

Performance Analysis of Optical Nyquist WDM Superchannel systems using Hybrid Modulation Techniques

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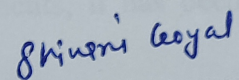
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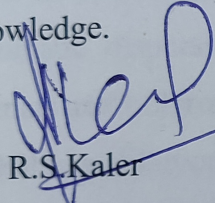
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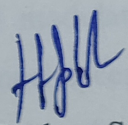
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ABSTRACT

In modern times, internet traffic is increasing by leaps and bounds to fulfil the demand of different services such as multimedia, over the top platforms, cloud services, online gaming etc. This all has resulted in network congestion and to cope up with these demands, high capacity optical transmission systems with efficient use of channel spacing are required. There are a lot of challenges in both short-reach and long-haul optical access networks when the system capacities are upgraded. The earlier capacity growth has been achieved by improving the intensity modulation rate and using the DWDM techniques. However, due to electronics devices limitations and their failure to compensate channel impairments, it has been very tough to increase the data rate beyond 100 Gb/s for each channel.

With the development of DWDM in association with digital coherent techniques, the capacity of the system has been increased up to 100 Gb/s for each channel. But Coherent techniques require a hybrid receiver structure to retrieve the phase of the electrical signal. With the help of phase information, distortions like polarization mode dispersion (PMD) and chromatic dispersion (CD) can be compensated. Therefore, more advanced modulation formats and polarization division multiplexing become feasible, enabling a channel speed to 100Gb/s and beyond. Going beyond and to the 100Gb/s per WDM channel requires the use of multiple carriers to make up a single WDM interface. The resulting multiplex, called a super-channel (or superchannel), and creates a multi-wavelength signal in which each wavelength will operate at the maximum data rate.

In this, multiple carriers are transmitted over a signal channel. To utilize the channel spacing between these subcarriers, the Nyquist WDM superchannel technique is used which can provide terabit signal transmission for each channel. Nyquist WDM superchannels with different algorithms have been developed as they provide terabit transmission, higher spectral efficiency and have less bandwidth requirement as compared to CO-OFDM. Further, the Nyquist WDM superchannel with different combinations of modulation techniques (Nyquist DP-16QAM, DPSK, and POLSK) has come into the picture to increase the data rate beyond 100 Gb/s for each channel and for simultaneous transmission of unicast and multicast data. For data transmission through fiber, Nyquist WDM superchannels technique is an adequate and efficient way of communication but its development poses several challenges like ISI, ICI, high OSNR and high power etc.

This thesis deals with the performance analysis of Nyquist superchannel systems and in association with hybrid modulation techniques for high capacity long haul and short reach transmission by efficiently utilizing the channel bandwidth. Nyquist superchannel with hybrid modulation technique is the most promising technique to improve the channel capacity with more tolerance to distortions. Further, the need of 1Watt power to each channel has forced to move towards the transmission of Nyquist superchannels through multi core or multi-mode fibers instead of standard single mode fiber. MC-MM utilizes the space division multiplexing for the transmission of signals and increases the fiber capacity by multiple numbers of cores or modes. Transmission through multi core or multi-mode fiber also protects the system from fiber non-linearities and fiber fuses. Next, the aim has been to access the networks in the field of passive optical network (PON) that are very cost-effective. Long-range and large splitting ratios are the key requirements for low cost PON. But splitters in the modern day networks cause unavoidable upstream losses, which have to be eliminated to improve the power budget and to increase the long reach. Therefore, MC-MMF with a mode combiner is proposed to reduce the upstream losses by removing the requirement of multiple feeder fibers in the field of a passive optical network.

Now in the thesis, the main objectives are to examine the optimum channel spacing for the optical WDM Nyquist Superchannel system and reducing both inter-channel interference (ICI) and inter-symbol interference (ISI) effects. Nevertheless, ICI and ISI effects are unavoidable due to tight channel spacing and they can also cause substantial performance degradations. Hence, the key research goal is to combat the ISI and ICI via a novel techniques named as driver signal adjust control algorithm that consists of band pre-distortion algorithm and root raised cosine (RRC) filtering.

Here, a driver signal adjust algorithm is proposed that enables the transmitter in Nyquist superchannel system to remove the predistortions. Besides the driver signal adjust algorithm, the RRC filtering is also used to further reduce the channel spacing and that channel spacing is utilized to transmit more number of subcarriers in one Nyquist superchannel. Then the proposed system evaluates the scaling coefficient according to the raised cosine filtering by using m-quadrature amplitude modulation (m-QAM) mapping and finally, it compensates the delay by using convolution with the inverse fast fourier transform (IFFT) and FFT. Due to this, the channel spacing between subcarriers has been reduced from 32.5 GHz to 26.5 GHz and this can be further utilized to improve spectral efficiency significantly. This proposed system has achieved a speed of 21 Tb/s with spectral efficiency $\times$ distance product of 18500 b/s/Hz.km using driver signal adjust algorithm and RRC filtering.

Further in the next objective, the Nyquist superchannel system with a hybrid modulations technique is proposed to support both unicast and multicast transmission simultaneously as compared to the conventional Nyquist superchannel system. At the same time, the channel spacing is reduced from 27 GHz to 15 GHz and has more tolerance to distortions. The performance of the Nyquist superchannel system using a multicast overlay system along with a hybrid modulation technique is analysed. The Hybrid modulation technique consists of Nyquist dual polarization quadrature amplitude modulation (DP-16QAM), polarization shift keying (POLSK) modulation, and differential phase shift keying (DPSK) modulation to transmit unicast and multicast data. The multicast overlay system transmits a total of 5.1 Tb/s data rate using 8×640 GB/s unicast signal and 40 Gb/s multicast signals. But in this system, 1Watt power is required to each channel which causes high OSNR, fiber non-linearities, and fiber fuses.

Thus, a novel trench assisted multicore fiber (TA-MCF) with SDM is proposed that can be easily interfaced with wavelength division multiplexing (WDM) in standard single mode fiber (SSMF). The parameters of TA-MCF are optimized to cover the long distance for Terabit transmission of Nyquist superchannels at multiple spans. However in multiple spans, the performance of the system varies as signal travel through multiple cores of MCF. So to avoid these variations, core to core rotation (CCR) scheme has also been proposed to transmit different Nyquist superchannels through TA-MCF. Using TA-MCF, five Nyquist superchannels are transmitted (each at 4.224 Tb/s data rate), which covers the 2688km distance at different loops by utilizing the 7.5 GHz channel spacing between Nyquist superchannels without any distortions. In one Nyquist superchannel 15 subcarriers are transmitted each at 35.2 Gbaud rate using proposed Hybrid modulation technique with acceptable inter-core crosstalk over seven trench assisted cores.

Further, the last objective is to investigate high speed optical Nyquist signals for passive optical network. To achieve this, an optimized multicore multimode fiber (MC-MMF) is proposed to enhance the capacity of the network and spatial efficiency. In passive optical networks (PON), the MC-MMF is preferred as compared to TA-MCF. However, TA-MCF covers large distance as compared to MC-MMF but it has large inter-core crosstalk and large upstream losses which are not tolerable in the PON system. MC-MMF with SDM comprises of MM fiber (that transmits information independently via individual mode) and MCF (with core multiplexing in which a single fiber is constructed with a high indexed core to transmit the information independently) to reduce the cost per subscriber. A single MC-MMF also transmits the signals for upstream/downstream data transmission without multiple feeder

fibers and accepts the multiple signals from multiple ONU's in PON with a lesser number of splitters/combiners. The simulation results reported that with the proposed MC-MMF system, the total link losses are reduced to -10 dB with average acceptable crosstalk of -42 dB in the PONs network and achieved BER is $<10^{-9}$ for all the modes for 50 Km transmission distance. The Nyquist superchannels system inscribed in MC-MMF can be used for accessing low cost passive optical networks. This system has great scope in submarine, terrestrial, and access networks areas and where high power delivery to fiber and upstream losses are major issues. Most of the research findings of this thesis have been published in different SCI/SCIE journals as listed below.

List of Publications

The thesis includes following research papers:

SCI Publications:

- [1] S.Goyal, R.S.Kaler and H.Singh, “Crosstalk Estimation of 21.12Tb/S Nyquist Superchannels with Hybrid Modulation using Trench Assisted Multicore Fiber”, IET Optoelectronics, vol.13, no.5, pp.218, 2019.
Doi: [org/10.1049/iet-opt.2018.5109](https://doi.org/10.1049/iet-opt.2018.5109) (I.F: 1.74)
- [2] S.Goyal, R.S.Kaler and H.Singh, “Performance Analysis of Nyquist Superchannel with Multicast Overlay System”, International Journal of Light and Electron Optics, vol.207, pp.16446, 2020.
Doi: [org/10.1016/j.ijleo.2020.164446](https://doi.org/10.1016/j.ijleo.2020.164446) (I.F: 1.9)
- [3] S.Goyal, R.S.Kaler and H.Singh, “Performance analysis of multi-core multi-mode fiber for passive optical network”, Microwave and Optical Technology Letters, pp.1-8, 2020.
Doi: [org/10.1002/mop.32383](https://doi.org/10.1002/mop.32383) (I.F: 0.9)

International Conference Publications:

- [1] S.Goyal, R.S.Kaler and H.Singh, “Investigation on trench Assisted Multicore fiber for Passive Optical Network”, International Conference on Science, Engineering, law and Management, vol.10, no.28, at Republic of Mauritius, 2017.
- [2] S.Goyal, R.S.Kaler and A.Singh, “Analysis of Optical unicast design using 1.65 Tb/s overlay system with 40 Gb/s multicast signal”, International Conference on Applied Science and Engineering, Moscow, at Russia, 2019.

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List of Acronyms

FTTH	Fiber to the Home
AON	Active Optical Network
PON	Passive Optical Network
CO	Central Office
OLT	Optical Line terminal
ONU	Optical Network Unit
MCF	Multi Core Fiber
CCR	Core to Core Rotation
TA-UMCF	Trench Assisted Uncoupled Multi Core Fiber
TMC	Tapered Multi core Connector
MC-MMF	Multi-core Multi-mode Fiber
SDM	Space Division Multiplexing
ASK	Amplitude Shift Keying
BER	Bit Error Rate
CD	Chromatic Dispersion
CW	Continuous Wave
DCF	Dispersion Compensating Fiber
DP	Dual Polarization
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
EDFA	Erbium Doped Fiber Amplifier
FWM	Four Wave Mixing
GVD	Group Velocity Dispersion

LO	Local Oscillator
MZM	Mach Zehnder Modulator
NRZ	Non Return to Zero
OSNR	Optical Signal to Noise Ratio
PBC	Polarization Beam Combiner
PBS	Polarization Beam Splitter
PRBS	Pseudo Random Bit Sequence
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RZ	Return to Zero
SE	Spectral Efficiency
SNR	Signal to Noise Ratio
SOP	State of polarization
WDM	Wavelength Division Multiplexing
PolSK	Polarization shift keying
SMF	Single Mode Fiber
DWDM	Dense Wavelength Division Multiplexed
OCDMA	Optical Code Division Multiple Access
MAI	Multiple Access Interference
SAC	Spectral Amplitude Coding
SDD	Spectral Direct Decoding
WDM	Wavelength Division Multiplexing
TDM	Time Division Multiplexing

SDM	Space Division Multiplexing
SM	Subcarrier Multiplexing
PON	Passive Optical Network
SSMF	Standard Single Mode Fiber
PSCF	Pure Silica Core Fiber
LEAF	Large Effective Area Fiber
PM-QPSK	Polarization Multiplexed-Quadrature Phase Shift Keying
PM-16QAM	Polarization Multiplexed- Quadrature Amplitude Modulation
GF-PON	Gigabit Ethernet-Passive Optical Network
ONU	Optical Network Unit
SOA	Semiconductor Optical Amplifier
OPC	Optical Power Combiner
OXC	Optical Cross Coupler
PC	Polarization Controller
PM	Phase Modulator
HDTV	High-Definition Television
OTDM	Optical Time Division Multiplexing
HOA	Hybrid Optical Amplifier

CHAPTER 1

INTRODUCTION

1.1 Introduction and Motivation

In recent years, the demand of broadband services and internet traffic has undergone an exponential growth due to online gaming, video streaming, video uploading and cloud computing etc. [1]. According to Cisco's report, the monthly internet protocol (IP) data traffic will surpass to 50 exabyte in 2021, which is nearly sevenfold of the IP data traffic in 2016 [2]. This huge expansion of IP traffic can be achieved only if optical fiber communication would permit terabit data transmission [3]. Therefore, the main goal of the research is efficient terabit data transmission for a single channel. In recent decades, WDM technique has been utilized to achieve high data transmission capacity. It offers the transmission capacity of 100 Gb/s for 40 channels at 100 GHz channel spacing. To further increase the transmission capacity for each channel, DWDM came into the picture which uses a large number of channels with small channel spacing. However, due to electronics devices limitations and their failure to compensate channel impairments, it has been very tough to increase the data rate beyond 100 Gb/s for each channel. With the development of DWDM in association with digital coherent techniques, the capacity of system has been increased up to 100 Gb/s for each channel. But Coherent techniques require a hybrid receiver structure to retrieve the phase of the electrical signal. With the help of phase information, distortions like polarization mode dispersion (PMD) and chromatic dispersion (CD) can be compensated. Therefore, more advanced modulation formats and polarization division multiplexing become feasible, enabling a channel speed to 100Gb/s and beyond. Going beyond and to the 100Gb/s per WDM channel requires the use of multiple carriers to make up a single WDM interface. The resulting multiplex, called a super-channel (or superchannel), and creates a multi-wavelength signal in which each wavelength will operate at the maximum data rate [4].

Therefore to address these issues, the superchannel has been brought up to handle huge internet data traffic by providing high spectral efficiency and high system capacity. In this, multiple optical carriers are transmitted over a single channel by using lower order modulations, e.g. polarization-multiplexed quadrature amplitude modulation PM-16QAM and polarization-multiplexed quadrature phase shift keying PM-QPSK. These lower order

modulations provide the superchannel transmission at 100 Gb/s data rate or more for each channel [5]. But it faces channel impairments like chromatic dispersion (CD), kerr non-linearities and polarization mode dispersion (PMD). These impairments can be reduced by polarization division multiplexed formats with coherent receiver [6] and followed by digital signal processing (DSP).

Further in a superchannel, the major issue in superchannels is the optical sub carrier spacing that should be optimized. To aggregate subcarriers spacing, two techniques are mainly used which are named as coherent optical orthogonal frequency division multiplexing (CO-OFDM) and Nyquist WDM. These techniques achieve data rate beyond 100 GB/s for each channel and have laid a foundation for the terabit signal generation.

Apart from this, space division multiplexing (SDM) is used recently to increase the channel capacity by using multiple core fibers (MCF) or multimode fibers (MMF). However the optimized parameters of fibers, connectors and different techniques are required to be reconfigured to support the SDM. Therefore many challenges needs to be overcome before the new structure fibers that can be deployed with superchannel techniques in the passive optical network.

1.2 Terabit Superchannel Systems

In previous research, to achieve Terabit transmission with the help of single wavelength by increasing the modulation format and symbol rate is difficult to realize. In coherent modulation, a single carrier with 107Gbaud PM-QPSK modulation has been demonstrated but its work depends on high speed ADC followed by offline DSP [124]. Using higher modulation formats like PM-64 QAM has achieved a lot of interest recently [69], but the reach is limited due to the requirement of high OSNR, high RX sensitivity and linearity. Therefore the most reliable way to implement the optical terabit link is the joint optimization of symbol rate, modulation formats and subcarriers. To resolve this issue, the superchannel concept has been come in to the picture, where the multiple optical carriers are transmitted over a single channel to increase the channel capacity and wavelength of each subcarrier operates at the maximum data rate permitted by commercially available ADC components. Lower Modulation formats like BPSK, QPSK or 16-QAM can be chosen to balance the reach and spectral efficiency. Further in a superchannel, the major issue in superchannels is the optical sub carrier spacing that should be optimized.

To resolve this issue for terabit signal generation, multiple numbers of subcarriers should be aggregated in one superchannel to utilize the channel spacing by maintaining both temporal and spectral orthogonality. To achieve this purpose, coherent optical orthogonal frequency division multiplexing (CO-OFDM) [7-11] and Nyquist WDM [12-15] are used that is shown in Fig. 1.1. In the first technique, the left side of Fig. 1.1 in CO-OFDM, to achieve high spectral efficiency the subcarriers spacing of sinc pulse is exactly equal to the baud rate and in the right-hand side; the rectangular symbols are time aligned for each sub carrier [9]. This scheme can be free from inter-symbol interference (ISI) and inter-channel interference (ICI) if proper sampling and filtering [7] is used in CO-OFDM. However, the recognition is difficult due to the requirement of a high BW at RX with high speed ADC [14] and also due to the requirement of a perfect rectangular shaped pulse in the time domain. Besides, to produce a terabit signal using the CO-OFDM technique, high BW and ICI cancellation [8] is also required. So, the best solution to generate a terabit signal is the Nyquist WDM technique. In the optical Nyquist superchannel system channel spacing is not restricted to the baud rate for balancing the requirement of channel spectral efficiency and system performance [16] [17]. It is more suitable to aggregate the subcarrier spacing by spectrally shaping pre-filtering (RRC) concept as compared to OFDM. In the Nyquist WDM technique, an ideal rectangular spectrum is required whose BW is close to the symbol rate [12] and it can produce sinc shaped pulse in the time domain.

Advantages of optical Nyquist Superchannel:

- 1) As shown in Fig.1.1, the spectral response of optical Nyquist superchannel system is not overlapped so ICI can be easily avoided.
- 2) In the time domain, sampling is performed at zero crossing points, so the Nyquist superchannel is free from ISI.
- 3) The Nyquist superchannel system is also free from high BW requirement at the receiver and also reveals non-linearity tolerance due to lesser overlapping in the spectral response as compared to the CO-OFDM system [7].
- 4) It has good tolerance against the distortion effects such as dispersion and fiber nonlinearity.
- 5) It provides high spectral efficiency and it is suitable for long distance transmission.

Disadvantages of optical Nyquist superchannel:

- 1) In a practical Nyquist superchannel system, an ideal flat rectangular spectrum response is not possible due to signal imperfections and also ICI occurs. Example, super

Gaussian electrical filters is used to shape the conventional NRZ waveforms and to suppress ICI in optical Nyquist superchannel.

- 2) The temporal pulses are not in the sinc shape perfectly because the subchannel spacing is not bounded to the baud rate and it causes ISI. So, the RC and RRC filtering is used to shaped the Nyquist pulse [18] [19].

