among the codes is a desired feature in order to reduce the bit error rate. In addition, interference can be reduced by using some kind of interference reduction techniques discussed in the next section.

1.5 Techniques for Reduction of Multiple Access Interference

Multiple access interference (MAI) is a phenomenon in FO-CDMA systems, which appears due to non-zero cross-correlation between the codes. Many techniques have been reported for the reduction of MAI. Hui (1985) has shown that MAI is reduced with the use of an optical hard-limiter placed at the front end of the receiver. Chen and Yang, (2001), have studied the system performance analysis with the hard-limiter using prime and extended prime codes. Yim et al. (2001) have used time gating alongwith superstructured fiber grating coders. Asymmetric error correction (AEC) codes embedded in optical orthogonal codes (OOC) and Reed Solomon (RS) codes have been used by Kamakura and Sasase (2001). The codes denote the respective users whereas AEC corrects the errors occurring due to the presence of MAI. Errors not corrected by AEC are corrected by the RS code. Ohtsuki (1997) has used double optical hard limiter to reduce the effect of MAI. Liu and Tsao (2001)
have used trellis coding along with the double optical hard limiters for suppressing the MAI. In another scheme, Lin and Wu (2000), have used Manchester coding to reduce the effect of multiple access interference. FBGs are very convenient for inscribing the spectral codes in FO-CDMA applications, but due to the non-flattened incoherent sources and non-ideal FBG filters, MAI results. Huang and Yang (2002) have described a scheme for compensation of MAI due to such non-flattened incoherent sources and non-ideal FBG filters. Andonovic et al. (1998) have demonstrated the encoding and decoding of phase and frequency codes for optical CDMA.

Figure 1.7 Principle of Successive Interference Cancellation Receiver. [Eltaif et al. (2009)].
Mendez et al. (2004) have used guard time with their 2-D wavelength/time Matrix codes to reduce MAI. Kim et al. (2004) have proposed the use of non-linear optical loop mirror (NOLM) for reduction of MAI in coherent optical CDMA systems.

Weng et al. (2005) have theoretically studied the performance improvement with the use of double optical hard-limiters. The analytical results are verified with simulations and it is shown that the system performance improves with the use of double optical hard-limiters.

Eltaif et al. (2009) have used successive interference cancellation (SIC) scheme to mitigate the multiple access interference. Figure 1.7 shows the block diagram of the SIC receiver. The SIC receiver detects and demodulates the strongest signal currently present in the overall received signal. The receiver works with the following algorithm: (i) Recognize the strongest signal (the one with the maximum correlation value), (ii) Decode the strongest signal, (iii) Regenerate the strongest signal using its chip sequence, (iv) Cancel the strongest signal, (v) Repeat (until all the users are decoded or a permissible number of cancellations are achieved).

Differential detection is also effective for reducing the multiple access interference in the differential receiver. This can be used with on-off keying (OOK) as well as antipodal signaling. The scheme is discussed below.

### 1.5.1 Differential Detection

Differential detection is a very popular means of eliminating MAI in coherent/non-coherent and synchronous/asynchronous optical CDMA systems. Figure 1.8 shows the schematic of the principle of differential detection. The outputs from the two branches of decoders are detected by two photo-diodes. The difference of the two detector currents is thus free of the MAI since MAI affects the two branches of the decoder evenly. If the MAI is not completely cancelled, it is significantly reduced.

Yeon et al. (2005) have used time delay lines and filter-groups for encoding/decoding operation. Huang and Yang (2002) and Huang and Hsu (2000) have used m-orthogonal codes differential detection for reducing multiple access interference. Heo et al. (2004) have utilized differential detection with the projected codes wherein only the ‘1’ bits are transmitted (on-off keying).
Figure 1.8  Principle of Differential detection.

Wan and Hu (2001), Yim and Bajcsy (2003) have used differential detection with the balanced codes for reducing the multiple access interference. Wan and Hu (2001) have studied prime/OOC codes using tunable Bragg gratings.

Yim and Bajcsy (2003) have proposed balanced codes for differential detection and use antipodal signalling/differential detection. Wang et al. (2007) have also used balanced detection (differential detection). They have used antipodal signaling to improve the data security. Wang et al. (2007) have emphasized the importance of code-shift keying from a security point of view.

Heo et al. (2004) and Huang and Hsu (2000), have used OOK with differential detection. The MAI reduces due to the subtraction of the signals in the two branches in the differential receiver.
In a U. S. patent application for asynchronous systems, Yeon et al. (2005) have reported codes derived using modified pseudo-random noise codes for wavelength-time coding which have zero MAI due to cross-correlation when the number of users is no more than $2 \times (M - 1)$, where $M$ is the length of the modified pseudo-random code.

