Chapter 7

Conclusions and Future Work

OOFDM being the potential candidature to meet the increased bandwidth requirement has gained the interest of researchers in recent few years. Traditional optical transmission was rigid using static communication strategies whereas current scenario expect network to be flexible fulfilling dynamic requirements. Recent growth in DSP has motivated the SDOT making optical network to be flexible, dynamic and reconfigurable as per the channel conditions, user requirement delivering more effective transmission in terms of performance, spectral efficiency. This work develops software defined optical transmission by making system dynamically adaptable and reconfigurable for performance improvement. The contribution includes developing SDOT to implement RCP-CO-OOFDM transmission for improving spectral efficiency and performance by employing less complex equalizer which is capable of compensating the effects of CD, non-linearities, laser phase drift, reducing CP overhead and adaptive subcarrier allocation.

7.1 Conclusions

First chapter describes the motivation behind the present work, followed by key contributions of present work and organization of the thesis. In chapter second, the literature associated with OOFDM transmission and their contribution is explored. It describes the increased interest of researchers in recent few years on the current area due to recent developments associated with DSP. It frames problem definition and describes thesis objectives. It outlines the proposed work and describes methodology of current work. Chapter 3 describes fundamentals associated with OFDM. It reviews the structure of OFDM followed by basics associated with optical OFDM transmission and detection. Chapter discusses the detection strategies associated with OOFDM including direct detection and coherent detection.
Chapter 4 describes various impairments associated during signal propagation. DSP associated with basic impairments like CD, non-linearities is presented. Various performance metrics for assessing performance are described. Research simulate OOFDM transmission system using Optsim and MATLAB and report various signal conditioning parameters including OSNR, Chromatic dispersion, PMD, electrical SNR, Channel noise, distortion of signal, group velocity dispersion and phase margin.

In chapter 5, research implements equalizer combating the effects of dispersion and non-linearities for OOFDM transmission. Performance is compared over higher order modulation formats including 16-QAM, 64-QAM and 256-QAM. Computational complexity comparison of implemented equalizer with conventional single carrier equalizer proves the present equalizer to be far less complex with complexity reduction by 95.09% for 256-QAM-OOFDM transmission, 91.41% for 64-QAM-OOFDM transmission and 82.62 % for 16-QAM-OOFDM transmission.

Transmissions are carried at 18.4 Gb/s for 16-QAM-OOFDM, 27.64 Gb/s for 64-QAM-OOFDM and 36.86 Gb/s for 256-QAM-OOFDM system. Performance comparison of simulated results with both dispersion and non-linearity compensation show deviation of 3.1-4.2 dB. The simulation results represents that system does not achieve target BER $10^{-6}$ and beyond when no compensation is provided.

The target performance of BER $10^{-9}$ is achieved using designed simulator for OOFDM transmission at 21 dB for 16-QAM-CO-OOFDM, 23 dB for 64-QAM-CO-OOFDM and 24.9 dB for 256-QAM-CO-OOFDM. A rise in modulation order from 16-QAM to 64-QAM to 256-QAM depicts increase in SNR from 21 dB, 23 dB to 24.9 dB, which can be attributed to the fact that lower modulation orders are more energy efficient. As the modulation order increases spectral efficiency may increase but it requires higher value of SNR to achieve same BER. Present equalizer reports significant improvement in BER and SNR with margin of approximately 1-1.5 dB in comparison to conventional results.
Research explores adaptive CP technique and develop an algorithm using DSP, which can efficiently compensate the effects of CD, fiber non-linearity, improved synchronization loss.

Research implements reduced cyclic prefix coherently modulated Optical orthogonal frequency division multiplexed (RCP-CO-OOFDM) system using chromatic dispersion (CD) and non-linearity compensation with reduced guard interval for producing spectrally efficient and high performance transmission. This RCP-CO-OOFDM incorporates the advantages of high spectral efficiency and tolerance to channel impairments including CD and non-linearities. One very important feature of equalizer implemented includes the compensation of laser phase drift that is very important side effect of coherent detection. Performance comparison of proposed RCP-CO-OOFDM system using CD, non-linearity and phase drift compensation are found to be superior than in comparison to conventional system.

Performance evaluation using 18.4 Gb/s 16-QAM-OOFDM, 27.64 Gb/s 64-QAM-OOFDM and 36.86 Gb/s 256-QAM-CO-OOFDM transmission over varying lengths of cyclic prefix 25%, 12.5 %, 6.25 % to 3.1 % (i.e \( r_{cp} = \frac{1}{4}, \frac{1}{8}, \frac{1}{16} \) to \( \frac{1}{32} \)) has been carried over by simulating system without any equalization. It find the best performance when CP is 12.5% \( (r_{cp} = \frac{1}{8}) \). RCP-CO-OOFDM with proposed equalizer reported reduction in CP overhead to about 0.78 % and approximate improvement in SNR performance by 8 dB. Target performance of BER10\(^{-9}\) is achieved at SNR of 31 dB with CP length 3.1 %, 28 dB with CP length of 1.5 % and 26.5 dB with CP length of 0.78% for 256-QAM-OOFDM transmission encoding 8 bits/symbol. Best performance is achieved with CP length 0.78% with an improvement of approximately 1 dB in comparison to CP length of 1.5 % and 4 dB in comparison to CP length of 3.1 %. For 64-QAM-CO-OOFDM transmission, CP of 3.1% achieve target BER 10\(^{-9}\) at 26.5dB SNR, where as an improvement of approximately 1 dB has been achieved with CP of 1.5 % attaining same target at approximately 25.5 dB. CP of 0.78% achieves target performance at 24 dB SNR with approximate improvement in performance by 1.5 dB. 16-QAM-CO-OOFDM transmission achieve BER of 10\(^{-9}\) at 21. 7 dB
SNR with CP of 3.1% where as at 20.9dB with CP of 1.5 % and 19.8 dB with CP of 0.78%.