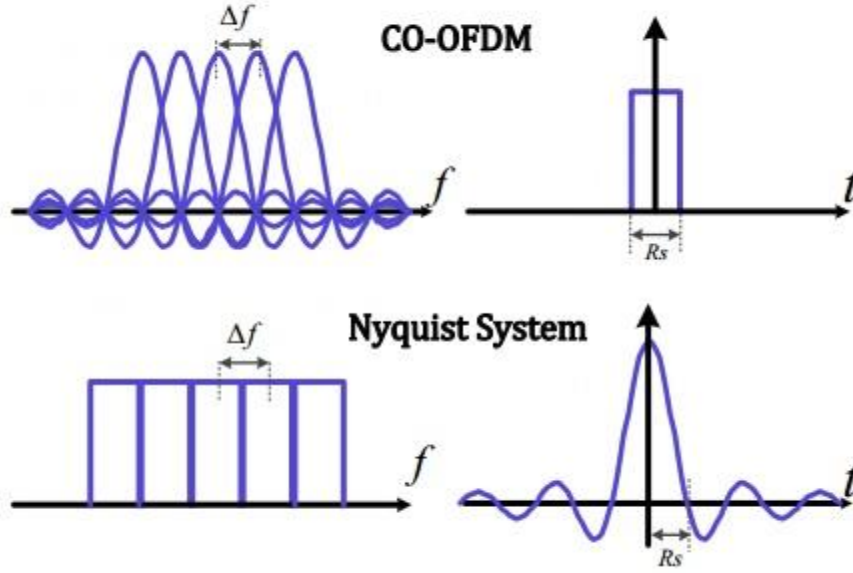


Fig. 1.1 Spatial and temporal response of CO-OFDM & Nyquist WDM system

These Nyquist pulses preserve the orthogonality of pulses in the time domain by using roll-off factor. The representation of RC pulses in frequency domain (FD) is in [19]

$$H(f) = \begin{cases} 1 & 0 \leq |f| \leq \frac{1-\beta}{2T} \\ 0.5 \left\{ 1 - \sin \left[\frac{\pi T}{\alpha} \left(|f| - \frac{1-\alpha}{2T} \right) \right] \right\} & \frac{1-\beta}{2T} \leq |f| \leq \frac{1+\beta}{2T} \\ 0 & \text{otherwise} \end{cases}$$

(1.1)

In the eq. (1.1), symbol period is represented by T and roll-off factor is represented by β ($\beta \in [0, 1]$) which controls the requirement of spectrum BW. Considering channel BW is being greater than signal bandwidth to avoid ISI. So, the received samples at T are not overlapping with the neighbouring symbols. Nevertheless, when a matched filter is used at the R_X and raised cosine pulse is used at T_X , the total response of the overall system is not raised cosine and it becomes the reason to lose the orthogonality of the received signals. To

overcome this issue, RRC filtering is used instead of RC that is represented in eq.1.2. RRC filtering maintains the overall system response and the received signal is also in RRC shape and it exactly matches the transmitted signal. The representation of RRC filtering by the T_x matched filter $Z_{TX,RRC}$ is [19]

$$Z_{TX,RRC} = \sqrt{Z(f)} = Z_{RX,RRC} \quad (1.2)$$

Fig. 1.2 indicates the spectral response of RC and RRC filters at different roll-off factors. As the value of β moves towards the zero, the spectrum takes the exact shape of a rectangular pulse. The RRC filtering is chosen over RC filtering to achieve the high SNR value. In the RRC, the spectrum tail is bigger than RC for the same value of roll-off factor which causes more ICI at close channel spacing.

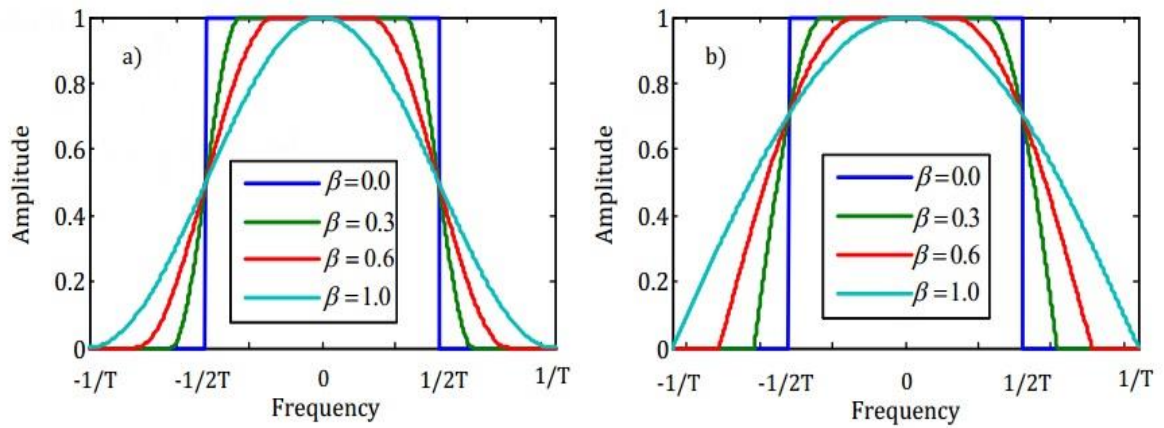


Fig. 1.2 Spectrum response of (a) RC (b) RRC with different roll-off factor

Previously, optical Nyquist pulses are also generated by wave shaper. However, in the wave shaper, the spectrum of sharp roll-off factor is tough to achieve because it provides 1GHz spectrum resolution. As sharp roll-off factor is tough to achieve, hence it induces ICI at reduced channel spacing [18]. In further researches, CMOS and DSP techniques are being used to overcome this issue. DAC provides an accurate resolution and also provides ideal rectangular spectra [18-21]. However, ISI losses are quite a lot due to limited bandwidth of DAC. Based on the above conversation, ISI and ICI are the two main losses in a Nyquist superchannel system. Our main research is to explore algorithms and design a system that can deal with these two impairments.

1.3 Nyquist Superchannel System

As said earlier in Nyquist Superchannel system, multiple optical subcarriers are aggregated in one superchannel by utilizing the channel spacing. The Nyquist superchannel needs a sinc pulse in the time domain and a rectangular shape pulse in spectral domain with a bandwidth equal to the baud rate. The Nyquist WDM system reduces the bandwidth requirement of the receiver as compared with CO-OFDM and exhibits better nonlinearity tolerance because of the smaller spectral overlap. In the case of Nyquist Superchannel, channel spacing is restricted to the baud rate. In the Nyquist system, the sampling frequency is equal to the twice of modulating frequency. However, for a perfect design of Nyquist Superchannel, $F_s = 2f_m$ and factor 2 can be reduced by band pre-distortion and RRC algorithm to optimize the channel spacing. Fig. 1.3 shows the temporal and spectral response of the Nyquist Superchannel system. Sinc pulses are in the time domain and rectangular pulses are in the frequency domain.

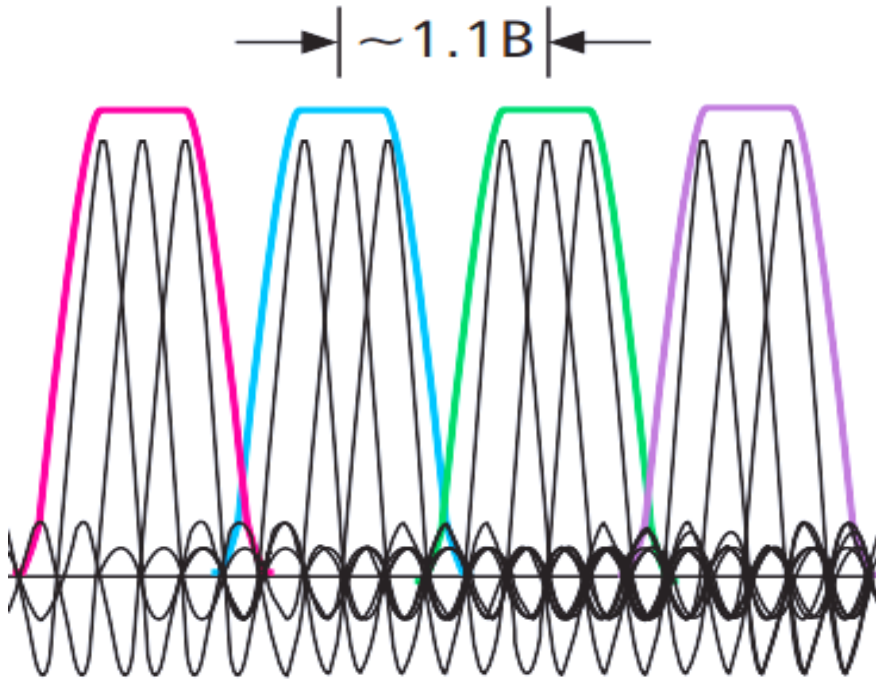


Fig. 1.3 Spectrum of Nyquist Superchannel

But, Orthogonality is required in both the time domain and frequency domain spectrum of the Nyquist Superchannel system. While maintaining the orthogonality, inter channel interferences arise in frequency domain due to tight channel spacing, and inter symbol interferences also arise in time domain due to pulse generator, optical modulator, and coherent receiver in Nyquist Superchannel system. In the frequency domain, if super

channels are not overlapped then ICI can be avoided. This is achieved by a perfectly shaped NRZ pulse and band pre-distortion algorithm. In the time domain response of the Nyquist spectrum, when sampling is performed at zero crossing points then the system is free from ISI using square root raised cosine filtering. In previous researches, root cosine (RC) filtering is used to find out sufficient scaling coefficient which is free from ISI and it is achieved if the spectrum of Nyquist pulse shape satisfies the below equation [22]

$$\sum_{n=-\infty}^{\infty} H\left(f + \frac{n}{T}\right) = \text{Symbol Period}$$

(1.3)

The symbol period is represented by T . For achieving zero ISI and efficient scaling factor, the bandwidth (BW) of the signal should be $1/T$. The spectrum of Nyquist is rectangular and its pulse shape function is like a sinc function which is represented as [22]

$$h(t) = \text{sinc}\left(\frac{\pi t}{T}\right) = \sin\frac{\left(\frac{\pi t}{T}\right)}{\frac{\pi t}{T}}$$

(1.4)

The major problem in the Nyquist sinc pulse is that its spectrum is difficult to achieve due to infinite impulse response. As the tails of Nyquist pulse shape $h(t)$ decay by a factor $1/t$, a large number of taps are required to approximate the filter practically and a small timing error in pulse shape signals results in large ISI. So to generate the Nyquist pulses practically, a roll-off factor (some additional BW usually expressed as a percentage of symbol rate) is used. In this case, roll-off factor is generated by using raised cosine filter and it is represented by β which varies from 0 to 0.225 with an interval 0.025. The corresponding impulse response of a raised cosine filter is [23]

$$h(t) = \sin\frac{\left(\frac{\pi t}{T}\right)}{\frac{\pi t}{T}} \times \frac{\cos\left(\frac{\pi \beta t}{T}\right)}{1 - 4\pi^2 t^2 \beta^2 / T^2}$$

(1.5)

According to the above equation, the tail in the signal will decay by factor $1/t^3$ for roll-off factor greater than zero. Therefore, impulse response decays fast and timing error generates smaller ISI for the signal and its frequency response is [23]

$$H(f) = \begin{cases} T, & |f| \leq \frac{1-\beta}{2T} \\ \frac{T}{2\{1+\cos[\frac{\pi T}{\beta}(|f|-\frac{1-\beta}{2T})]\}}, & \frac{1-\beta}{2T} \leq |f| \leq \frac{1+\beta}{2T} \\ 0, & \text{otherwise} \end{cases} \quad (1.6)$$

When the response of RC is compared with the rectangular spectrum then it occupies β/T extra bandwidth. So, RRC filtering is chosen over RC filtering to achieve the high SNR value. However in the RRC, the spectrum tail is bigger than RC for the same value of roll-off factor which causes more ICI at close channel spacing. So to smooth out the characteristics of root raised cosine spectrum, the square root of the above equation is taken and it is named as square root raised cosine filter (SRRC). In the RRC, T_X and R_X act like a matched filter and the overall response of the system is RC. In the RRC, T_X and R_X avoid ISI and optimize SNR. So to remove the ICI and ISI, band pre distortion algorithm is proposed in this research along with RRC filtering.

1.4 Modulation Techniques

In the field of analog and digital communication system, modulation is the process of varying the properties of the carrier signal according to the message signal or information signal. Modulation is also known as bandpass signal and the modulating signal is known as baseband signal (information signal). Generally, modulation is a process of carrying information signal in an efficient way. There are three categories of modulation in the communication system, one is an analog field, the second one is digital and the third is optical field. In the analog field, the analog pulse is taken as a carrier to convey the information. Carrier is also known as modulating signal which is used to carry a message signal. Whereas in the digital field, a digital signal waveform (carrier signal) is changed according to the information signal. In the optical field, a light signal is used as a carrier signal for transmitting the information. Information can be an analog or digital type.

Optical modulation is that one modulation, which not only makes the use of amplitude but also uses phase and polarization to encode the electrical signal on an optical carrier signal. Further, there are two categories of optical modulation, one is analog optical modulation and another one is digital optical modulation. In analog optical modulation design, optical (light) power is used as a carrier signal and it is varied according to the input current of the message signal. It is also known as intensity modulation or amplitude/frequency modulation. Analog optical modulation has three types named as amplitude modulation/ intensity modulation (AM/IM),

frequency modulation (FM/IM), and phase subcarrier modulation. Phase subcarrier modulation is the advanced one modulation as compared to the AM and FM, in which electro-optical principle is used to produce a phase shift and phase shift is proportional to the applied electrical field. In the digital optical fiber modulation technique, a digital information signal is imposed on an optical carrier. It also includes a coding technique to check the transmission errors. In the digital optical modulation technique, high frequency signals up to 200 THz can be transmitted. In this modulation, information symbols are mapped on a complex plane. A complex plane is used to show the modulation of amplitude and phase of the carrier signal. Digital optical modulation techniques are explained in detail as:

1.4.1 Binary Amplitude Shift Keying/ On-Off Keying (BASK/OOK)

In optical fiber communication, the low-frequency message signals are modulated onto high-frequency signals (optical carriers). In OOK modulation, the information signal is multiplied by a carrier signal, here the binary 0 is represented with 0 Watt and binary 1 is represented by A Watt. The demodulation of digital optical modulation signals is performed by photodetectors like PIN diode and APD etc. M-ary ASK digital optical modulation techniques are also developed, in which $M = 2^a$ where a is the number of bits per symbol which is used to double the transmission capacity. But M-ary ASK is poor in terms of bandwidth efficiency and information capacity.

1.4.2 Binary Frequency Shift Keying (BFSK)

In BFSK, an optical carrier signal is varied according to the frequency of the information signal to transmit the data over optical fiber. The requirement of frequency variation depends upon the existing bandwidth. In BFSK, the bandwidth is represented by $2\Delta f + 2b$, where b is the bit rate. When Δf is greater than b , then bandwidth becomes independent of bit rate.

1.4.3 BPSK

In the BPSK, the binary data is modulated with the optical carrier signal using the phase shift of 90° . The binary 1 is represented by $\sin\omega t$ and binary 0 is represented by $-\sin\omega t$. Its demodulation is quite complex as compared to other modulation techniques but except complex demodulation, it has many advantages as compared to other modulation techniques. The BPSK and BFSK are preferred over BASK due to minimum interference and non-linearities. BFSK is quite easy to generate as compared to BPSK but BFSK requires the double bandwidth as compare to BPSK. The error rate of BFSK is more as compared to BPSK

because in the case of BFSK the distance between signal points in the constellation diagram is less as compared to BPSK. So BPSK is much better than BFSK.

Recently, scholars have worked on DPSK which is a recent version of non-coherent PSK, where no coherent detection is required and the input binary sequence depends upon the previous bits. In DPSK, less bandwidth is used as compared to BPSK.

The DPSK is also preferred due to its high strength to tolerate the non linear propagation and stable and fast modulation format and is well-matched for many optical communication applications. In the DPSK, the major advantage is that there is no need to identify the absolute phase and its information capacity is two times to the BFSK.

1.4.4 Quadrature Phase Shift Keying (QPSK)

In QPSK modulation, the different phases of carrier signals are used to denote the four promising combinations of two bits that are 00,01,10 and 11. The QPSK is twice the bit rate as compared to BASK, for example a 25 Gbaud line rate is applied to get 50 Gb/s data rate. It also has higher polarization mode dispersion (PMD) tolerance as compared to M-ary DPSK and good error performance as compared to BPSK and BFSK. With constant optical output power, it provides four phases to carry the information signal.

1.4.5 Differential Quadrature Phase Shift Keying (DQPSK)

DQPSK is the advanced version of QPSK which transmits a pair of two bits (like 00, 01, 10 and 11) for each symbol. DQPSK is better than QPSK because the phase of one symbol is relative to the previous one and it also provides the phase synchronization between TX and RX. It has higher tolerance to compensate polarization mode dispersion (PMD) and chromatic dispersion (CD) by having a narrower optical bandwidth. With the help of DQPSK, tight channel spacing can be set for advanced communication applications. As a result, it provides 50 GHz channel spacing to transmit the 40 Gb/s data rate. With the help of tight channel spacing, DQPSK has the capability for long reach communication and high efficiency.

1.4.6 M-ary Quadrature Amplitude Modulation (M-QAM)

M-ary QAM can transmit m bits for each symbol in one time slot. Recently, QAM is used with polarization division multiplexing to double the bit rate that will further improve the system performance and capacity. In M-QAM, the spectral efficiency can be doubled as compared to m-QPSK because in quadrature amplitude modulation more number of bits can be transmitted and OSNR is increased for the same baud rate in QAM as compared to QPSK

modulation. Further in advanced researches, M-ary QAM is used with Nyquist superchannels to efficiently utilize spectral efficiency [25-27].

Apart from this, Polarization of the light is an important characteristic in addition with M-QAM. By using orthogonal polarization, information of each subcarrier is carried independently. The process to combine two signals with orthogonal polarization is called polarization division multiplexing for enhancing spectral efficiency [28]. With the help of polarization division multiplexing, channel capacity is doubled without increasing its symbol rate. PDM with 16QAM [29-30] has been achieved by multilevel generation using different combinations of binary signals to get a 224 Gb/s data rate [25-26] and for 448 Gb/s data rate [27].

In the previous researches, bandwidth requirement in PD-mQAM modulation [31] have been reduced by factor 2 as compared to PD-QPSK. But the sensitivity of the receiver has been decreased due to this modulation. So PD-mQAM and PD-mQPSK modulations have been used with the Nyquist WDM superchannel. In this, to increase the spectral efficiency, the flattening of subcarriers of each superchannel has been achieved by pulse-shaped filtering. While utilizing the channel spacing of the Nyquist WDM superchannel, only a few lines contribute to the required power. So, to reduce the lines (sub-channels) for 20 GHz line spacing, PD-mQAM and PD-mQPSK modulations have been used as shown in Fig. 1.4.