Hence, differential detection is an established technique of reducing the cross-correlation due to MAI. Differential detection simplifies the receiver design in addition to the improvement in the system performance. The threshold level can be set to zero as the average MAI is very low. But due to non-zero cross-correlation between the codes, the MAI may not be eliminated completely.

1.6 Effect of Fiber Medium on the Performance of FO-CDMA

Multiple access interference is the major source of degradation in optical CDMA systems which mainly arises from the correlation properties of the codes employed for the design of the encoders and decoders. The use of low-cost broadband sources having non-ideal spectrum also generates MAI. In the encoders/decoders, the non-ideal spectral response of the wavelength-tunable components also contributes to MAI. This loss can be mitigated with the application of some interference reduction techniques (described in Section 1.5).

In addition to MAI, the signal deteriorates due to the optical medium impairments. In-line optical amplifiers are used for maintaining the signal power in the optical fiber. These introduce their own noise in addition to amplification of the signal and noise. Dispersion can be compensated with the use of dispersion compensating techniques like dispersion compensating fibers, fiber Bragg gratings etc. In a multi-user environment where every user uses the same signal bandwidth, the non-linear effects become more severe. The optimization needs to be done for all the above-listed degrading effects present in the optical medium. In addition to these, the noise contribution of the amplifier, the non-ideal switching times and crosstalk of the switches add to the degradation of the signal.
Uddin and Majumder (2005) have evaluated the performance of optical CDMA systems considering the four-wave mixing (FWM) effects only. They have carried out the analysis for power constraints in the FWM scenario. The degradation due to the fiber dispersion has been analyzed by Majumder et al. (2005). Ferdous et al. (2008) have carried out the analysis of the effect of cross-phase modulation in optical CDMA systems. The various sources of noise in the receiver like shot noise and the thermal noise further contribute to the degradation of the received signal.

1.7 Synchronous vs. Asynchronous Optical CDMA

Prucnal et al. (1986) have described synchronous multiple access schemes for TDMA and CDMA. Though TDMA gives collision-less and interference-free transmissions, it lacks in terms of the number of supported users which is at most equal to the number of time slots. The synchronous CDMA (S/CDMA) systems have an edge over the asynchronous systems as more users can be supported compared to asynchronous systems, leading to larger throughput, as suggested by Kwong et al. (1991) and Kwong and Prucnal (1990). This can be made possible by synchronizing the transmissions to a rigorous timing for all the users which can not transmit randomly and hence collisions are avoided. It requires that all the users should be synchronized to chip rate clock. Kwong et al. (1991) have modified the $p$ prime codes for use in synchronous systems to generate $p^2$ codes where $p$ is a prime number. It also shows that S/CDMA systems have better BER performance than asynchronous systems. Wu et al. (1992) suggest that the performance of S/CDMA systems can be improved further by use of error correction coding which results in an increase in the number of simultaneous users for a given bit error performance. Shalaby (2001) has presented techniques for interference cancellation in S/CDMA systems.

In S/CDMA, the number of supported users depends on the code properties. Hence synchronous-CDMA is better in comparison to TDMA and asynchronous-CDMA in terms of number of supported users and the system performance but it has the following constraints:
• Synchronization among users at the chip rate
• Waiting time for the transmissions
• Need for a stringent network coordination

The first constraint helps in collision-less transmissions. But this also imposes the second constraint that the transmissions begin at the start of time slot. Hence a stringent network coordination is required which provides increased number of users. All other features of CDMA like anti-jamming, soft capacity etc. are inherently available.

1.8 Coherent/Non-Coherent Systems

Coherent systems recover the clock signal in the receiver whereas it is not so in the non-coherent systems. Coherent systems give better system performance than the non-coherent systems. A lot of work has been reported on coherent CDMA systems. Davis and James (1984) and Jackson et al. (1986) have separately demonstrated the prototype coherent CDMA networks. Maric and Chang (1989) have proposed an energy efficient ladder network using couplers and polarization controllers. This arrangement does not give any side-lobes in the matched decoder. The efficient fiber-optic ladder network requires two distribution stars. Chang and Marhic (1992) have used only one distribution star for carrying out the decoding while it used two orthogonal polarizations as spatial channels.

Salehi et al. (1990) have reported a coherent CDMA network in which the different user addresses are generated by spectral phase coding. The technique has already been described in section 1.3.2.2. Griffin et. al. (1992) have described an optical CDMA network using phase coding. Sinusoidal phase modulation is applied at different frequencies to each stage of the fiber-optic ladder network encoder and the output of a stage gives the phase information at that stage. This phase relationship between the encoder and decoder and between the different decoders is maintained by using a master source and all the encoders/decoders are locked to it.