Further, the research investigates the transmission performance of adaptively modulated optical OFDM (AMOOFDM) transmission with dispersion and nonlinearity compensation. The simulated system is analysed for adaptive modulation under three adaptive strategies.

Adaptive modulation over proposed system is explored following three adaptation schemes where selection of each depends upon the requirement of BER efficiency or spectral efficiency. Adaptation strategy developed accomplishes good substitution between spectral efficiency and overall BER. Strategy developed follows that for poor channel conditions, energy efficient techniques like 8-QAM, 16-QAM can be used and that for improved channel quality 64-QAM or 256-QAM can be used. Lower modulation format like 16-QAM has lower SNR to achieve target BER of $10^{-9}$ thus has superior SNR efficiency, whereas higher order modulation format provide superior spectral efficiency. Selection of the SNR values used in developing the algorithm to adapt modulation order has been based on SNR specifications IEEE 802.3bm standards issued for performance Model of Optical network under normal operating conditions. An improvement of data capacity by approximately 52.71% with algorithmic scheme-I, approximately 44.89% with algorithmic scheme-II and approximately 35.21 % with algorithmic scheme-III has been analysed with adaptive modulation in comparison with fixed modulation. Current work analysed spectral efficiency 6.1 b/s/Hz with adaptation scheme-I, 5.7 b/s/Hz with adaptation scheme-II and 5.4 b/s/Hz with adaptation scheme-III.

Adaptive subcarrier allocation allows assignment of subsets to users in adaptive manner as per the data requirement and channel conditions. This provides effective utilization of important resources like subcarriers leading to improvement in performance and spectral efficiency. This research explores adaptive subcarrier allocation for reduced cyclic prefix CO-OOFDM with equalizer compensating CD, non-linearities and phase drift. Performance comparison is performed on allocation of subcarriers examined over two different
strategies including proportional allocation and equal allocation. Applicability of each strategy depends on the network requirement, which may demand fair distribution of data rate among all users or high throughput. Performance comparison for two subcarrier allocation strategies implemented following 16-QAM, 64-QAM, 256-QAM found the superior performance of fair distribution strategy in terms of capacity and BER. Implementation of adaptive technique with proportional subcarrier allocation strategy reflect improvement of 8-12 dB in terms of SNR for achieving same BER in comparison to equal allocation. BER of $10^{-9}$ has been achieved at SNR 24.5 dB for 16-QAM-RCP-CO-OOFDM transmission whereas, at 29 dB for 64-QAM-RCP-CO-OOFDM and at 30 dB for 256-QAM-RCP-CO-OOFDM system when maximum number of subcarriers are 256 for 8 users. On increasing number of subcarriers to 512 BER $10^{-9}$ has been obtained for 16-QAM-RCP-CO-OOFDM system at 22 dB of SNR value, at 25.5 dB of SNR for 64-QAM-RCP-CO-OOFDM transmission at 27 dB for 256-QAM-RCP-CO-OOFDM system. Approximate 2-3 dB gain is observed on increasing the number of subcarriers, which can be attributed to enhance tolerance to dispersion.

7.2 Future Scope

OOFDM has been emerging as rapid growing area of research in optical domain involving advanced ideas in transmission and reception. Although the OFDM implementation has quite matured for wireless communication with assistance of number of already developed techniques for equalization and compensation but there exits few peculiarities in their direct implementations to optical domain as optical transmissions are processed at very high speeds.

Therefore there exits various opportunities of exploration in high speed photonics for exploring DSP techniques for better utilization of various advantages offered by OFDM. Real time experimental demonstrations for RCP-CO-OOFDM system using chromatic dispersion (CD) and non-linearity compensation with reduced guard interval and adaptive subcarrier allocation can be explored for evaluating true potential of proposed scheme.
Although passive optical network (PON) has been preferred due to economical optical to electrical and electrical to optical conversion but the area is yet unexplored utilizing potential of RCP-CO-OOFDM. Therefore, implementation of RCP-CO-OOFDM for PON can be tested on real time scenario.

An alteration to implement OFDM using FFT/IFFT is by using wavelets function instead of sinusoids. These wavelets can provide better spectral roll-off reducing need of CP. Thus wavelet implemented CO-OOFDM can be explored for better spectrum utilization by adaptive subcarrier allocation.

Forward error correction is method for ensuring reliable transmission of information and error control by sending some redundant data. This technology enable receiver to identify and correct errors without any retransmission. As data flow is moving forward always so it is named as forward error correction. There is effort to make FEC design that takes the transmission limits to reach Shannon limit (Maximum level of information that can be sent through channel). But, the application of FEC technology in optical transmission systems must take system requirements into consideration. Code are rated on the $E_b/N_0$ value that guarantee a word error rate like $10^{-6}$ which means that on average only one bit out of 1000000 may be wrong. FEC codes with large coding gains $> 10$ dB, low parity overhead, high data rate, low complexity and good BER performance are desirable. FEC should be planned such that coding scheme uses a rational overhead and decision method, with low design complexity.

Error correction codes can be implemented with adaptive subcarrier allocations for CO-OOFDM system investigating the advantages of various forward error correction (FEC) solutions for performance monitoring and adaptive subcarrier utilization for enhanced utilization of resources.