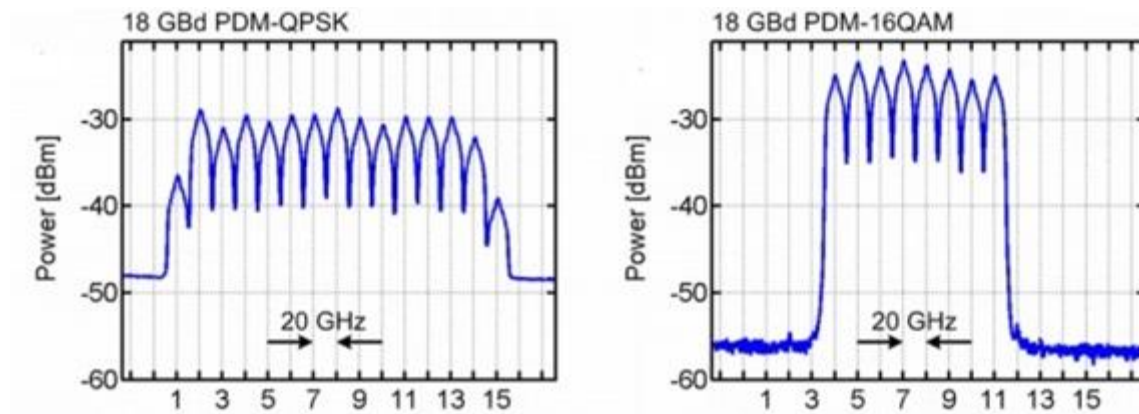


Fig. 1.4 Superchannel spectrums by using 18 GHz line spacing [32]

In the 20 GHz line spacing 15 numbers of sub-channels are required in PD-mQPSK modulation with Nyquist WDM superchannel. While by using PD-mQAM modulation with Nyquist WDM superchannel [32], the numbers of lines are reduced from 15 to 7. With the help of 20 GHz line spacing, high spectral efficiency and high-speed data rate is achieved for long-distance communication. Hence, only few lines are contributing to the required power with the help of PD-mQAM modulation. With the help of 20 GHz line spacing in PDM-

mQAM, a greater distance between adjacent point in In-phase and quadrature-phase plane has been achieved by distributing the point more evenly as compared to PDM-mQPSK. So Nyquist superchannels that have been generated by PD-mQAM mapping have greater spectral efficiency as compared to PD-mQPSK.

Terabit superchannels are obtained by the cumulative of multiple subcarriers using the Nyquist-WDM superchannel technique using PM-mQAM, based on 10 percent spacing of each superchannel which allows very narrow spacing and utilizes the 90 percent spacing of each superchannel thereby increasing the speed of data rate for long distance communication.

1.5 Current Digital Optical Modulations and Optical Multiplexing Techniques

Nowadays many researchers are working on the combination of different digital optical modulation schemes such as NRZ, DQPSK, and POLSK. The combination of these techniques are called hybrid modulation schemes. The advantage of adopting such techniques is that they not only increase the speed of the overall system but also increase the number of users at the same time. With the help of hybrid modulation techniques, multiple users can transmit their data on a single channel at distinct parameters of signal.

1.5.1 NRZ Modulation

It is a binary code where the number of zeros present in a message signal are represented by negative voltage and the number of ones are represented by a positive voltage. This modulation makes the system simple and beneficial because it requires less bandwidth as compared to return to zero (RZ) modulation. It is the basic modulation used by researchers due to its simple transmitter design and signals can be easily detected by photodiodes.

The design of the NRZ transmitter in the optisystem software consists of data source, CW laser, and MZM modulator as shown in Fig. 1.5(a). The data source comprises a Psuedo Random Bit Sequence (PRBS) generator and an NRZ generator which is further connected to fork. From the fork, two output ports are connected to the Mach-Zehnder modulator in which one is connected to its upper terminal and another one is connected to lower terminal. The input of MZM is provided by a continuous wave laser (CW laser).

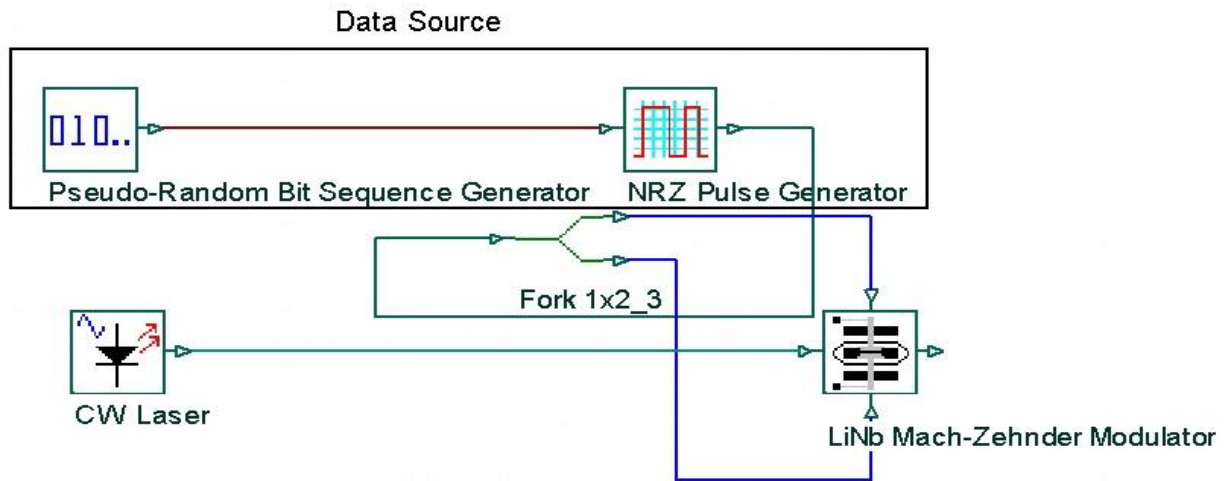


Fig. 1.5 (a) Design of NRZ Transmitter

A laser diode is used to feed the continuous beam into LiNb Modulator and it modulates the data (with 25 Gbps data rate) in the NRZ pattern. From continuous wave laser, an electrical signal is generated which is further modulated by LiNb Mach-Zehnder modulator. The power of continuous wave laser is 5 dBm while the frequency is 193.1 THz. However, its proficiency does not satisfies high transmission data rate and also vulnerable to eavesdropper. For such a reason, other modulations are combined with NRZ modulation.

In the design of the NRZ receiver, it comprises two different components named as low pass bessell filter and a PIN photodetector as shown in Fig. 1.5(b). The photodetector has a responsivity of 0.75 A/W and a dark current of 0.1 nA while the low pass bessell filter has a frequency of 193.1 THz with a bandwidth of 10 GHz.

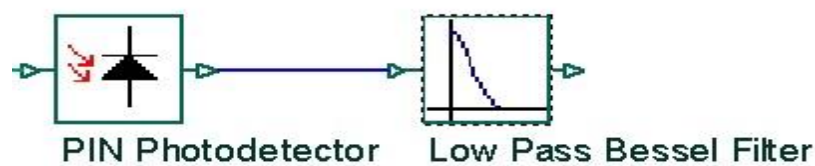


Fig. 1.5 (b) Design of NRZ Receiver

1.5.2 DQPSK (Differential Quadrature Phase Shift Keying) Modulation

It conveys information by establishing a certain phase of one symbol relative to the previous symbol. The design of the DQPSK transmitter can be implemented by four different

components as shown in Fig. 1.6(a). The data source comprises a Psuedo Random Bit Sequence (PRBS) generator and an RZ generator. The RZ pulse generator is used as compared to NRZ because DQPSK itself has very low losses in it but if the user wants to save power then the user can use the NRZ pulse generator. The signal from the data source is splitted and is given to the phase modulators PM1 and PM2 which modulate the phase of the incoming signal from the data source. The first phase modulator (PM1) modulates the optical signal at an angle of 0° or 180° whereas the second phase modulator (PM2) adds the 0° or modulating phase to produce the DQPSK signal. It modulates the data at 40 Gb/s data rate.

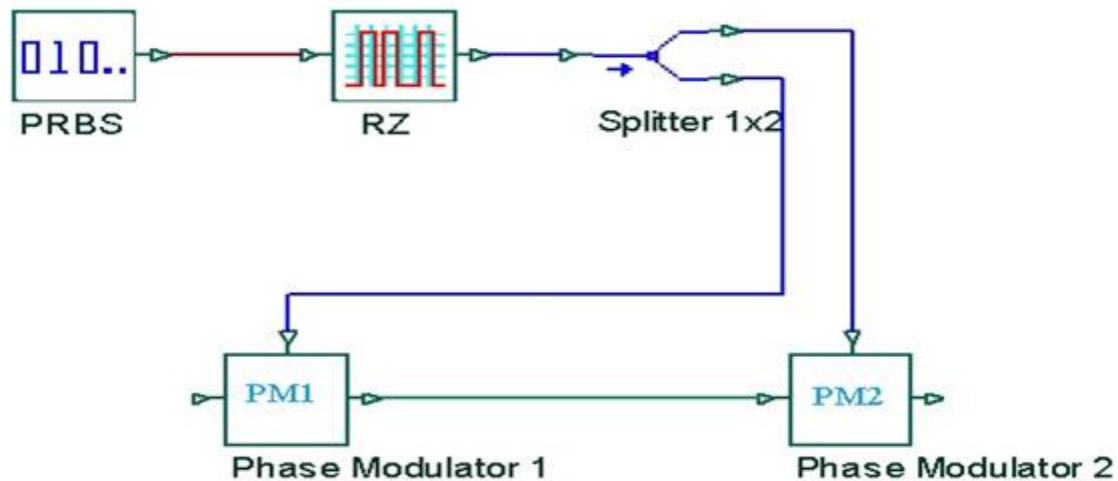


Fig. 1.6 (a) Design of DQPSK Transmitter

In the receiver design of DQPSK receiver as shown in Fig. 1.6(b), the output signal from the linear polarizer is splitted into two parts with the help of a fork and is transmitted to the inputs of Mach-Zehnder Interferometers (MZI). The Mach-Zehnder Interferometer is a device that is used to determine the variations of relative phase shift between parallel rays which are derived from splitting of light of a source and are received by photodetectors. To combine these, mach-zehnder power combiner is used to receive the required data signal.

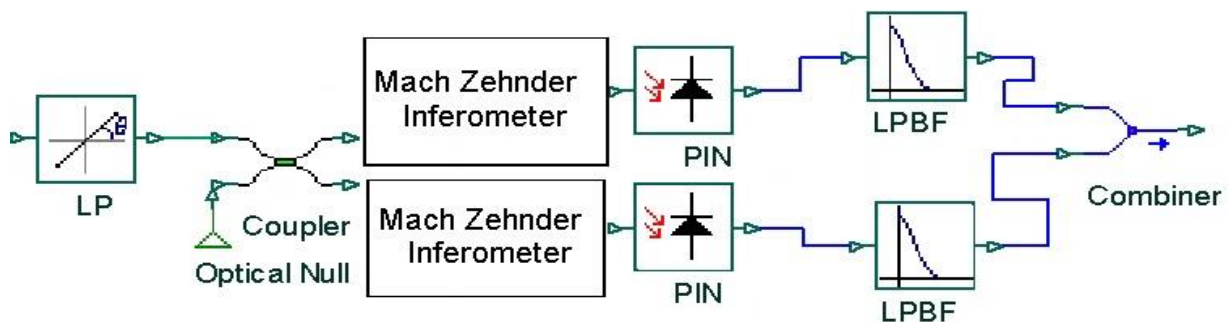


Fig. 1.6 (b) Design of DQPSK Receiver

In this proposed research, NRZ with DQPSK is the promising technique for a high data transmission rate up to 65 Gb/s data rate. Its narrower spectra provides the high dispersion tolerance and high spectral efficiency but it has non-linearity issues. So, in the proposed research NRZ-DQPSK modulation has to be combined with another modulation.

1.5.3 PolSK (Polarization Shift Keying) Modulation

In PolSK binary bits are encoded as an orthogonal state of polarization at an angle of 45° , in which bit 1 is represented by $+45^\circ$ linear polarized and 0 is by -45° linear polarized. The polarization shift keying transmitter, data source comprises PRBS generator and return to zero. As shown in Fig. 1.7 (a), the response from the data source is fed as an input to phase modulator (PM). PM has two inputs; one from the data source and second input from polarization beam splitter (PBS). The output from PM at 45° phase deviation is connected to a polarization combiner. POLSK modulates the signals at 40 Gb/s data rate.

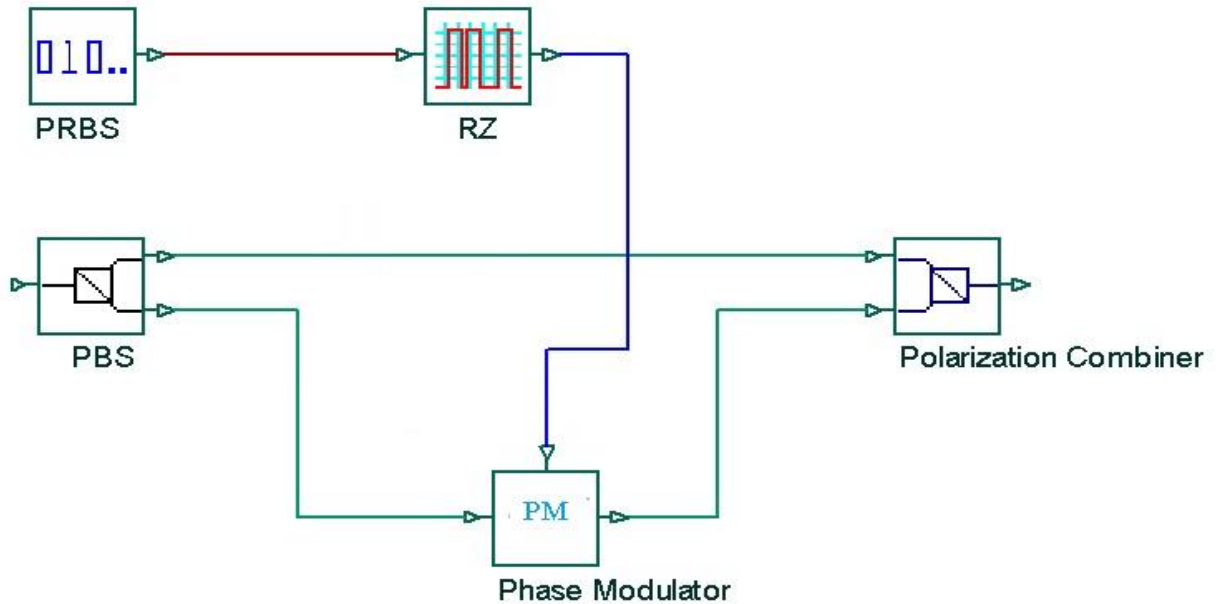


Fig. 1.7 (a) Design of POLSK Transmitter

In POLSK receiver as shown in Fig. 1.7 (b), it consists of a polarization beam splitter (PBS) and PIN photodiode. PBS is used to split the signal into two parts. Before polarization beam splitter (PBS), a bessell optical filter and a polarization controller is connected where bessell optical filter has a frequency of 193.1THz and bandwidth of 10 GHz while the polarization controller has ellipticity of -45° . Then the ouput of PBS is given to PIN photodiode which is used to demodulate the transmitted signal.

In this thesis research, Nyquist WDM superchannel with different combinations of modulation technique (Nyquist DP-16QAM-DPSK-POLSK) has been proposed to increase the data rate beyond 100 Gb/s for each channel and for simultaneous transmission of unicast and multicast data.

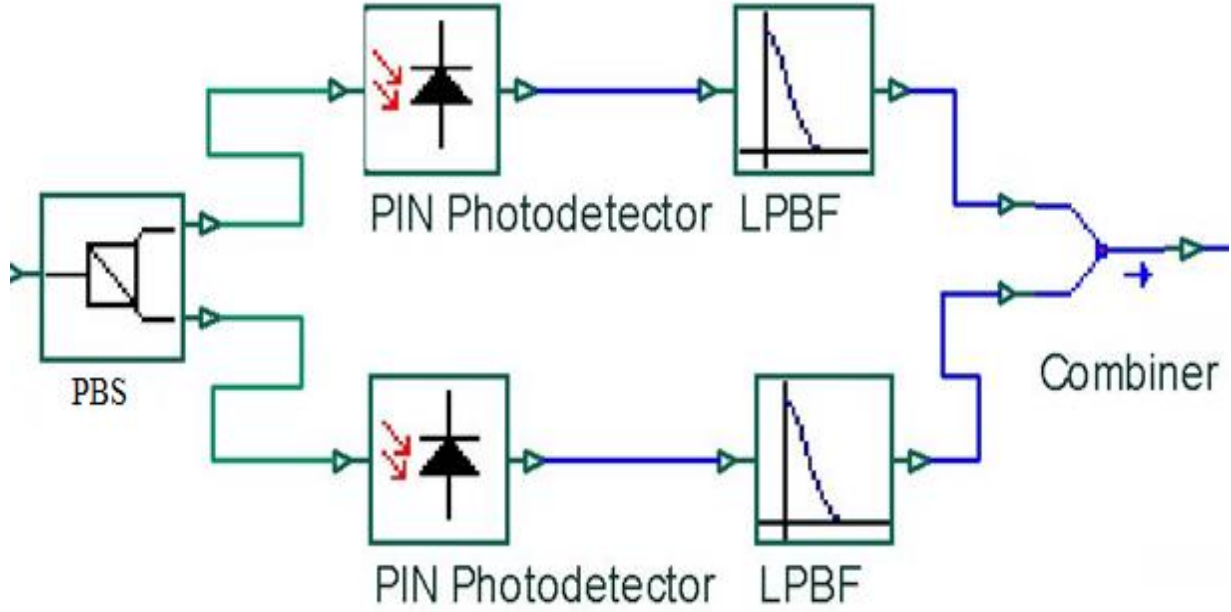


Fig. 1.7 (b) Design of POLSK Receiver

This technique helps to reduce the channel spacing up to 15 GHz which increases the spectral efficiency of overall system and efficiently utilizes the BW. Nyquist superchannel with hybrid modulation technique is the most promising technique to improve the channel capacity with more tolerance to distortions. Further the need of 1Watt power to each channel has forced to move towards the transmission of Nyquist superchannels through multi core or multi-mode fibers instead of standard single mode fiber using space division multiplexing.