Karafolar and Uttamchandani (1994) have proposed a coherent CDMA system with spread spectrum phase shift keying. In the detector, the signal is split
into two paths. In one path the signal is delayed and phase modulated and then combined with the signal from the other branch. A matched decoder gives an auto-correlation peak whereas a low noise signal corresponding to the cross-correlation is obtained for an unmatched decoder. Papannreddy and Weiner (1999) have theoretically compared the performance of coherent and incoherent optical CDMA systems and shown that the former has a better performance. The effects of phase errors and shot noise have been studied by Singh and Shevgaonkar (2004).

1.9 Data Security

Tancevski and Andonovic (1996) have studied the hybrid wavelength/time spreading systems using extended quadratic congruence sequences for wavelength hopping and prime sequences for time spreading. The system security has been evaluated using the above codes.

Shake (2005) emphasizes that the user data security against an eavesdropper is a very critical issue, as the data can be tapped even without the knowledge of the user optical code (OC) by the analysis of the data pattern, i.e. by a data-rate power measurement. Wang et al. (2007) have described a code-shift-keying scheme to increase security against an eavesdropper. A similar work using code switching in the spectral phase coded OCDMA system has been carried out by Leaird et al. (2005). Many other proposals for increasing the security have been suggested and evaluated by Prucnal et al. (2008), Glesk et al. (2007), Nasaruddin and Tsujioka (2008). Prucnal et al. (2008) have carried out code swapping on bit-by-bit basis. In Glesk et al. (2007), either of the two codes is transmitted depending on a RF code swapping sequence. It has been shown by Nasaruddin and Tsujioka (2008) that by increasing the number of codes reserved per user for encoding, the probability of breaking of the user code by an eavesdropper is reduced. All the above techniques (Prucnal et al. (2008), Glesk et al. (2007), Nasaruddin and Tsujioka (2008)) hence are based on reserving additional codes for a user i.e. the number of codes assigned per user are increased in order to reduce the chances of an eavesdropper to detect and analyze the data patterns of a user.
1.10 Important Developments and the Latest Challenges

With a description of the background of optical CDMA, its classifications, the different codes used in FO-CDMA systems, the important developments and its applications, the brief review of the important contributions and the latest developments is given below.

Petrovic and Holmes (1990) have used variable bit interval codes to increase the capacity of the fiber-optic LANs. Gagliardi et al. (1993) have studied the multiplexing of digital video signals using FO-CDMA. A spatial spread-spectrum optical FO-CDMA system to carry image transmission has been studied in Kitayama (1994). Maric et al. (1996) have proposed a multimedia and multirate transmission using FO-CDMA. The probability of error has been calculated for different numbers of users of low and high data rates. Variable weight optical orthogonal codes have been developed by Yang (1996) for multiple performance requirements.

Two-dimensional wavelength-time ($W/T$) codes with zero-MAI have been proposed for asynchronous FO-CDMA systems with differential detection in Yeon et al. (2005). The number of users supported with zero-MAI is twice the length of the pseudo-random code used. If users more than this number are active, multiple access interference appears. This work has been extended by the same authors [Yeon et al. (2006)] to increase the number of supported users. Because of the virtue of the synchronization provided among the intra-group users, the number of users supported with zero-MAI is increased.

Garba and Bajcsy (2007) have proposed a scheme to increase the spectral efficiency of wavelength/time OCDMA network transmission by using forward error correction while using a unit spreading length OCDMA coding. They have used turbo coding and Reed-Solomon coding with zero-padding to increase the achievable spectral efficiency to 0.740 bits/sec/Hz.

Galli et al. (2008) have proposed a method to increase the spectral efficiency of optical CDMA systems by using multi-dimensional modulation. The authors exploit the unused set of codes to assign a set of codes to each user for implementing multi-dimensional modulation.
Deng et al. (2008) have demonstrated the implementation of 2-D wavelength-hopping/time-spreading incoherent optical CDMA using a CW laser source where the different wavelengths are obtained by the pulse carving of the laser.

Deng et al. (2009) have demonstrated the MAI and interferometric noise reduction by using a dispersion-imbalanced loop mirror with heavily-doped GeO$_2$-doped fiber. For the two-user system, the noise power penalty has been shown to decrease by 7 dB.

The MAI arising out of the encoder-decoder mismatch due to wavelength and time misalignments in wavelength/time systems has been analyzed by Adams and Chen (2005).

