Chapter 6

Conclusions

In this thesis, an attempt has been made to improve the system performance of the fiber-optic CDMA systems by designing two new code families of three-dimensional codes and analyzing their system performance. The results obtained in the previous chapters are briefly discussed in the section below.

6.1 Discussion of the Results

In second chapter, two systems for optical CDMA are simulated in OptSIM in order to evaluate the performance of differential detection vs. direct detection. The matrix codes of Mendez et al. (2000) have been used which are based on Golomb ruler of order ‘4’. The first system uses direct detection and on-off keying i.e. only ‘1’ bits are transmitted. The second system uses differential detection and antipodal signaling i.e. two codes are assigned to each user for transmission of ‘1’ and ‘0’ bits. Both the systems are designed for four users.

Figures 2.4 (a) and (b) show the BER performance of each user for the cases of differential detection and direct detection. The plots show that the user BER performance is better with differential detection compared to direct detection. In Figure 2.4 (c), BER curves are plotted for user 3 with differential detection and user 4 with direct detection. These users have the worst BER performance in their categories. It shows that user with worst performance with differential detection performs better than the user with worst performance with direct detection. Hence this is verified that differential detection yields better system performance by virtue of its ability to reject the multiple access interference so differential detection has been employed in the rest of the work.

In chapter 3, a new code family of 3-D wavelength/time/space named Single pulse per plane codes for differential detection (SPDD) is constructed. The auto-
correlation and cross-correlation for 3-D codes are defined. The code size should be at least two times the value of the last element in the Golomb ruler for the code to satisfy the unity cross-correlation constraint. Figure 3.5 verifies this condition. In Figure 3.6 (a) the system performance of SPDD users is plotted and it is shown that the system performance increases with the increase in the time slots $T$ while wavelengths $W$ and space channels are kept fixed. Figure 3.6 (b) shows that the system performance improves with the increase in number of wavelengths $W$ keeping $T$ & Space channels fixed. Similar trend in the system performance is observed when the number of space channels is increased as is shown in Figure 3.7 (a). In Figure 3.7 (b), the system performance is plotted w.r.t. the wavelengths and the time slots taken together which shows that the system performance improves with the increase in $W$ and/or $T$.

Figure 3.8 (a) shows the system performance comparison of our proposed 3-D orthogonal codes with the 2-D optical orthogonal codes of Shivaleela et al. (2005). Since 2-D and 3-D codes have different dimensions, so to carry out their performance comparison, the 3-D SPDD are written as 2-D code $[(W \times S) \times T]$. The BER curves have been plotted for the 2-D OOC code of Shivaleela et al. (2005) with a code size 2080 (Single pulse per row code), and for the SPDD code with a code size of 2052. It has been observed that the SPDD codes with a code size of 2052 give better performance in comparison to the 2-D OOC code having a code size of 2080. Despite a smaller code size of SPDD, the BER is tremendously better and the number of simultaneous users at BER of $10^{-9}$ is significantly increased over those supported by the 2-D code.

The SPDD codes can be compared to 2-D PCBD codes of Heo et al. (2004). The PCBD codes can’t have more than $p-1$, ($p$ is prime number used to generate the codes) simultaneous users in the worst case. Hence the SPDD codes are significantly better than the 2-D PCBD codes.

The comparisons with the 3-D prime codes of Kim et al. (2000) has been shown in the Figure 3.8 (b) in which the BER performance of SPDD codes outperforms that of the 3-D prime codes for nearly the same code sizes. In Figure 3.9, the 3-D implementation of the optical CDMA system with the SPDD codes is proposed wherein only the details for space channel 1 are shown in order to reduce the expanse of the design.
In the fourth chapter, a novel family of 3-D wavelength/time/space codes (W-T-S) for asynchronous optical CDMA access networks, with ‘zero’ off-peak auto-correlation and ‘unity’ peak cross-correlation has been proposed. These codes are named Golomb ruler-with-zero-insertions balanced codes for differential detection (GRZI-BCDD).

The relation between the number of codes generated and the number of space channels relative to other code dimensions is given in Table 4.1. Figure 4.3 shows the BER performance of GRZI-BCDD codes with increase in the number of wavelengths in the code, \( W \); number of time-chips in the code, \( T \) and number of space channels. It also shows that the performance for \( W > T \) and \( W < T \). This is shown that the performance is better for the case when \( W > T \).

Table 4.2 gives the performance comparison of our GRZI-BCDD codes to the 3-D Time-Wavelength-Polarisation Codes. With a code size of 78, GRZI-BCDD code supports ten users at a BER of \( 10^{-9} \), whereas the 3-D Time-Wavelength-Polarisation code with a larger code size of 88 supports only 4 users simultaneously for the same BER. It shows that GRZI-BCDD codes can support comparatively much larger number of users.