1.5.4 Spatial Division Multiplexing (SDM)

In the SDM technique, multiple spatial channels can be transmitted and received. SDM is one of the core technology which can solves the capacity crunch issues in near future in optical fiber communication. In optical fiber transmission, the fiber non-linearity, requirement of high spectral efficiency, and use of multilevel modulation [33-34] are increasing day by day, SDM can handle all these problems more efficiently. The best fibers that can be used with SDM are shown in Fig. 1.8 which embraces single-mode fiber with a large effective area [35], MDM with few-mode fiber [36]-[37] and with multi core fiber (MCF).

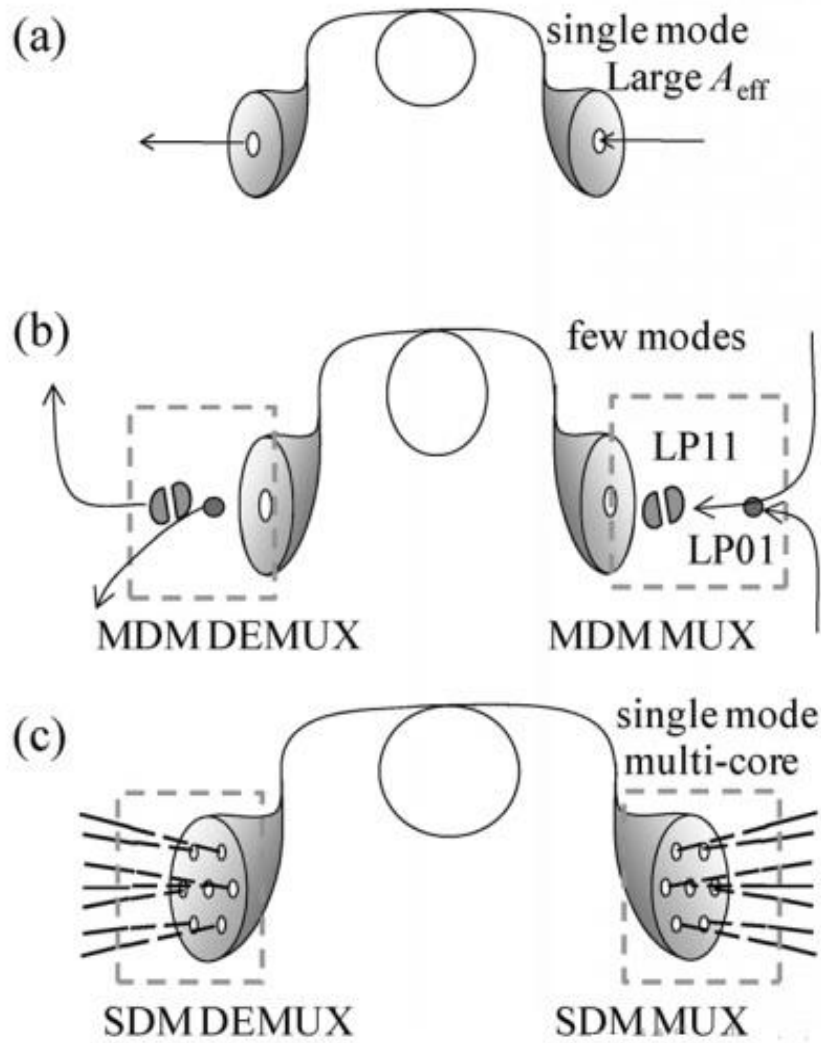


Fig. 1.8 Efficient utilization of SDM (a) Using large Affective area in optical fiber, (b) MDM with FM, (c) space division multiplexing with MCF [123]

1.5.5 Mode Division Multiplexing (MDM)

The MDM technique permits several orthogonal spatial modes to be guided and transmitted simultaneously through a single core fiber, is shown in Fig. 1.8. Theoretically, it is possible to modulate N independent signals onto each spatial mode to obtain a channel capacity which is N times of single mode fiber. Thus, by adding a spatial degree of freedom, fiber capacity of Few-mode fiber (FMF) or Multimode fiber (MMF) can be increased in the form of MIMO transmission. MDM permits transmission of several channels upon different modes, generated by different mechanisms like few-mode fiber or multimode fiber, signal processing [38], spatial light modulator (SLM) [39], spatial modulation with lens [40], photonic crystal fiber

[41] and dual-mode fiber [42]. The research in the field of MDM was started in 1982 [43] but for 30 years researchers never took interest in this novel technique.

1.6 Fiber Access Networks

For achieving low noise and high bandwidth, the optical fiber communication technique has been most popular. In recent technology, the major focus is on the optical network to reduce the cost of customer per unit. Because of low preservation cost and high capability, optical fiber is far better as compared to copper cables on large scale applications. But the overall cost of optical fiber is quite high. In recent years, new technologies are integrated with optical fiber to reduce its overall cost. For these, a fiber can be launched in to curb, home [44], or in-between home or office.

1.6.1 Fiber to the Curb/Home

For providing large area service, a high capacity optical fiber has been launched between the central office and the curb. FTTC uses fiber optic cables right up to the street cabinet (gray or green cabinets on the street cabinet that use active and passive broadband equipment), and then uses copper wires to connect the cabinets to homes and businesses so as to reduce the distribution costs and additional costs. It also reduces the fitting charges of multiple fibers for all the users and it requires two optical transceivers only. But the disadvantage of this technique is that it needs large spacing, availability of power, and requirement of the complex converter at the curb. However, Fiber to the Home (FTTH) is a pure fiber-optic cable connection running from an Internet Service Provider (ISP) directly to the user's home or business. Table 1.1 and Fig. 1.9 shows the difference between FTTC and FTTH.

Table 1.1 Difference between Fiber to Curb and Home

Parameters	Fiber to curb	Fiber to home
Installation of fiber	Between CO to Curb	Between CO to subscriber
No. of transceivers	2	2N, CO to subscriber
Powerful	Lesser because small amount of BW is available	More because large amount of BW is available

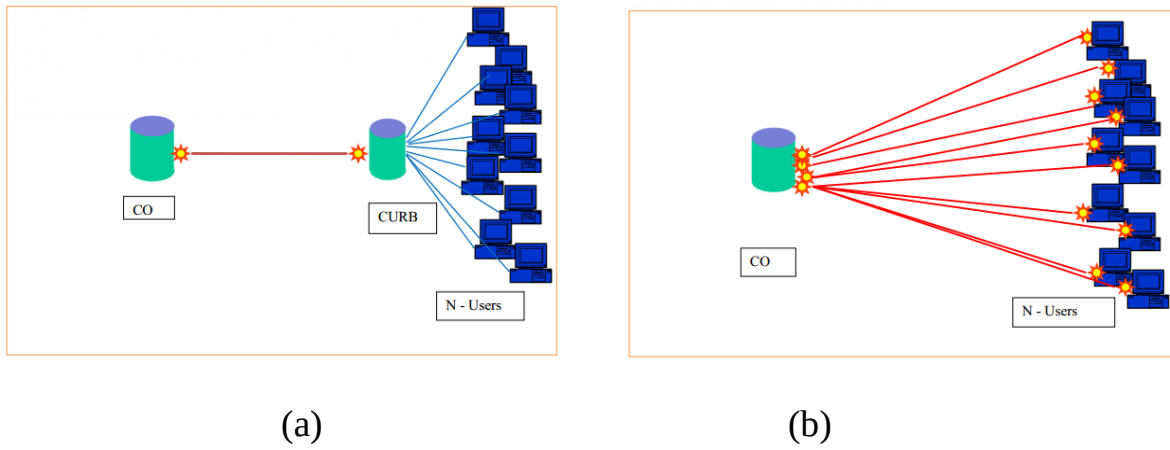


Fig. 1.9 Fiber access networks (a) FTTC (b) FTTH

1.6.2 Active Optical Network (AON)/Passive Optical Network (PON)

In AON as shown in Fig. 1.10 (a), an active switch has been installed in the basement of the construction that transmits the signals to the users. It also utilizes the space of the central office as compared to FTTC because single fiber is connected between CO and curb. But the requirements of transceivers are $2N + 2$, $2N$ transceivers are required between the curb and end subscriber, and 2 between the central offices and curb. To overcome the requirement of the number of transceivers, PON's are used. As shown in Fig. 1.10(b) in the PONs network, $(N+1)$ transceivers are used and instead of using curb, passive splitters are used to pass the signal.

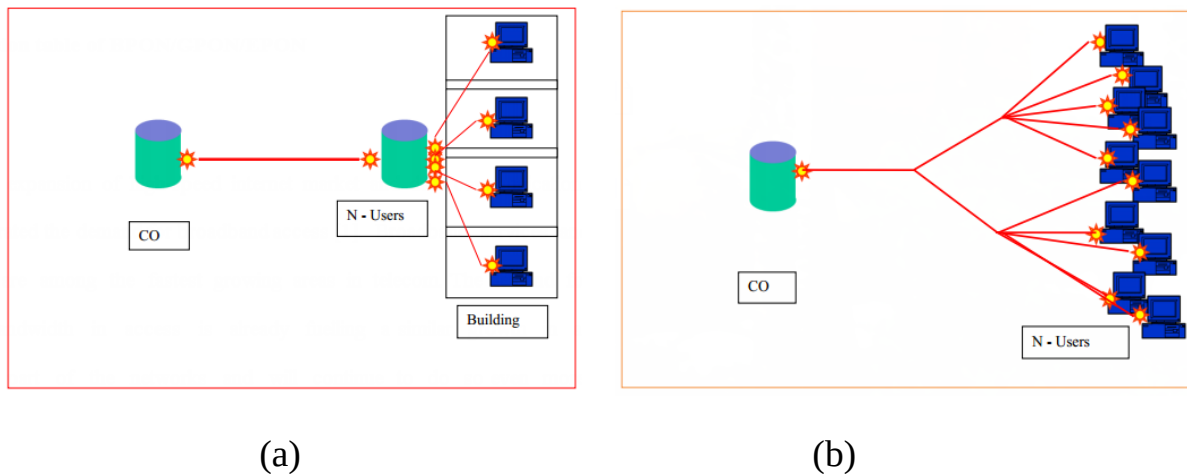


Fig. 1.10 Architectures of Optical networks (a) AON (b) PON

The major benefit of a passive optical network is that there is no requirement of external power and no need to convert the signal from electrical to optical. PON technologies are further categorized as direct to direct (D2D) and single user to multipoint (P2M) technology.

In D2D there is a straight fiber connection between subscriber and central office CO but it is quite costly. In P2M, different subscribers can transmit/receive the data using the same optical fiber link. In PON, data is transmitted/received using time division multiplexing (TDM), wavelength division multiplexing and space division multiplexing. On behalf of different multiplexing techniques, Hybrid PONs is implemented for high speed data rate.

1.6.3 Hybrid (WDM/TDM) PON

In hybrid PON previously, two multiplexing techniques named as wavelength division multiplexing (WDM) and Time-division multiplexing (TDM) have been used. As shown in Fig. 1.11, different wavelengths have been used to set communication between a remote node (RN) and optical network units (ONUs). In hybrid PONs, communications are done in two ways, firstly each wavelength is assigned to ONU and secondly, the assigned wavelength is shared by several ONU on the behalf of a different time slot. So in the hybrid PON, both WDM and TDM multiplexing are used [45].

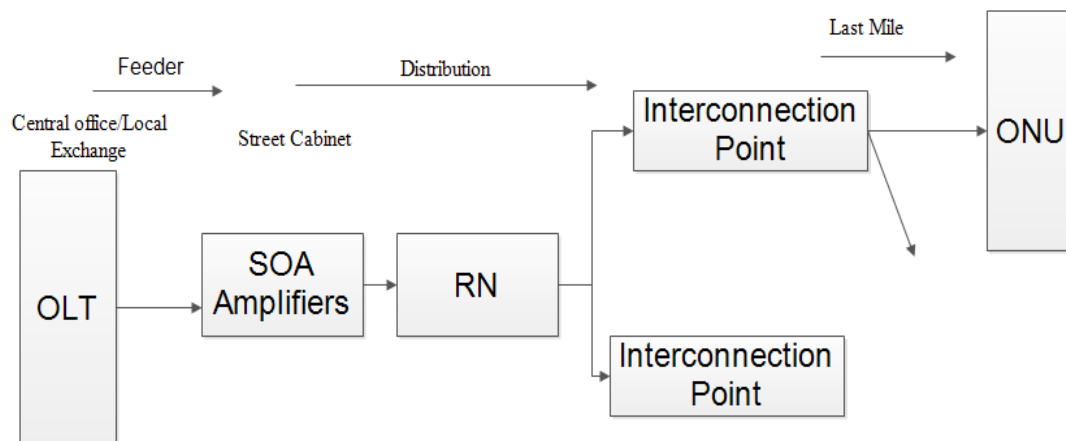


Fig. 1.11 Hybrid PONs

In the proposed system, WDM/SDM is used to transmit the signal through multiple cores or multiple modes for high speed data rate communication in field of passive optical network.

1.7 Multi Core Fiber (MCF)

Previously, for broadband access services passive optical networks (PONs) have been used. With the increasing demand for data traffic, the requirement of high capacity access networks is also raised. To achieve this, multiple feeder fibers are required and high dense cables are essential to construct a practical PONs system.

Multi core fiber offers a practical solution to improve the fiber density within the available fiber cross-sectional area. Various types of MCF have been designed by researchers to reduce the core density with low inter-core crosstalk [46]. Because of the dense core, connectivity of each core between MCF is quite difficult. For example, splicing should be precisely aligned. Ideally, signals should be coupled properly while entering and coming out of each core. To overcome this issue, a connector is required which individually couples the signals into and out of the cores of MCF. The micro and macro bending losses should also be low in the design of MC-MMF which further depends upon the core size, cladding index profiles, and core pitch.

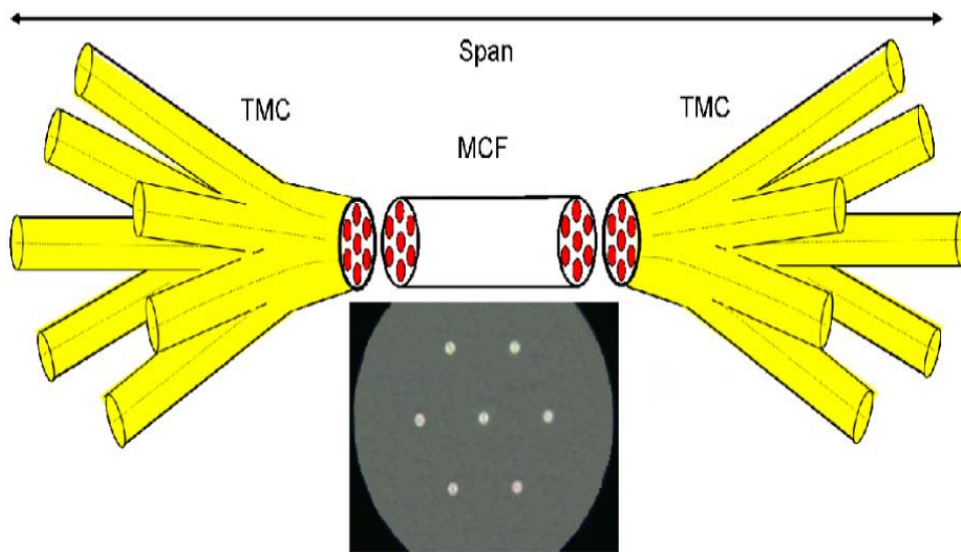


Fig. 1.12 MCF coupled with TMC [46]

As shown in Fig. 1.12, a new connector has been designed and fabricated with low crosstalk/insertion loss that provides in-out coupling for parallel transmission in MCF and is named as a tapered multicore connector (TMC). Recently researchers have worked on MCF coupled with TMC that is used to minimize the power coupling between the cores of MCF and interface the signals from SSMF into MCF.

1.7.1 Core to Core-Rotation Scheme

In multiple spans of MCF, performance varies as signal travel through multiple cores of MCF but these variations should be less. For avoiding these variations core to core rotation (CCR) scheme [46] has been used which also provides fast transmission. In the design of seven core MCF, center span loss has been 3dB lesser than outer spans due to variations in TMC losses and core losses.

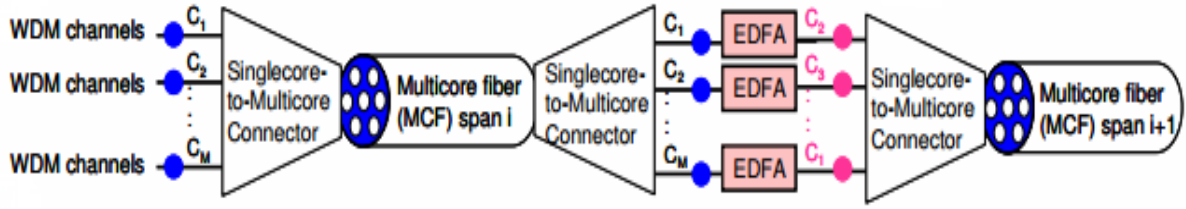


Fig. 1.13 WDM to SDM transmission

As shown in Fig. 1.13, WDM channels are launched into the single-core to multicore fiber with the help of tapered multicore connector (TMC). TMC also helps the signals to come out from MCF. All WDM channels are inserted into seven core of MCF. At first span, the WDM channels are passed spatially through the first core to seventh core of MCF and in the second span, the channels travel from the second core to the end of the first core in a clockwise direction. The above architecture totally covers seven spans. This scheme summarizes the different variations received from span losses and it also reduces the inter-core crosstalk.