From the above discussion it is evident that the system performance can be improved by designing better codes. The most important challenge that always exists is to develop codes with larger code-set-size to code-size ratio. Codes with larger code-set-size to code-size ratio can generate larger codes for the same hardware availabilities. The codes in addition, should give improved system performance.

Since data security requires that code-switching be employed, hence the surplus codes can be utilized for code-switching.

### 1.11 Motivation and Objectives

From the discussion in the above, this has been observed that the performance of FO-CDMA system depends largely on the MAI characteristics i.e. on the code correlation properties. An efficient coding should have lowest peak cross-correlation, lowest off-peak auto-correlation, highest code-set-size to code-size ratio (this provides the flexibility of supporting larger number of simultaneous users for a gradual degradation in performance) and a large number of active users operating with the specified BER performance. The spectral efficiency is determined by the number of active users. Also a large code-set-size to code-size ratio makes available an increased number of codes so that the surplus codes can be used for code-switching and hence for improving data security.

A 3-D code family can generate a larger code set with better BER performance compared to the 1-D/2-D codes. Differential detection has been reported as a technique for reduction of MAI, so this can be utilized in the receiver.
In order to improve the performance of the FO-CDMA systems, the work has been carried out in the following directions:

1. Understanding of some important codes and study of the correlation characteristics of 2-D and 3-D codes.
2. To verify the ability of differential detection for reduction of MAI.
3. To design 3-D wavelength/time/space codes with good correlation properties, a large code-set-size to code-size ratio and larger number of active users.
4. Determine the conditions under which the developed codes satisfy the desired correlation constraints.
5. Determine the size of the generated code family and study the code performance.
6. The implementation of the encoder-decoder based on the 3-D codes.
7. 2-D Encoder-decoder implementation for the 3-D codes so that the space couplers and the fiber-ribbons are not required.
8. Implementation of the system model based on the designed codes so that the system performance can be studied in the presence of the physical medium impairments.

1.12 Contribution of this Thesis

In this thesis, an effort has been made to improve the performance of fiber-optic CDMA communication systems. Two new families of codes namely SPDD codes [95] and GRZI-BCDD codes [97] have been designed. The newly designed code families show significant improvement in system performance over the earlier proposed codes for optical CDMA systems. Further, the GRZI-BCDD codes have been used to study the link performance of a fiber-optic CDMA system using CSRZ and DPSK-RZ formats. This has been found from the study that CSRZ format has better performance compared to the DPSK-RZ format.

The organization of the thesis is as follows. While the introduction to fiber-optic CDMA and review of the literature have been given in Chapter 1, in Chapter 2, an analysis has been carried out to study the performance comparison of two techniques of detection i.e. differential-detection and direct-detection for wavelength-time coded optical CDMA systems. It is verified that because of the
MAI reduction capability, differential detection has superior system performance over direct detection.

In Chapter 3, a new family of codes of three-dimensional (3-D) SPDD codes for asynchronous systems has been suggested which uses the wavelengths, time chips and the space channels. The algorithm for code generation is outlined; correlation constraints are defined and evaluated. For satisfying the unity cross-correlation constraints defined therein, the code size requirements have been given and it has been shown that under the defined conditions, the correlation properties of the codes are met. The number of users supported for the given code dimension has been determined. The analysis for BER performance has been carried out considering MAI only. The design of wavelength/time/space encoder/decoder and the network connectivity is given for the 3-D codes.

In Chapter 4, the design and analysis of a new highly spectral efficient code family of 3-D codes for asynchronous systems has been presented using another novel algorithm by inserting the zero-strings. The generated codes have been named as Golomb Ruler-with-Zero-Insertions Balanced Codes for Differential Detection (GRZI-BCDD) codes. The analytical evaluation of the conditions for unity cross-correlation has been presented and the different possibilities have been studied. The code cardinality is determined and code performance has been evaluated. Comparison with various other 2-D/3-D codes has also been given. The 2-D implementation has been proposed for the 3-D codes giving the encoder/decoder design and the network architecture. The 2-D implementation eliminates the need for fiber ribbons and multiple star couplers. The suitability of GRZI-BCDD codes for a secure optical CDMA network is analyzed.

In Chapter 5, the evaluation of the performance degradation of the GRZI-BCDD codes has been carried out considering the fiber linear and non-linear effects. CSRZ and DPSK-RZ are the two formats known for their resilience towards the non-linear effects. The performance of these modulation formats is compared in the presence of the physical layer impairments.

Finally the work has been concluded in Chapter 6. The results obtained in the previous chapters have been discussed briefly. The conclusions have been summarized and the justification of the suitability of the results to meet the challenges posed in the present scenario is given. The directions for the future work are suggested.