In Figure 4.4 (a), the performance comparison of 3-D GRZI-BCDD code (code size \( 59 \times 7 \times 5 = 2065 \)) with 2-D W/T OOC code (with a code size \( 8 \times 260 = 2080 \)) of Shivaleela et al. (2005) is shown. The 2-D W/T code supports nearly 25 simultaneous users whereas approximately 130 users are supported with 3-D GRZI-BCDD code for a BER of \( 10^{-9} \).

Figure 4.4 (b) shows the performance comparison of 3-D GRZI-BCDD codes with code size=2065 to the 3-D \( S-W-T \) codes [(Kim et al. (2000)] with code size=4096 (of code size nearly two-times the size of GRZI-BCDD). This corresponds to the case \( S \leq W \) when the users supported with the 3-D \( S-W-T \) codes are given as \( W \times T = 254 \) and only 78 users can operate simultaneously at a BER of \( 10^{-9} \) with a code size = 4096. On the other hand, the 3-D GRZI-BCDD codes with a code size nearly half of that of 3-D \( S-W-T \) codes, can support \( 0.5 \times (W \times T + 1) \times W = 12213 \) users and nearly 130 users can operate simultaneously at the same BER of \( 10^{-9} \). Hence it is shown that the 3-D GRZI-BCDD code has significantly better performance compared to the other two codes.

The performance of our codes has also been compared with the 2-D PCBD codes of Heo et al. (2004) and the results have been tabulated in Table 4.3. The 2-D
PCBD codes (pseudo-random noise code length \( L = 7 \), prime number \( p = 17 \); code size = \( L \times p \times p = 2023 \)) have a cross-correlation peak higher than unity and is equal to the weight of the m-sequence used to generate the code. Hence, the PCBD can support \((p-1)\) simultaneous users in the worst case; \( p \), the prime number for prime-hop code. For \( L = 7 \), \( p = 17 \); a spectral efficiency of 0.117 only is achieved. With 3-D GRZI-BCDD (code size = 2065), the total number of users supported is much higher at 12213 compared to 238 for that of 2-D PCBD code.

The performance of 2-D codes of U.S. Patent Application No. 0100338 A1 of Yeon et al. (2005) is also compared to the 3-D GRZI-BCDD codes in Table 4.3. The 2-D codes have a limited number of users given by \( 2 \times (M-1) \) for a given \( M \) irrespective of the value of \( N \) (where \( M \) and \( N \) are the lengths of the modified PN codes used for wavelength and time spreading). The 2-D codes of Yeon et al. (2005) can, for example, support nearly 126 users in the C-band (with 0.4 nm wavelength spacing) regardless of the number of time-chips in the code, whereas the number of simultaneous users at \( 10^{-9} \) (as well as the total users) for 3-D GRZI-BCDD codes can be increased just by addition of some more time-chips for the same bandwidth and space channels (or only time-chips if 2-D implementation is used for the same wavelength window). For a fair comparison with codes of Yeon et al. (2005), nearly same code size and number of wavelengths are considered which explicitly shows that these codes show no improvement if \( N \) is increased.

In Chapter 5, the simulation is carried out to study the effects of physical layer impairments on the system performance in addition to MAI. The optical CDMA system is designed for four users wherein the encoders/decoders utilize GRZI-BCDD codes. CSRZ and DPSK-RZ are two robust formats for their resilience towards the physical layer impairments. Two systems are simulated; one employing CSRZ and the other DPSK formats. BER performance with the increase in the transmission distance is studied for the two formats.

Figures 5.3 and 5.4 show the BER vs. the received optical power for the two formats for different link-lengths and low per-user launched powers so that non-linear effects are negligible. It shows that CSRZ has better link performance than DPSK-RZ which is also observed from the BER vs. link-length plots in Figure 5.5. When the user launched power is increased to -3dBm, CSRZ again shows better performance. Table 5.3 and Figure 5.6 depict the system performance comparison of
the two formats for larger per-user launched powers of -10.94 dBm and -7.84 dBm for CSRZ and DPSK-RZ respectively.

When the per-user launched power is increased to -3 dBm so that the non-linear effects become significant, the performance of CSRZ still remains better than DPSK-RZ as is observed in Figure 5.7.

6.2 Concluding Remarks

Optical CDMA is a good candidate for very high-speed multiple access networks compared to other multiple-access techniques such as TDMA and FDMA. Optical CDMA also has many incomparable features like no access delay, data security, simultaneous network access, graceful degradation of system performance etc.

The performance of optical CDMA systems depends to a larger extent on the code correlation properties, which compel for the use of longer code-length 1-D sequences. To reduce the code-lengths, a number of 2-D and 3-D codes have been proposed. A code should satisfy the following constraints for its use in optical CDMA system.