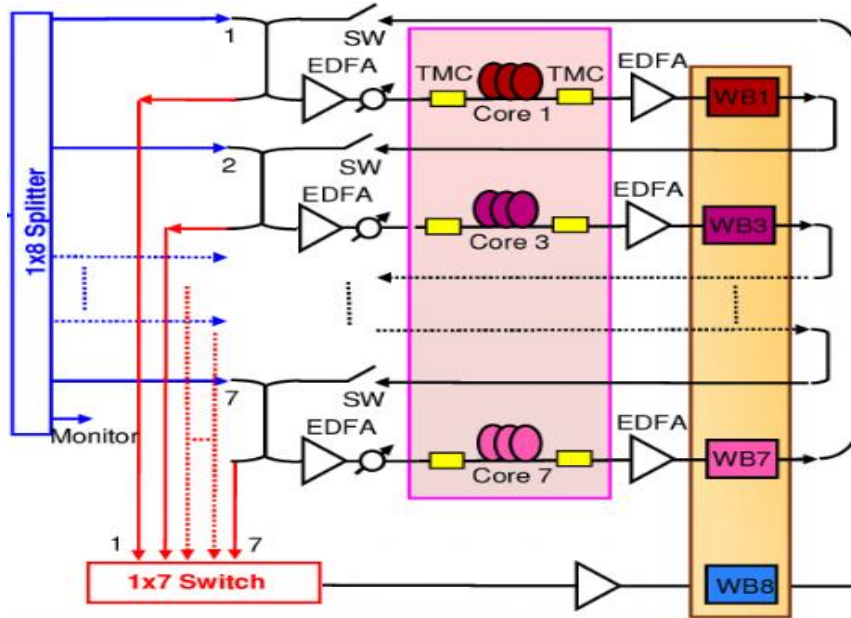


Fig. 1.14 CCR scheme [54]

As shown in Fig. 1.14, a common 1×7 switch is used to load the WDM channels into seven circulating loops using 1×8 splitter. At each loop stage, before launching into seven core of MCF, the signal is first amplified by erbium-doped fiber amplifiers (EDFAs) for compensating the fiber losses through TMC. A second TMC connector is used to couple out the data. A wavelength blocker (WB) array block is used to compensate the power of each channel and equalize them. After this, the WDM signals are transmitted to the next core of MCF in the next loop in a cyclic order.

1.7.2 Trench Assisted Uncoupled Multi-core Fiber TA-UMCF

For achieving high capacity optical network and high spectral efficiency, MCF is used which is operated on C band (1550 nm-1565 nm) and L band (1565 nm-1645 nm) for SDM applications. MCF is categorized into uncoupled MCF and coupled MCF. In uncoupled MCF, each core is arranged suitably with low inter-core crosstalk for long-distance communication with SDM transmission. On the other hand, in coupled MCF, cores of MCF are strongly and weakly coupled with each other. Coupled MCF is also preferred for high power transmission applications with mode division multiplexing (MDM) but it is used for short-distance communication.

In proposed work, uncoupled MCF is used, which further divided into Homogenous MCF and heterogeneous MCF. Homogeneous MCF means multiple identical cores i.e. same core diameter and same effective area for all cores and in heterogeneous MCF, different size of core radii with their different effective area is used. In the proposed system, homogenous uncoupled MCF is used. To estimate inter-core crosstalk between the cores, two theories are used. First is the Couple mode theory in which a large no of samples are taken and simulated. The second is Couple power theory in which the average crosstalk value is obtained by single simulation. As core to core distance increases (at least 45 μm), crosstalk reduces and large effective area (used to calculate nonlinear effects and based on MFD) is achieved. But core density (mass/volume) is reduced, so to improve the core density, a trench core arrangement with a limited size of cladding is proposed. A trench assisted uncoupled multicore fiber is intended to obtain low micro bending losses (an imperfection in the geometry of core) and macro bending losses (caused by entire curvature of fiber axis or propagation angle is more than critical angle) and low crosstalk.

Trench Assisted uncoupled MCF provides low inter-core crosstalk between each core to core and central core to outer cores and decreases the outer cladding thickness which results in high core density with limited cladding size. In order to realize low crosstalk and a dense core arrangement simultaneously in MCF, trench assisted MCF has been proposed. The relative refractive index between the core and inner cladding is represented by Δ_1 , between the trench and inner cladding is represented by Δ_2 and between the trench and outer cladding is represented by Δ_3 and their values are set to 0.260%, 0.00%, and -0.73% respectively in the design of TA-UMCF as shown in Fig. 1.15.

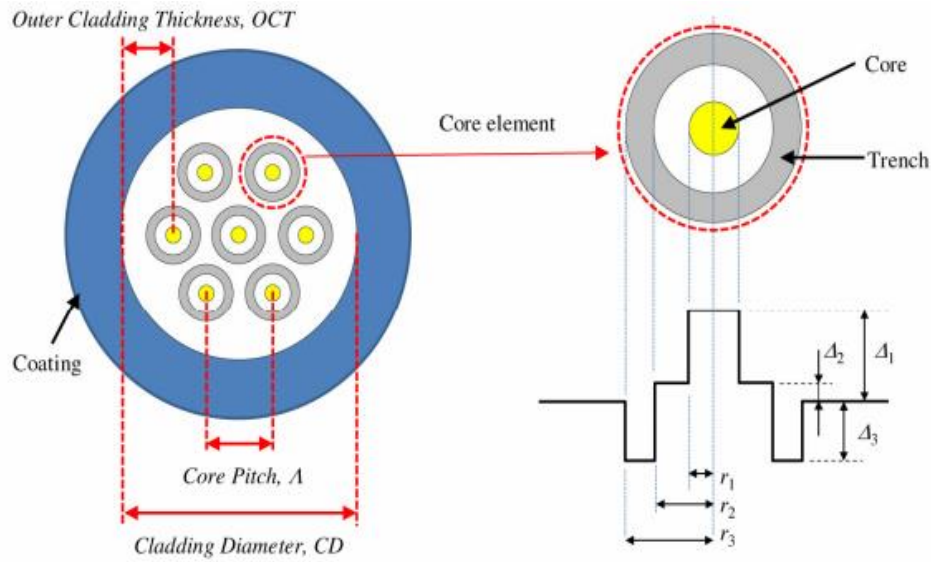


Fig. 1.15 Cross sectional view of MCF with seven cores

1.8 Conclusion

The demand of internet is increasing day by day for high speed data rate. This demand can be fulfilled if optical fiber communication allows terabit data transmission. Therefore, the Nyquist superchannel is one of the vital solutions to generate terabit data transmission with efficient spectral efficiency. In this, multiple subcarriers are aggregated over a single channel using lower order optical digital modulations. The motive of the Nyquist superchannel system is to optimize the channel spacing to achieve high spectral efficiency without ISI and ICI. Further, different digital optical modulations have been discussed and compared on the behalf of their capacity per channel, tolerance to interference of the signal, and spectral efficiency. As compared to the digital optical modulations techniques, PD-mQAM modulation is more efficient to generate Nyquist superchannels for high capacity data rate. Further such combination of modulation is required so that Unicast and multicast data transmission is possible. Also with the help of different modulation techniques, multiple users should be able to transmit the data on a single channel at distinct parameters to get security from eavesdropping. Thus the hybrid modulation techniques (unicast and multicast transmission) and perspectives, different combinations of modulations are also discussed which are used in combination with Nyquist superchannel system. Additionally to increase the channel capacity TA-MCF, CCR scheme, is discussed that can be used for low cost access network and can be deployed with superchannel techniques where 1 watt power to each channel and long reach are the major issues.

1.9 Thesis Organization

Based on the above discussion, the thesis is organized into seven chapters. The chapter first is devoted to introduce the reader with Nyquist superchannels to generate terabit data rate by optimizing the channel spacing with the help of different modulation techniques. As compared to the digital optical modulations techniques, PD-mQAM modulation is more efficient to generate Nyquist superchannels for high capacity data rate. From the hybrid modulation techniques (unicast and multicast transmission) perspective, different combinations of modulations are discussed. Further to increase the channel capacity multi core fiber and core to core rotation scheme is discussed that can be used for low cost access network that can be deployed with superchannel techniques in the passive optical network where upstream losses is the major issue. The motivation for carrying out this research work is also given in chapter 1.

Chapter 2: presents the comprehensive literature survey of Nyquist superchannels with different modulation techniques and different types of fiber optical fiber based on utilization of channel spacing. The state of art work done by various researchers will be acknowledged in this chapter. Thereafter, the gaps in the present study will be pointed out and objectives achieved in the work will be elaborated.

Chapter 3: This chapter deals with the first objective which is used to investigate the optimize channel spacing for optical Nyquist Superchannel for WDM system. It presents the contribution of work related with the band predistortion principle which is used to optimize the channel spacing for Nyquist superchannels to enhance the system capacity. This chapter also deals with the second objective which is used to depict a system without ISI interference and to improve the system's overall performance. A pre-distortion algorithm and RRC filtering is used to remove the ISI interference and optimize the channel spacing.

Chapter 4: This chapter deals with the third objective which is used to depict a new architecture of hybrid modulation technique using Nyquist WDM superchannel to increase the spectral efficiency. To increase the system performance a combination of three different modulation techniques are depicted with Nyquist superchannel. In this system, a BW efficient system is depicted in which Nyquist DP-16QAM and POLSK is used as a unicast data and DPSK as multicast data transmission. From the simulation results, best BER, input power, and Q-factor is analyzed for multicast overlay system, which is best of our knowledge as compared to other existing works of literature for multicast overlay system.

Chapter 5: This chapter also deals with the third objective which is used to depict a new architecture of hybrid modulation technique using Nyquist WDM superchannel to increase the spectral efficiency with new optimized design of multi-core fiber. So to implement this, a Trench Assisted Multicore Fiber with optimized parameters is depicted with Nyquist Superchannel Technique. A Trench Assisted Multicore Fiber [46] is designed with optimized parameters and further optimized Trench Assisted Multicore Fiber interface with Nyquist superchannels in VPI transmission maker software.

Chapter 6: This chapter deals with the fourth objective which is to implement the high speed optical networks in passive optical network. In this chapter, the optimized design of heterogeneous multicore multimode fiber is used to transmit the signals to multiple ONU's in passive optical network. Further to reduce the budget loss, a new system of multicore multimode fiber is implemented with passive optical network to eradicate the use of multiple feeder fibers and implemented the results with the help of VPI transmission maker software. Finally, in **chapter 7**, the main conclusions, recommendations and scope for future work are outlined.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Under the requirement of high speed transmission rate with efficient use of channel spacing, hybrid multiplexing and hybrid modulation techniques are upgrading by time to time on the customer demand basis. The losses and distortions should be lesser while achieving high transmission data rate with efficient use of channel spacing. Driven by the immense need for transmission capacity expected in future optical transmission networks, hybrid modulation techniques presenting high spectral efficiency such as PD-mQAM or even higher modulation orders have been recently considered. . But even in these designs, the sensitivity of the receiver decreases in case of high order modulations and the requirement of high optical to signal noise ratio (OSNR) increases [3].

To reduce these losses, diverse options have been recently discussed. Most of them depend on WDM super-channel, optical OFDM super-channel and Nyquist WDM superchannel. In WDM super-channel and optical OFDM super-channel [4-5], shape of the spectrum is sinc pulse which generates crosstalk between subcarriers in superchannel. While in Nyquist WDM superchannel shape of the spectrum is square pulse which avoids the crosstalk between subcarriers and another benefit of Nyquist superchannel is utilization of channel spacing between each subcarrier to improve the spectral efficiency.

2.1.1 Issues in Higher Order Hybrid Modulation Techniques with Nyquist Superchannels

For achieving high speed transmission rate with efficient use of channel spacing, multiple/hybrid modulation formats in combination with advanced multiplexing scheme are required for generating optical spectrum of Nyquist Superchannels.

Liu et al. [47] reported the demonstration on VSSB Nyquist SCM to remove the ISI using symbol predistortion algorithm. The simulation results depicted that the system can achieve the speed of 40 GB/s over 100 km with sensitivity of the receiver at 2.6 dB using single mode fiber. They demonstrated the concept of frequency domain equalization in the raised cosine filtering to achieve the band predistortion. At the backend they have used FFT and IFFT

algorithm as compared to DFT and IDFT so that they could achieve the lesser compositional complexity.

Zhang et al. [48] demonstrated the DFT algorithm for channel estimation to improve system performance. They presented a WDM TX system that could be achieved from CO-OFDM (coherent optical orthogonal frequency division multiplexing) with 64 QAM and polarization division multiplexing. The experimental results of this paper demonstrated that the system can achieve the signal speed at high speed data rate and also can reach up to the distance of 2000 km. In the DFT algorithm, it was demonstrated that the estimated value of threshold between IDFT and DFT, which provide estimated channel response at the sampling points was used in cyclic prefix.

Xie et al. [49] simulated the Nyquist WDM system using PD-QPSK modulation in combination with DSP to improve the spectral efficiency of the system. This technology utilizes the channel spacing of Nyquist WDM channels by allowing channel spacing close to the symbol rate. Simulation results depicted that FDE filters are used to utilize channel spacing. The square root cosine filter has better performance as compared to root cosine filter for improving the spectral efficiency in polarization division multiplexing with Quadrature phase shift in WDM system.

Rahman et al. [50] demonstrated the hybrid amplification including PM-16QAM. They presented the investigation on hybrid amplification to achieve high spectral efficiency and better system performance. For achieving the speed of 1.28 Tb/s and reduced intersymbol interference, they choose a subcarrier spacing = $1.2 \times$ symbol rate. In this experimental work, they used the algorithm of forward error correction for removing ISI and OH effects. Further they used the criteria to optimize the spectral spacing of subcarriers so that they could achieve the long distance communication at high speed data rate. In the result part, they used the different fibers with Nyquist superchannels and compared their results according to different fiber spans for achieving 1.28 Tb/s transmission rate with EDFA Raman amplifier in WDM communication.

Bash et al. [51] demonstrated the high speed data rate by using efficient modulation formats with polarization division multiplexing and they designed coherent trans-receiver for transmitting and receiving the superchannels at same speed for long distance communication. At the end they compared PDM-OFDM-mQAM with different m-array modulation for long distance communications with data rate beyond the Gb/s.

Liu et al [52] demonstrated that for terabit/s superchannels transmission, polarization diversity Optical hybrid modulator was used and for efficient reception of superchannels, coherent RX was designed. In the coherent receiver, the same amount of polarization diversity optical hybrid modulator was used according to the number of superchannels and the system became costlier, temp dependent and bulkier. So to remove this drawback they used the polarization diversity optical hybrid module with average wave guide grating for reception of terabit/s superchannels. In the array waveguide guide grating 4×40 demultiplexer was used for reducing the requirement of multiple number of polarization division optical hybrid modulation modules

Basco et al. [53] experimentally demonstrated the terabit superchannel transmission using PM-QPSK and wave shaper filter for utilizing the channel spacing of subcarriers in Nyquist WDM superchannel. They also demonstrated the channel spacing algorithm for estimating polarization mode dispersion and chromatic dispersion for different fiber span in long distance communication. At the end experimental results depicted that at the 5th subcarrier 10⁻² bit error rate was achieved for 9000 km distance.

Cuei et al [54] demonstrated that QAM modulation can be generated by using single dual drivers MZM at different m-array levels. They simulated the results for different levels with different modulators and compared the return to zero pulses with different levels of DQPSK for receiving improved received signals. At the end when they used RZ modulator with DQPSK modulator and the simulation result was received being unaffected by ripples

Pfeifle et al [55] experimentally investigated that the terabit/s superchannel transmission with different comb line spacing by using different modulation formats of Nyquist superchannel. The improved spectral efficiency achieved by using different hybrid modulator format for long distance communications in big pipes. The system capacity was increased by utilizing the line spacing along the symbols rate by using hybrid modulator formats with Nyquist WDM superchannels. Finally they compared the results with previous research and concluded that the gain switched laser source was beneficial for generating terabit/s superchannels

Jia et al [56] experimentally demonstrated the multiple carrier terabit superchannels transmission using post polarization algorithm at back end of DSP with polarization multiplexing m-array quadrature modulation. In the least mean square algorithm, crosstalk and intersymbol noise was predicted on the basis of adjustable impulse response. With the help of least mean square algorithm, the intersymbol interference and interchannel

interference was detected and removed in the transmission of terabit superchannel for long distance communication.

Cai et al. [57] investigated that better receiver sensitivity and high spectral efficiency achieved by using forward error correction algorithm with digital signal processing at the backend. High spectral efficiency was achieved for long distance spans by using hybrid modulation formats and EDFA amplifiers. Overall capacity of the system was improved by utilizing the feature of Nyquist spectral spacing with forward error correction algorithm at the backend.

Xieng et al. [58] investigated the advanced modulation format techniques with coherent receiver and digital spectral shaping algorithm. In the coherent receiver they used 2 tap post equalization filter combination with least square distance technique at the backend for reducing the number of iteration. They removed the complexity of the system and achieved high spectral efficiency for long distance communication.

Lucent et al. [59] experimentally performed multicarrier superchannel transmission for utilizing the channel spacing using PDM-mQPSK modulation with digital coherent receiver. High spectral efficiency and high receiver sensitivity was achieved using balanced photodiodes with polarization diversity optical hybrid. At the end, they compared the multiple numbers of subcarriers according to received next data rate with efficient OSNR by using ADC and DSP at the backend.

Zhou et al. [60] proposed a pulsed shaping filtering technique with reconfigurable optical add drop multiplexer for high speed data rate transmission over long distance. High spectral efficiency was achieved by PD-mQAM modulation with pre-equalization algorithm. At the receiver end, they used 90 optical hybrid polarization divisions multiplexing with offline DSP to achieve high receiver communication with high data rate.

Chen et al. [61] demonstrated the self-phase modulation with OFDM without using amplifiers for removing subcarrier to subcarrier interference and transmit the signal for long distance communication with high speed data rate over different spans of optical fiber. At the end, they compared the results of received SNR with and without SSI cancellation by using self-phase modulation.

Singh [62] demonstrated a design of hybrid modulation technique at data rate of 3.5 Tb/s for minimum utilization of bandwidth. In his research, three combinations of hybrid modulations named as NRZ at 25 Gbps, DQPSK at 40 Gbps data rate and POLSK at 40 Gbps have been used for transmission of 105 Gbps data rate using 35 channels for 50 km transmission

distance. From the results it has been observed that DWDM channels have been successfully received with acceptable OSNR and BER for high-speed DWDM communication.

Wang [63] simulated Nyquist WDM superchannel and PD-QPSK modulation in combination with DSP which improved the spectral efficiency of the system. This technology utilized the channel spacing of Nyquist WDM channels by allowing channel spacing close to the symbol rate. Simulation results demonstrated that FDE filters have been used to utilize the channel spacing. The square root cosine filter has better performance as compared to the root cosine filter for improving spectral efficiency in PMD-QPSK WDM system.

Zhang [64] demonstrated the generation of Nyquist signals by polarization division multiplexing with Nyquist 16-QAM. This technology also efficiently demodulated the signal using coherent receiver with time division multiplexing. From the simulation results, it has showed that total transmission of 1.2 Tb/s has been achieved for a single carrier using PM-16QAM.

Xieng [65] demonstrated the M-ary QAM modulation Nyquist WDM superchannel in association with direct detection and least square algorithm to utilize the channel spacing of each WDM superchannel. The least square algorithm is applied in addition with DSP at the backend for achieving high spectral efficiency. The simulation results have improved the Q-factor after long distance communication for single mode fiber.

Pfau [66] proposed a new digital feedforward carrier recovery algorithm for high order M-QAM constellations for achieving a lower phase noise tolerance because of the smaller spacing in between adjacent constellation points. No feedback loops have been present in this approach and has high resistance against phase noise.

Zhang [67] demonstrated the transmission of 20×440 Gb/s Nyquist super channel using a single carrier over a distance of 3600 km. From the results, the system efficiently provides the high spectral efficiency of 4 bit/s/Hz. The PM-QPSK modulation has been used in for transmission of Nyquist super channels at 110 Gbaud.

Hu [68] proposed multiple optical phase conjugations to remove the fiber non-linearities with in WDM transmission system and to achieve good Q^2 factor. The system also provides a better performance with the use of multiple optical phase conjugations instead of using a single optical phase conjugations (OPC) and void OPC. Here, the optical signal launched power has been enlarged by 5 dB and 2 dB as compared to void OPC and single mid span OPC.

Poti [69] experimentally demonstrated a signal transmission over long haul distances with the use of sub-Nyquist time frequency packing approach. The signal covers the distance of 995km for uncompensated single mode fiber which was installed between Sydney and Melbourne. Eight sub-channels were transmitted all together in a superchannel with the use of DP-QPSK modulation to provide a good OSNR and less complexity as compared to lower order modulation formats.

Erikssonetal [70] demonstrated the Nyquist superchannel system with DP-16QAM and DP-QPSK modulation to achieve a spectral efficiency of 4.17bit/s/Hz. This system proposed the 3×18.67 Gbaud for both DP-16QAM and DP-QPSK to improve the average Q value for two channels and also covers the distance of 480km and 560km using standard single mode fiber.

In addition to these, some work concerning to Hybrid modulations (NRZ, Polarization shift keying, DQPSK and Dual polarization-M-QAM) and hybrid multiplexing (TDM/WDM/OCDMA) techniques with efficient utilization of channel spacing are tabulated in Table 2.1.

Table 2.1 Growth in Nyquist Superchannel technique with Hybrid modulation format between 2015 & 2020

Reference [year]	Channel Spacing (GHz)	No. of Channels	Techniques	Data Rate (Gb/s)	Spectral Efficiency (b/s/Hz)	Transmission Distance (km)
Pfeifle et al. [2015][55]	20	13	Nyquist Superchannel and gain switched comb source and PDM-QPSK-16QAM	72	3.4	300
Weng et al. [2016][69]	28	3	Nyquist Superchannel Concept and PM-64QAM	336	12	960

S.Singh et al. [2016][70]	32	8	WDM-OTDM Multicast and SC- DQPSK+POLSK+ DPSK	120	12	200
Zhou et al. [2017] [71]	51	28	Nyquist Super- channel and PM- QPSK	200	3.92	359
D.Sharma et al. [2018] [72]	33.33	5	Nyquist Super- channel + Mixed Line rate and PM- QPSK+PM- 16QAM	222	4.5	3300
Y.K.Prajapati et al. [2020][73]	27.75	4	Nyquist Super- channel WDM+ Mixed Line rate and PM-QPSK	100	4.16	5500

2.1.2 Research on Multicore Multimode Fiber with Nyquist Superchannel Technique & Passive optical Networks

Many papers related to Hybrid passive optical network with standard single mode fiber and Trench assisted uncoupled multi core multi-mode fiber with passive optical network have been read and their brief discussion are given below:

Xu and chow [74] proposed and demonstrated a bidirectional transmission, WDM PON with colourless transmission means no extra signal was required at OLT end [21]. It also provides the error free transmission using subcarrier modulation (SCM) techniques up to distance of 25 km using standard single mode fiber (SSMF).

Mandal, Patra [75] demonstrated a hybrid PON with hybrid multiplexing for triple play services with FTTH that transmitted video, voice and data for 128 ONU network units for single access subscription. In this paper, DPSK modulation transmits the data at 10 Gbps rate which is used to represent internet data as well as voice data. For transmitting analog data, SCM and radio frequency has been used. A single mode (SM) fiber of 50 km length is used to convey 10 Gbps data rate. TDM PON has a striking feature of low cost as compared to WDM PON but at the same period it was incapable to encounter the future demands. So to

overwhelm this problem hybrid PON (WDM+TDM) has been used, so that it can transmit individual wavelength at diverse time slots. From the results, acceptable optical power and BER has been achieved for a SSF with the help of WDM/TDM PON.

Fady and nahala [76] proposed a bi-directional SCM–WDM PON with reflective filter and transmit the data at 1 Gbps data rate for uplink and downlink transmission at a distance of 10km distance with optical bidirectional fiber link.

Neto and Klingler [77] proposed a hybrid passive optical networks (wavelength division multiplexing/ time division multiplexing) WDM/TDM-PONs that could perform the responsibility in upcoming-generation of large symbol rate for cost-reductive customer-shared facilities.

Goyal and Kaler [78] simulated the viability of a hybrid PON technique with 128 optical network units for three play services (voice, video and data) for a distance of 28 km. They also simulated the results on different modulation formats and achieved the acceptable BER with respect to best modulation technique.

Singh and Kaler [79] demonstrated the Hybrid passive optical network with different amplifiers and observed the results on best amplifier for best modulation format for 460 GB/s and 960 GB/s data rate for 10 channels. They also analysed the results using BER and Quality factor as a function of distance on NRZ line coding.

Koacher and Randhawa [80] proposed a Fiber to the Home scheme for Hybrid passive optical network and also related different PONs standards that are governed by ITU and IEEE. They observed the results on different standards of hybrid passive optical network up to 50 km transmission.

Goyal and Kaler [81] introduced a cost effective approach using common carrier for optical networks for hybrid passive optical network. This technique also demonstrated the non-linear impacts on passive optical network and diminished it using common carrier that is received from optical line terminal.

Takenaga and Arakawa [82] demonstrated a trench assisted multicore fiber to reduce the core density with minimum cladding thickness. This design also minimized the micro and macro bending losses by increasing the core to core distance and observed the span losses for each core of the trench assisted multicore fiber.

Zhu and Taunay [83] proposed a seven core trench assisted multi core fiber for passive optical network and verified the experimental results using mathematical equations. This

design also estimated the inter core crosstalk of each outer core of trench assisted multi core fiber with respect to their centre core.

Chandrasekhar [56] demonstrated a core to core rotation scheme in the design of trench assisted multi core fiber using 10 channels each having data rate of 128 GB/s using polarization division multiplexing- quadrature phase shift keying (PDM-QPSK) modulation. This design covers the distance of 2688 km using seven spans at fiber length of 76.8 km.

In addition to these, some work concerning to multi core multi-mode fiber (MC-MMF) in WDM/SDM transmission systems from 2013 to 2019 for long and short distance communications is tabulated in Table 2.2.

Table 2.2 Research on different types of MC-MMF in WDM/SDM transmission systems from 2013 to 2019

Reference [year]	Mode Type	No. of Cores	Cladding Diameter (μm)	Core Pitch (μm)	Crosstalk/length @ dB/Km	Distance (Km)
Sakaguchi [2013][85]	SM	10	204.4	40.5	-46	3.9
Zhang [2014][86]	SM	7	195	49	-84	75×14 Loop
Igarashi [2015][87]	SM	19	200	35	-42	10.1
Liu [2015][47]	FM	7	150	40	-70	100
Igarashi [2016][88]	MC- MMF	6 Modes and 19 cores	318	62	-50	9.8
Cristian	TA-	10	-	-	-	20

[2016][89]	FMF	modes				
Savovic [2018][90]	MC- MM	5	660	100	-60	5.4
Djordjevich [2019][91]	MC- MMF	5	745	200	-62	1.38

2.2 Research Gap in present study

This section lists the common limitations encountered while dealing with polarization division-mQAM with optical Nyquist WDM superchannel. This would make the reader realize the importance of these drawbacks and elucidate the reasons for making an attempt to get solution to these problems.

- Emerging Nyquist WDM superchannel system requires improvement in digital signal processing, Nyquist superchannel compatible with SDM TX/RX to better exploit the multicore multimode fiber compatible with Nyquist superchannel hybrid modulation.
- Less development in this area poses significant challenges as there is a transmission of multiple optical carriers in one superchannel.
- The major technical challenge is management of channel spacing in Nyquist WDM superchannel system as study reveals that 10% spacing is required to avoid intersymbol interference.
- In present technology Nyquist WDM superchannel fabrication imposes major challenge.
- In future, Nyquist WDM superchannel will provide high spectral efficiency, without increasing symbol rate and improvement in high speed data rate.

2.3 Objectives of Research

The objectives of the research have been formulated in accordance with the above mentioned aspects and are listed below:

1. To investigate the optimize channel spacing for optical Nyquist Superchannel for WDM system.

2. To analyze the ISI cancellation effects in optical modulated spectrum of Nyquist superchannel for optimum performance.
3. To design a new architecture of hybrid modulation technique using Nyquist WDM superchannel to increase the spectral efficiency.
4. To investigate the effects of High speed optical Nyquist signal for passive optical network application.

2.4 Research Methodology

The research has been started with extensive literature survey to achieve the above said objectives. The implementation of the said objectives will be done by using simulation software's such as VPI transmission maker version 9.7 [124], and Optisystem software's version 15.0 [125] which are available in the Fiber Optics Lab of the Department.

1. VPI transmission maker software with tool optical systems accelerates the design of new optical components and new photonic system and subsystems for short haul and long haul communication and allows the technology to integrate the codes written in MATLAB and python etc. With the help of this software latest design of multicore multi-modes fibers can be implemented.
2. OptiSystem software is an innovative optical communication system simulation package which has been explored by Optiwave Company in order to meet the academic requirement of the system designers, optical communications engineers, researchers. It integrates design, test and optimize all types of broadband optical network physical layer functions such as virtual optical connection. From the long-distance communication systems to LANS and MANS, it can be well used. It has a huge database of active and passive components, including power, wavelength, loss and other related parameters. Parameters allow the user to scan and optimization of device specific technical parameters on the system performance.

The research will be carried out as:

- Mathematical analysis of ISI cancellation effects using governing equations inside the optical Nyquist WDM superchannel.
- This step includes the analysis of pulse shaping filtering with varying roll off to maintain the spacing between Nyquist WDM superchannels will be done with python software.

- Different configurations of superchannel signal processing will be designed and investigated with the help of VPI transmission maker software to minimize the interference.
- Different components including PM-mQAM modulation TX, Mach zehnder modulator and coherent RX will be investigated to design Nyquist WDM superchannel using VPI transmission with designing tool of optical systems.
- These designed modules are further interfaced with the optimized parameters of multicore multimode fibers to build the entire design.
- This step includes the software modelling of Nyquist WDM superchannels using optimized parameters and future design specimen will be validated against passive optical network application.

CHAPTER 3

UTILIZATION OF CHANNEL SPACING FOR WDM TRANSMISSION SYSTEM IN NYQUIST SUPERCHANNEL

3.1 Introduction

In this chapter, the first and second research objectives are discussed in which the first one is to investigate the optimum channel spacing for optical Nyquist Superchannel for WDM system and the second one is to analyze the ISI cancellation effects in an optical modulated spectrum of Nyquist superchannel for optimum performance. In Nyquist superchannel, channel spacing is not restricted to the baud rate. As per Nyquist criterion, sampling frequency F_s should be equals to $2f_m$ (maximum frequency) to avoid aliasing effects. But the multiple factor of 2 can be reduced to utilize the channel spacing with minimum acceptable intersymbol interference (ISI). To achieve these two objectives, a powerful Driver Signal Adjust algorithm module is proposed to optimize the channel spacing of subcarriers in Nyquist Superchannels for WDM transmission with reduced ISI. This algorithm firstly implements the first objective using band predistortion algorithm that is used to check and to remove the predistortions and it also reduces the channel spacing. Then, it compensates the delay by using the convolution with Inverse Fast Fourier Transform (IFFT) and FFT. Due to this, the optimum channel spacing has been achieved to 26.5 GHz from 32.5 GHz.

Secondly driver signal adjust algorithm implements the second objective that uses the root raised cosine filtering to analyse the ISI cancellation effects by optimizing the Nyquist pulses. Due to this, channel spacing between subcarriers in one superchannel has been further reduced to 26.5 GHz from 28.5 GHz that is used to improve spectral efficiency significantly in addition pre-distortion algorithm. This proposed system has achieved a speed of 21 Tb/s with spectral efficiency (SE) $\times$ distance product of 185000 b/s/Hz.km using predistortion algorithm and RRC filtering. These objectives are presented in different sections as follows.

The organization of optical Nyquist superchannel with band pre-distortion principle, IFFT and FFT in driver signal adjust algorithm module is evaluated in section 3.2 and RRC filtering which is used to optimize the Nyquist pulses that are free from ISI is explained in section 3.3. Section 3.4 illustrates the simulation set up of the optical Nyquist superchannel. Results using the driver signal adjust algorithm module are presented in section 3.5. Conclusions are given in Section 3.6.

3.2 Principle of Band Pre-distortion

In the band predistortion algorithm, the expression in the code modulator and driver block is being written to adjust the driver signal without any distortion. In the m-QAM mapping, the m continuous symbols are combined as a band $\vec{B} = [B_0 + B_1 \dots B_{m-1}]$. The Nyquist base band signals after pulse shaped filter (using square root raised cosine filter with varying roll-off) are combined with 2 sinusoidal signals, which are used to drive AM-PM and MZM modulator. The optical output of superchannel can be prolonged into a Fourier series, $E = Ae^{-jN\omega t} + \sum_{k=-N}^N E_k e^{jk\omega t}$, where ω represents the harmonic distortion of the first order, the k^{th} order harmonic E_k provides the complex information; the highest order harmonic index is represented by N and the amplitude of RF-tone is represented by A at the frequency of $-N\omega$. The optical Nyquist superchannels signal has a same expression as that of OFDM signal [46]. Thus after fiber broadcast and coherent detection, the converted electrical current signal can be articulated as [47]:

$I =$

$$|H(-N)A|^2 + 2\text{Re} \left\{ H^*(-N)A^* \sum_{k=-N}^N H(k)E(k)e^{j(k+N)\omega t} + \left| \sum_{k=-N}^N H(k)E(k)e^{jk\omega t} \right|^2 \right\} \quad (3.1)$$

Where the complex conjugate is represented by the * sign as shown in equation (3.1), $H(k)$ is the fiber transmission response with the distance L, the group-velocity dispersion parameter β_2 and void fiber loss, $H(k) = e^{-jk^2 \beta_2 L^2 / 2}$. The first part in Equation (3.1) is the DC component, the second part represents the desired block signal, and the third part represents the nonlinear distortions. In the pre-distortion algorithm, the four driving signals are being acknowledged at the driver signal adjust controller module (as shown in Fig. 3.1(b)). Out of four driving signals, two of them are of rectangular shape pulse named as *Upper pulse_{output}* and *Lower pulse_{output}* and remaining two signals are the output of square root raised cosine filter named as *Input Filter Up* and *Input Filter Low*. The *Upper_{output}* and *Lower_{output}* are the outputs of the driver signal adjust controller module that are used to adjust the amplitude of driving signals. The pre-distortion algorithm is used to remove non-linear ISI distortions. The pre-distortions (Z) are pronounced as [48]:

$$Z = \begin{cases} 1 & \text{then, } Upper_{Output} = 1 \text{ for } Upper_{Output} > 1 \text{ and } \neq 0 \\ & -1 \text{ for } Upper_{Output} < 1 \text{ and } \neq 0 \\ Lower_{Output} & = 1 \text{ for } Lower_{Output} > 1 \text{ and } \neq 0 \\ & -1 \text{ for } Lower_{Output} < 1 \text{ and } \neq 0 \end{cases}$$

(3.2)

If predistortions does not arise then

$$\begin{aligned} Lower_{Output} &= Lower_{Output} \times \text{linear gain} \times \frac{V_{\Omega}}{\Omega} \\ Upper_{Output} &= Upper_{Output} \times \text{linear gain} \times \frac{V_{\Omega}}{\Omega} \end{aligned} \quad (3.3)$$

When pre-distortions are removed, delay (arises due to external filtering) has to be compensated by cross correlating the signals that are $Upper_{Output}$ and $Lower_{Output}$ and its representation are expressed as [48]:

$$\begin{aligned} \tau_{delay,low} &= \text{ifft} \left(\text{fft}(Lower_{Output}) .* \text{fft}(Lower \text{ pulse}_{Output}) \right) \\ \tau_{delay,up} &= \text{ifft} \left(\text{fft}(Upper_{Output}) .* \text{fft}(Upper \text{ pulse}_{Output}) \right) \end{aligned} \quad (3.4)$$

In eq. (3.4), the cross- correlation of two signals is represented by (*). FFT (Fast Fourier Transform) is used internally by driver signal adjust controller module that converts the signals from the time domain to frequency domain. FFT is performed on the signals received from the code modulator and is used to compensate the delay by cross correlating the signals. In cross correlation, its maximum value represents that time where the signals are aligned together and is represented by the maximum value of argument, which is expressed as [49]:

$$\begin{aligned} Upper_{delay} &= \text{abs}[\text{argmax}_{\tau}(Upper_{Output} \times Upper \text{ pulse}_{Output})] \\ Lower_{delay} &= \text{abs}[\text{argmax}_{\tau}(Lower_{Output} \times Lower \text{ pulse}_{Output})] \end{aligned} \quad (3.5)$$

In the eq. (3.5), abs calculates the absolute value of $Upper_{Output}$ and $Upper \text{ pulse}_{Output}$. After the eq. (3.5), in the power combiner, power of allied signals is combined. At this stage, fifteen subcarriers are transmitted in one superchannel with the help of reduced channel spacing (4GHz).