- Low peak cross-correlation so that errors due to multiple access interference can be minimized.
- Low off-peak auto-correlation so that the synchronization at the receiver becomes easier in the presence of multiple users.

The codes employed in optical CDMA systems with direct detection at the receiver should also have a larger code weight as the decision threshold is set to the code weight. For the systems employing differential detection, the decision threshold can be set to zero thus simplifying the receivers due to its ability to reduce multiple access interference.

The codes should have higher spectral efficiency, a larger \[
\frac{\text{code set size}}{\text{code size}}
\] ratio and better BER performance. All these goals have been achieved with the 3-D wavelength/time/space codes developed in this thesis. The need of multiple star couplers and the fiber ribbons in the case of 3-D codes is eliminated with the use of
$W^2T$ scheme which converts the 3-D $W \times T \times S$ matrix into a 2-D $(W \times S) \times T$ matrix with $W \times S$ wavelengths and $T$ time slots.

In this thesis, two new code families of systematic 3-D codes for differential detection are designed with the above said aims. The designed code families are single pulse per plane (SPP) codes since, as reported in the literature, SPP codes have better system performance compared to the multiple pulse per plane (MPP) codes. These are generated from the Golomb rulers which have unique inter-pulse distance between any of its elements. The first code family has been named as Single Pulse per plane codes for Differential detection (SPDD). Following results have been derived for SPDD codes:

- The condition on the code size has been defined in order to satisfy the unity peak cross-correlation constraint. The cross-correlation properties under the specified code size conditions have been verified using MATLAB.
- The design methodology has been illustrated. Complete code family is simulated using MATLAB. The code set size has been determined and the BER performance evaluated. The dependence of the system performance on the code dimensions has also been evaluated.
- Three-dimensional wavelength/time/space encoder/decoder design is presented.

Another novel family of 3-D SPP code has been designed and named as Golomb Ruler-with-Zero-Insertions Balanced Codes for Differential Detection (GRZI-BCDD). The study and the results obtained are outlined below:

- The different possibilities of chip-overlap are studied and this is shown that the code satisfies the unity cross-correlation constraint.
- The design algorithm is outlined. The system performance has been determined by simulating the complete code set using MATLAB.
- The effect of the three code dimensions on the system performance has been investigated.
- The supported users come out to be maximum when $S \leq \min(W, T)$
- The maximum number of supported users is equal to $0.5 \times [(W \times T + 1) \times W]$.
- The performance is compared to the other 2-D/3-D code families reported in the literature and this is shown that the system performance of our 3-D codes is much better than the other systematic code families reported in the literature.
A 2-D implementation of the proposed 3-D codes has been suggested which eliminates the need of the fiber ribbons and the multiple space couplers.

The code-breaking probability has been calculated.

Since the codes have a large code set size to code size ratio, these are suitable for high security optical CDMA systems when code reconfiguration is employed by assigning multiple codes per user.

A fiber-optic CDMA system supporting with four active users is simulated using RSoft’s optical simulator OptSIM. The users employ antipodal signaling in the transmitters while differential detection is used in the receivers. The encoders/decoders use 3-D GRZI-BCDD codes. The system performance is studied in the presence of the optical medium degradations. The comparative performance of CSRZ and DPSK-RZ formats has been studied. The analysis is carried out for different fiber lengths. The following are the findings of the study:

The receiver sensitivity is improved with CSRZ than DPSK-RZ for low per-user launched power.

CSRZ shows better BER performance even when the per-user launched power is smaller at -20 dBm for CSRZ than -16 dBm for DPSK-RZ for 50 Km of link-length.

With increased link-length of 100 Km and 300 Km and low per-user launched power, CSRZ performs better than DPSK-RZ.

For per-user launched power of -3 dBm, when the non-linearities in the optical fiber are significant, the BER performance of CSRZ is better than DPSK-RZ for the link-length varied upto 2300 Km.

### 6.3 Future Scope

Since MAI is the major source of degradation, codes with better correlation properties can be designed.

In addition to the cross-correlation properties of the codes and the modulation formats, the performance of fiber-optic CDMA system depends on many factors such as the component parameters, component sensitivities to polarization etc. and the fiber non-linearities including inter-channel and the intra-channel effects. The
components such as sources, filters, (de-)multiplexers, couplers, amplifiers etc affect the system performance, for example, optical sources affect the performance due to the non-ideal spectral response, stability of the optical frequency. So there is always a scope to optimize the system performance by designing systems more robust with respect to the non-ideal behaviour of the components.

The beat noise and interferometric noise though very small compared to MAI, also affect the system performance. This study can be extended by considering these noise sources.