3.3 Raised Cosine Filtering

The expression of Raised cosine filtering is written in the external filter circuitry block. It is used to find out the sufficient scaling coefficient which is free from ISI and it is achieved if the spectrum of Nyquist pulse shape satisfies the equation below [23]

$$\sum_{n=-\infty}^{\infty} H\left(f + \frac{n}{T}\right) = \text{Symbol Period} \quad (3.6)$$

The symbol period is represented by T . For achieving zero ISI and efficient scaling factor, the bandwidth (BW) of the signal should be $1/T$. The spectrum of Nyquist is rectangular and its pulse shape function is like a sinc function which is represented as [23]

$$h(t) = \text{sinc}\left(\frac{\pi t}{T}\right) = \sin\left(\frac{\pi t}{T}\right) \frac{T}{\pi t} \quad (3.7)$$

The major problem in the Nyquist sinc pulse is that its spectrum is difficult to achieve due to infinite impulse response. As the tails of Nyquist pulse shape $h(t)$ decay by a factor $1/t$, a large number of taps are required to approximate the filter practically and a small timing error in pulse shape signals results in large ISI. So to generate the Nyquist pulses practically, a roll-off factor (some additional BW usually expressed as a percentage of symbol rate) is used. In this case, a roll-off factor is generated by using raised cosine filter and it is represented by β which varies from 0 to 0.225 with an interval of 0.025. The corresponding impulse response of a raised cosine filter is [24]

$$h(t) = \sin\left(\frac{\pi t}{T}\right) \times \frac{\cos\left(\frac{\pi \beta t}{T}\right)}{1 - 4\pi^2 t^2 \beta^2 / T^2} \quad (3.8)$$

According to the above equation, the tail in the signal will decay by factor $1/t^3$ for roll-off factor greater than zero. Therefore, impulse response decays fast and timing error generates smaller ISI for the signal and its frequency response is [24]

$$H(f) = \begin{cases} T, & |f| \leq \frac{1-\beta}{2T} \\ \frac{T}{2\left\{1 + \cos\left[\frac{\pi T}{\beta}\left(|f| - \frac{1-\beta}{2T}\right)\right]\right\}}, & \frac{1-\beta}{2T} \leq |f| \leq \frac{1+\beta}{2T} \\ 0, & \text{otherwise} \end{cases} \quad (3.9)$$

When the response of RC is compared with the rectangular spectrum then it occupies β/T extra bandwidth. So, RRC filtering is chosen over RC filtering to achieve the high SNR

value. However in the RRC, the spectrum tail is bigger than RC for the same value of roll-off factor which causes more ICI at close channel spacing. So to smooth out the characteristics of root raised cosine spectrum, the square root of the RRC is taken and it is named as square root raised cosine filter (SRRC). In the RRC, TX and RX act like a matched filter and the overall response of the system is RC. In the RRC, TX and RX avoid ISI and optimize SNR. Table 3.1 represents the required parameters for Nyquist superchannel system. Table 3.2 describes the characteristics of SMF for design of Nyquist Superchannel System

Table 3.1 Parameters of Nyquist Superchannel System

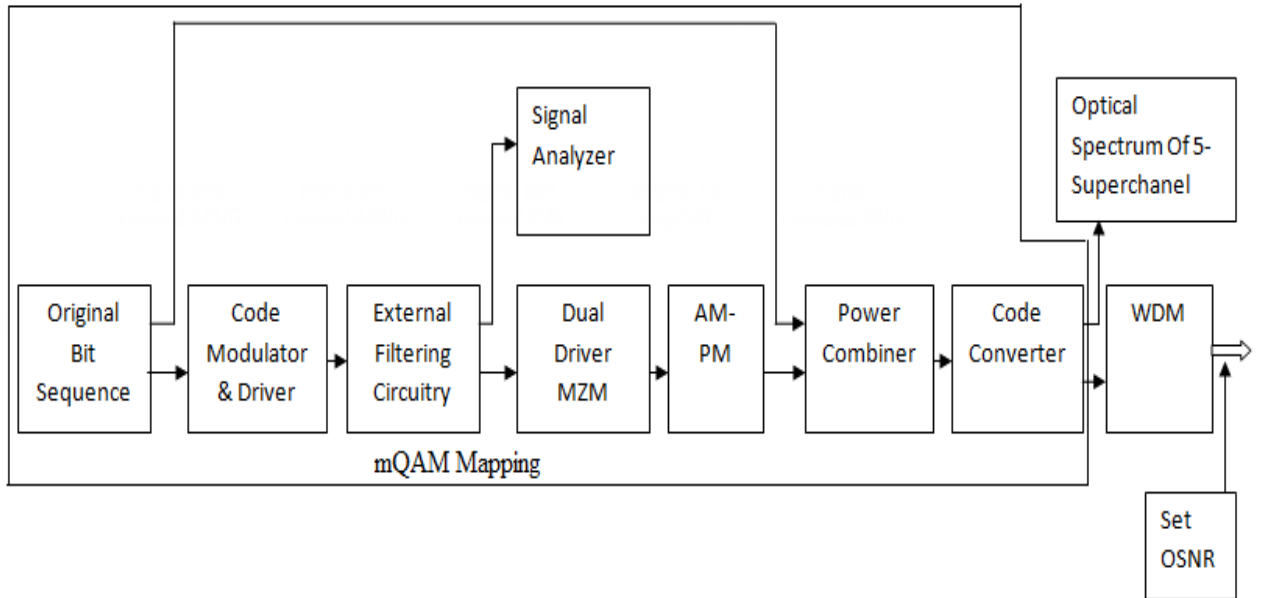
Name of parameter	Value
Channel spacing to Symbol Rate Ratio	1.0
Symbol Rate	35.2 Gbaud
Bits/Symbol	2
Roll-off factor	0
Nyquist Response	Square Root Raised Cosine
Transmission Type	IQ-SD
Pre-distortion	YES
Modulation format	DP-16QAM
Output data type	Blocks
Laser Emission Frequency	$193.1e^{12}-2*\text{channel spacing}$
Laser average power	$e^{-3}W$
Insertion Loss of MZM	2dB
Extinction Ratio	35dB
V_{Ω} DC & V_{Ω} RC	3V
Photodiode	PIN
Fiber Length	1850 km

Fiber Type	Universal
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In the end to compensate the delay, the convolution of Fast Fourier Transform with Inverse Fast Fourier Transform is done in the driver signal adjust algorithm module. At this stage, the channel spacing is further reduced by 2 GHz without any ISI.

3.4 Simulation Set-up

In this simulation setup, with the help of one m-QAM block, fifteen subcarriers are generated that can be further divided into even and odd sub carriers and they are considered as one superchannel. As shown in Fig. 3.1 (a), the code modulator and driver block generates a sequence of electrical impulses that are further filtered by external filtering circuitry and are observed at the signal analyser using VPI transmission maker software version 9.7 [125]. In the external filtering circuitry, square root raised cosine filtering is used to avoid the ISI and to optimize the SNR. To shape up the spectral of subcarriers, the shape of driving signals is adjusted using MZM modulator and AM-PM modulator. The power received from AM-PM modulator and original bit sequence is combined at the power combiner block to efficiently utilize the power.



(a)

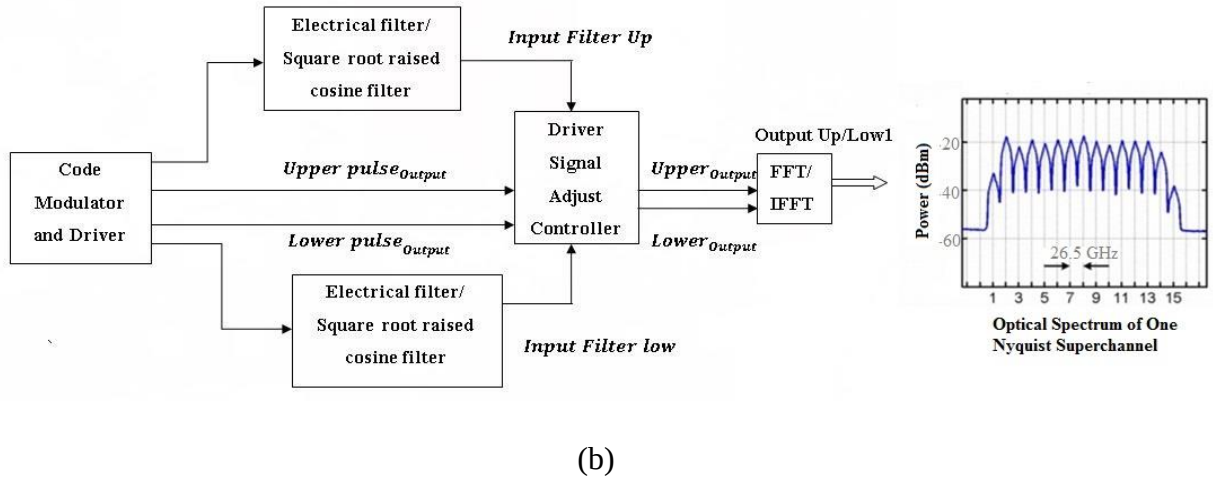


Fig. 3.1 (a) Simulation Setup of Transmitter for generating electrical and optical Superchannels with Driver Signal Adjust module (b) internal architecture of external filtering circuit [125]

Table 3.2 Characteristics of SMF for design of Nyquist Superchannel System

Fiber Type	Fiber Length (km)	Attenuation (dB/km)	Dispersion (ps/nm/km)	Dispersion Slope (ps/nm ² /km)	Effective Area (μm ²)
SMF	100	0.22	16.7	0.075	80

The code converter is used to join the parameterized signal and distortions into one signal and discard signals with power smaller than the specified threshold value. At the output of the coder converter, an optical modulated spectrum of Nyquist superchannels is generated with efficient utilization of channel spacing. The optical spectrums of 5 superchannels are generated after the code converter block. Five Terabyte superchannels are obtained through the aggregation of multiple sub carriers using Nyquist WDM technology [92] [93]. This technology is based on tight spectral shaping of each sub carrier which allows very narrow spacing. Hence, in proposed research the channel spacing has been further reduced to 26.5 GHz.

The driver signal adjust algorithm that consists of pre-distortion algorithm and RRC filtering is written in the driver signal adjust controller block. In Fig. 3.1(b) the internal architecture of the external filtering circuit is shown where four driving signals are generated, here two signals are from rectangular pulse ($Upper/Lowe\ pulse_{Output}$ and other two from square root raised cosine filter ($Input\ Filter\ Up/low$) and the outputs of driver signal adjust control module is represent as $Upper_{output}$ and $lower_{output}$ that are used to adjust the amplitude of

driving signals and these outputs are further given to FFT. External filtering circuit helps the dual driver MZM [48] and AM-PM to reduce ISI. The optical spectrum for one Nyquist superchannel with 26.5GHz channel spacing between subcarriers is shown in the Fig. 3.1 (b) at the output of FFT.

As per Fig. 3.2, the input signal consists of several WDM channels and after that OSNR is connected to the polarizer beam splitter [95], to achieve the double bit rate and further is connected to a coherent receiver. The output of the coherent receiver is given to python $f(x)$ block where the predistortion and squared root raised cosine filter algorithm is written in python language. This is done to observe the results of the bit error rate according to the corresponding channel spacing.

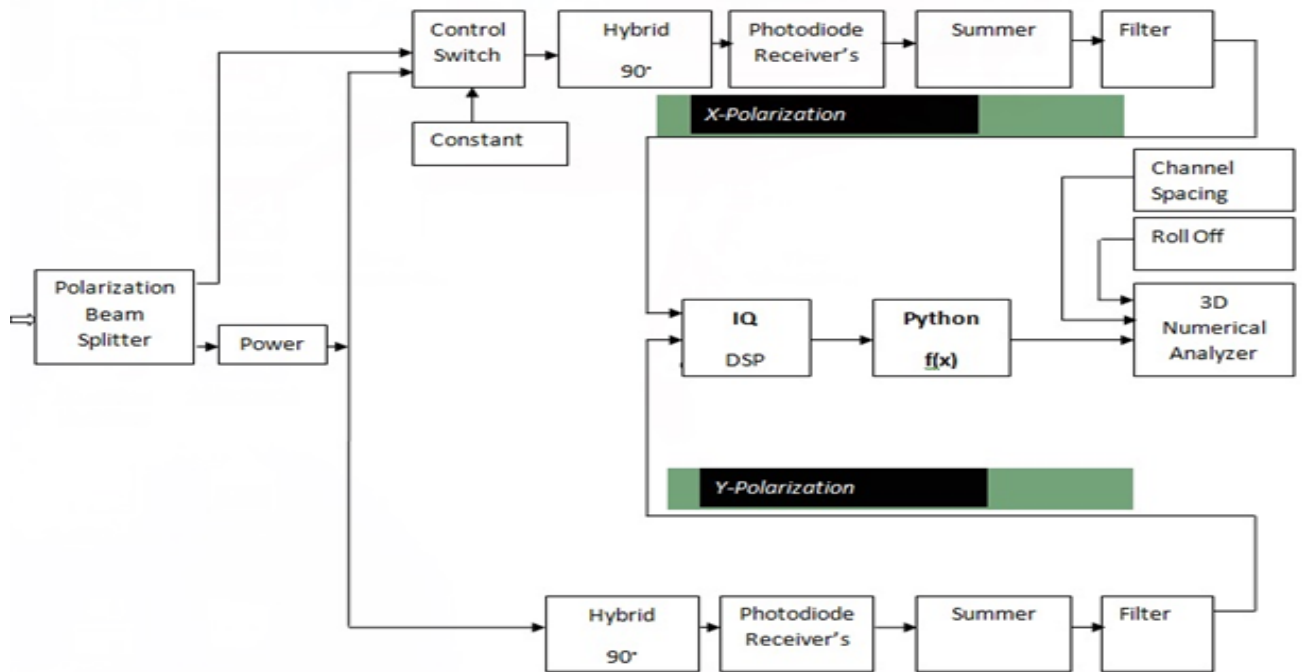


Fig. 3.2 Simulation setup of coherent receiver

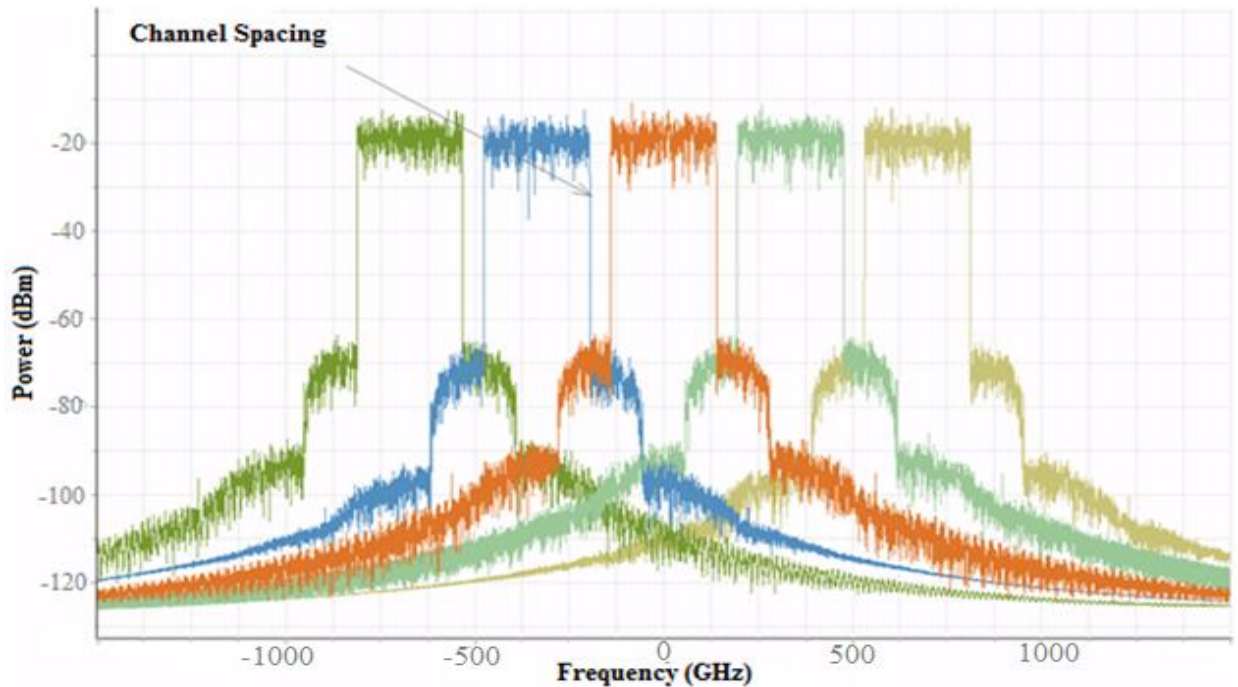
3.5 Results and Discussion

The optical spectrum of five Nyquist superchannels has been observed using optical spectrum analyser with the help of VPI transmission Maker™ Version 9.7 simulator [125]. After the simulation of the driver signal adjust algorithm module, the channel spacing between subcarriers for each Nyquist superchannels is optimized and reduced up to 26.5 GHz. Fig. 3.3(a) ascertained that Five Nyquist superchannels are transmitted without any pre-distortions at 32.5 GHz channel spacing between subcarriers for each Nyquist superchannels. Also,

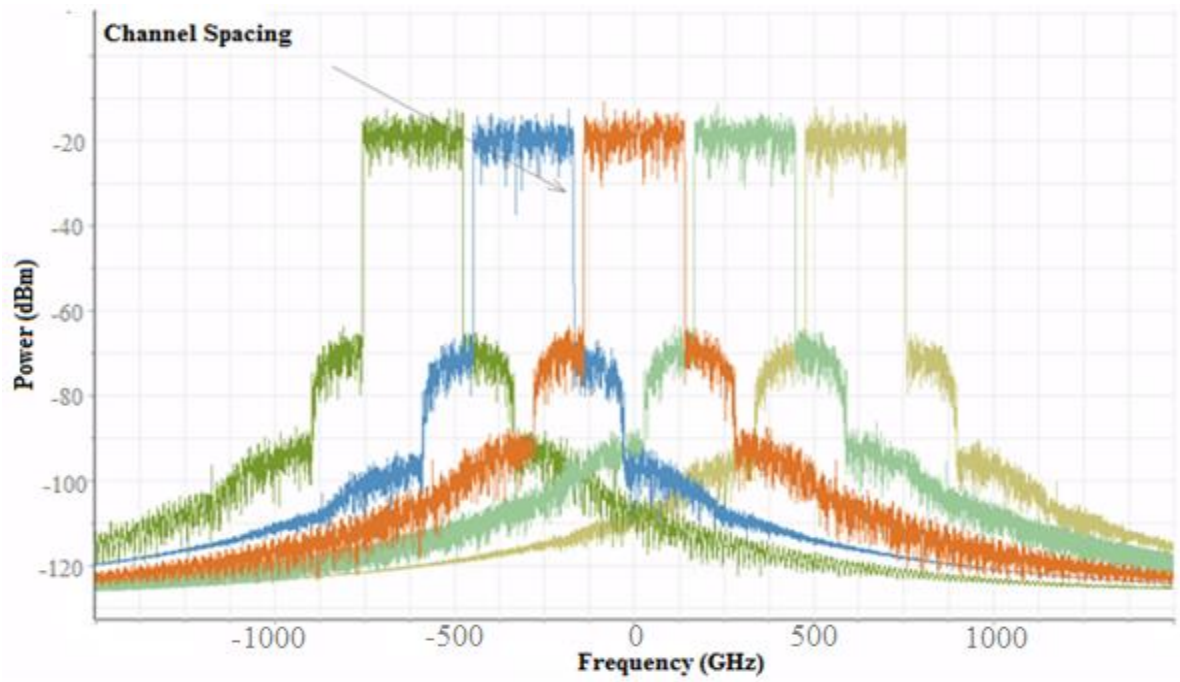
channel spacing has been optimized to 28.5 GHz from 32.5 GHz without any predistortion using Pre-distortion algorithm as shown in Fig. 3.3(b). The Fig.3.3 is taken before the RRC filtering and superchannels are so noisy due to intersymbol interference (ISI). This ISI has been removed using RRC filtering as shown in Fig.3.4 (b) with further reduced channel spacing of 26.5GHz. The reduced channel spacing is utilized by fifteen subcarriers to be transmitted in one Nyquist superchannel for long distance communication.

Fig. 3.4 shows that RRC filtering is used to shape-up the Nyquist pulses by reducing the intersymbol interference at 26.5GHz channel spacing between subcarriers for each Nyquist superchannel. Fig. 3.4(a) shows that the channel spacing has been reduced upto 26.5GHz from 28.5 GHz (as shown in Fig. 3.3 (b)). In Fig. 3.4(b), RRC filtering is also used to reduce the intersymbol interference effects. After reducing the channel spacing and intersymbol interference, five Nyquist superchannels are transmitted over the fiber.

From these diagrams, we can observe that the bandwidth of each superchannel becomes narrower. After computing the spectral efficiency of Nyquist superchannel (10 bit/s/Hz at 4.224 Tb/s data rate of each Nyquist superchannel), it can be inferred that wavelength division multiplexing system using Nyquist superchannel with Driver Signal Adjust Algorithm module presents a significantly high spectral efficiency.

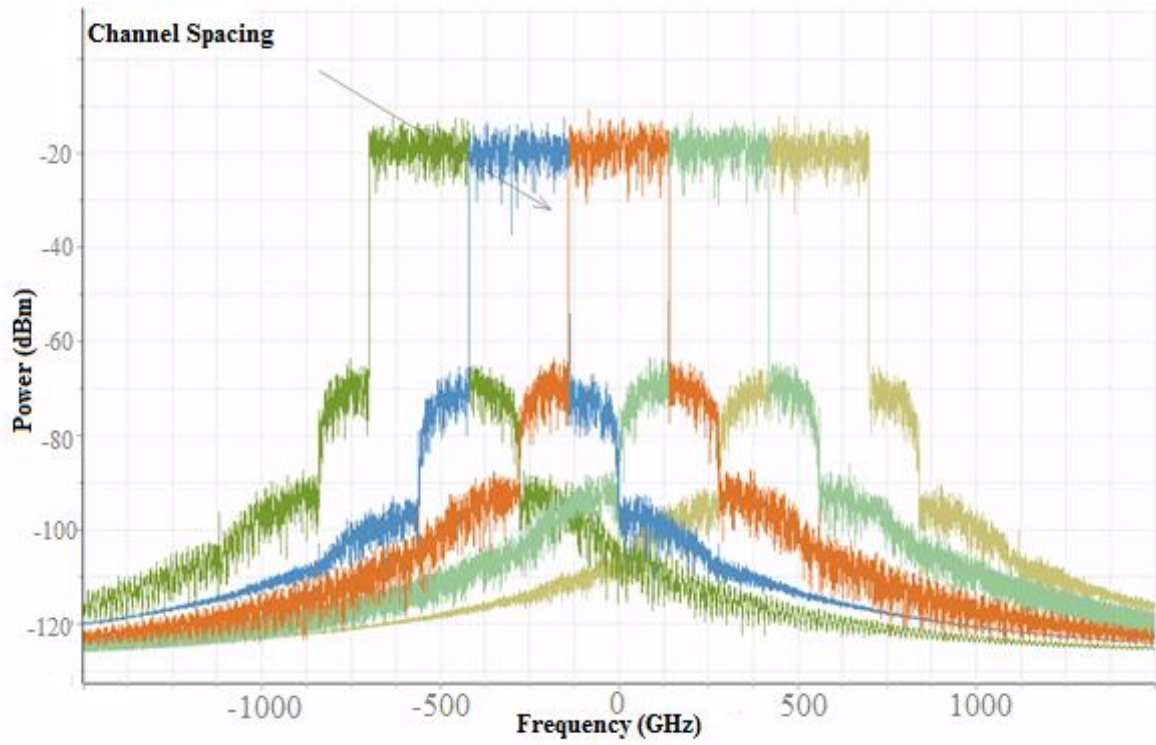


(a)

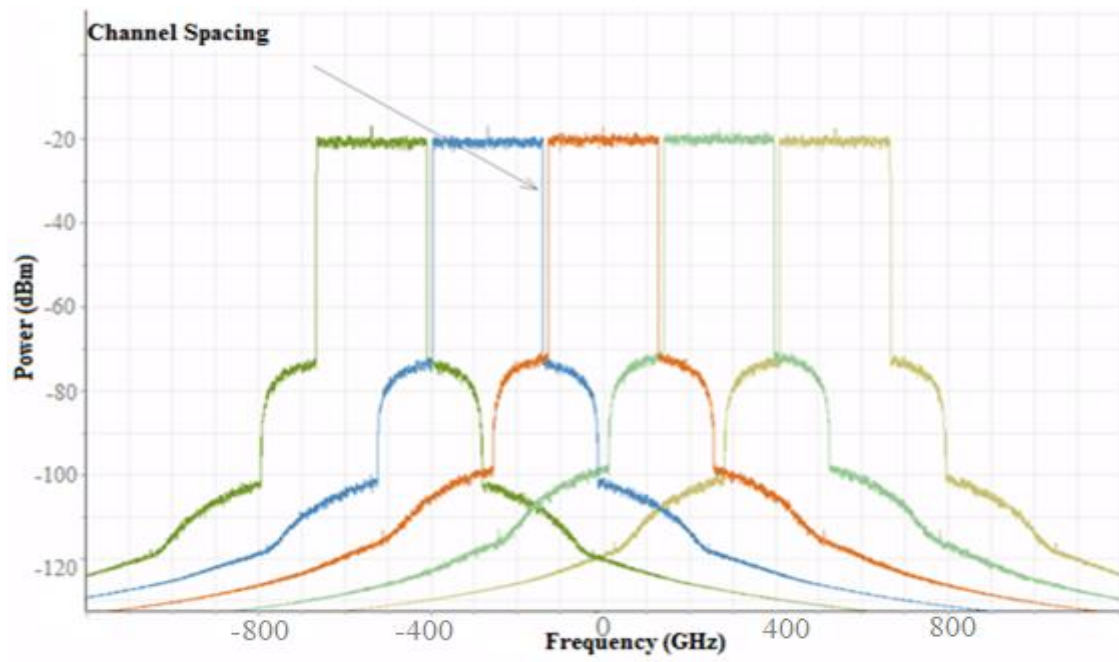


(b)

Fig. 3.3 Pre-distortion Algorithm (a) Before Algorithm at 32.5 GHz channel Spacing between subcarriers (b) After pre-distortion algorithm at 28.5 GHz channel Spacing between subcarriers

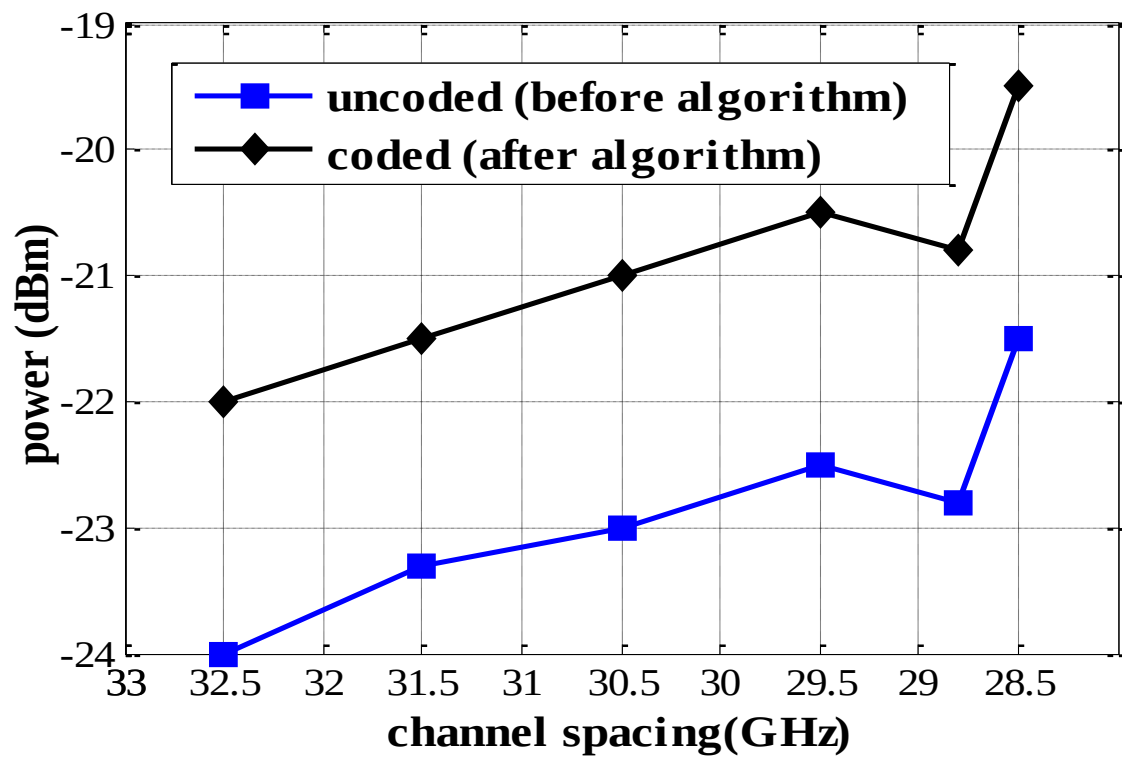


(a)

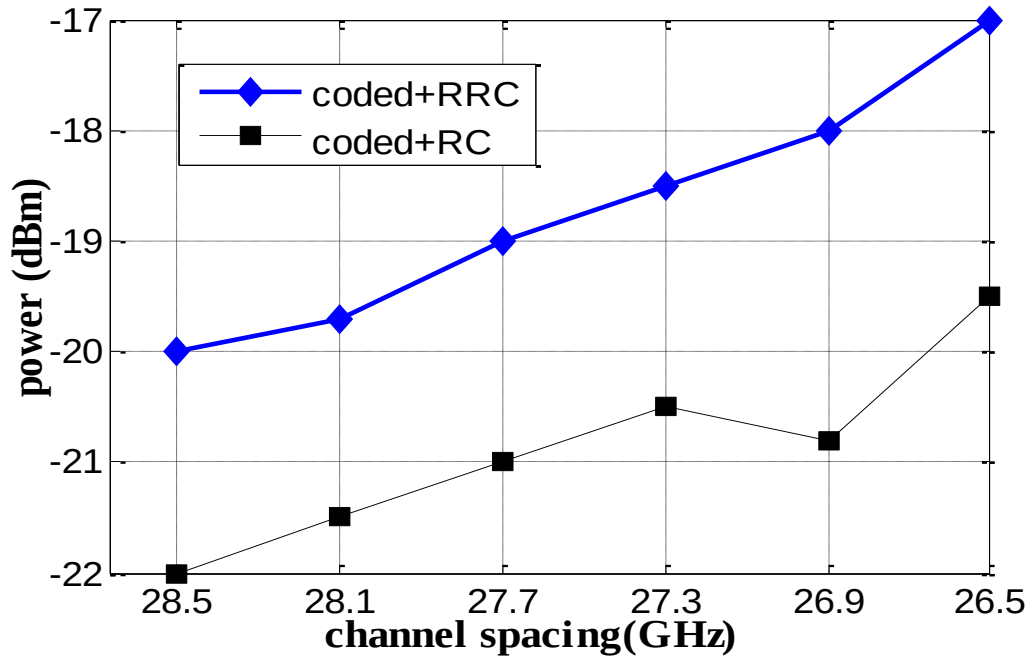


(b)

Fig. 3.4 RRC Filtering (a) at 26.5 GHz Channel Spacing with ISI (b) With reduced ISI

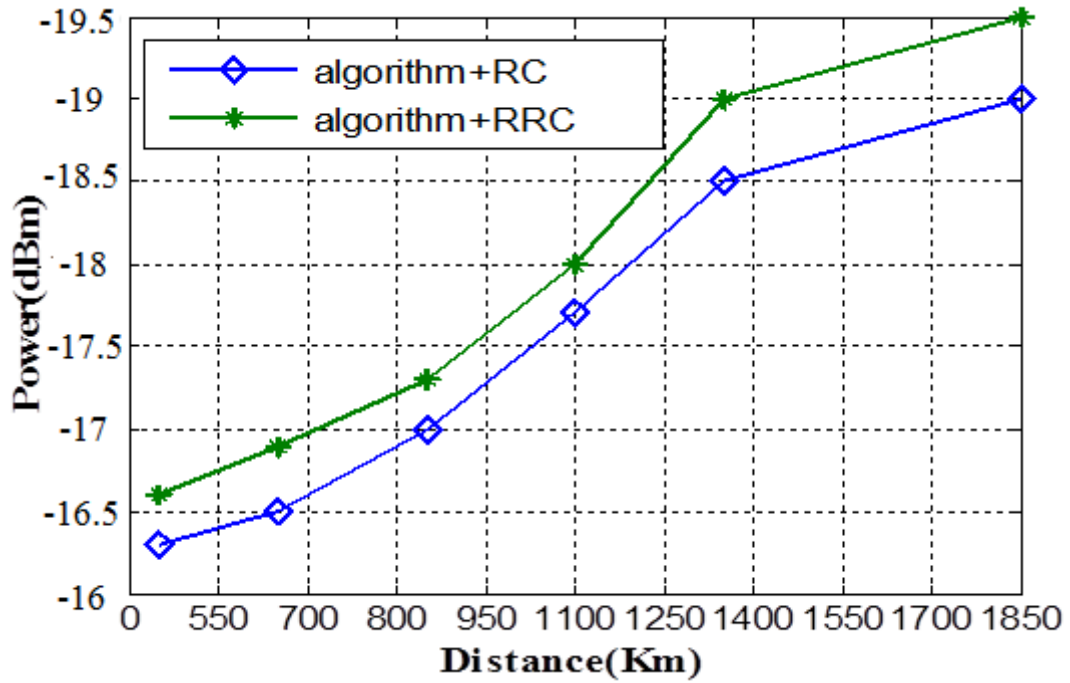


(a)

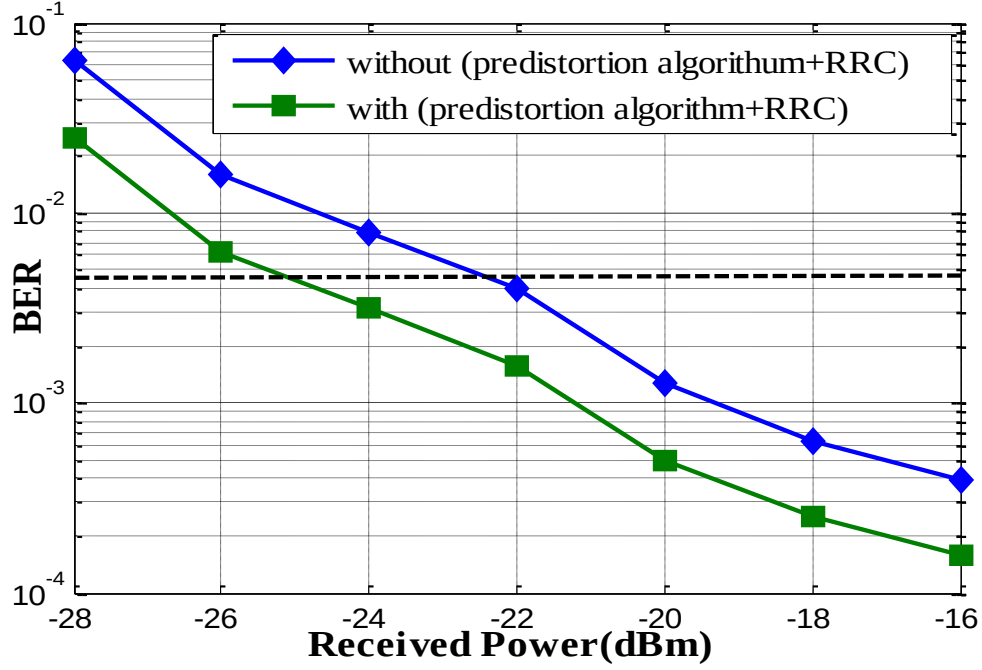


(b)

Fig. 3.5 Results of received optical power w.r.t channel spacing after transmission of five Nyquist Superchannels (a) uncoded (before predistortion algorithm) and coded (after predistortion algorithm) (b) For predistortion algorithm with RRC and RC filtering



(a)



(b)

Fig. 3.6 After utilization of channel spacing using predistortion algorithm with filtering (a)
Power w.r.t. of distance (b) Bit Error Rate as a function of Received Power

Fig. 3.5 shows received optical power with respect to channel spacing without any predistortions and with reduced ISI. In Fig. 3.5(a), channel spacing between subcarriers is reduced by 4 GHz (from 32.5 GHz to 28.5 GHz) after the predistortion algorithm. Fig. 3.5(b) indicates that the channel spacing between subcarriers is further reduced by 2 GHz after using the RRC filtering with predistortion algorithm. It is observed that the proposed system using predistortion algorithm and RRC filtering is less profound to predistortions and ISI with acceptable power of -17 dBm. The response of transfer function at a coherent receiver should be same as that of the transmitted rectangular pulse to satisfy Nyquist criterion for utilizing the channel spacing efficiently with reduced ISI and pre-distortions. Fig. 3.6(a) depicts the different values of power w.r.t distance after utilization of channel spacing with predistortion algorithm and RRC filtering. The bit rate of Fig. 3.6 (a) is 5×4.224 Tb/s for transmission of Nyquist superchannels over 1850 km distance. Maximum utilization of channel spacing is achieved with -19.5 dBm power for a distance of 1850 km. From the Fig. 3.6(b), it is observed that the received power at the FEC threshold of Bit Error Rate 4.5×10^{-3} is -25.3 dBm using the predistortion algorithm with RRC filtering and is -22.4 dBm without using them respectively with 7% overhead [96]. The Nyquist superchannels channel also passes

through In-line EDFA amplifiers without dispersion compensated fiber (DCF) to strengthen the signal power [97]. While conceptualizing a simple design, the main objective is transmission of 5×4.224 Tb/s Nyquist superchannels using the predistortion algorithm and RRC filtering at reduced channel spacing without any predistortion and it has been attained by mathematical equations depicted in section II. The proposed system has achieved a spectral efficiency (10 b/s/Hz) $\times$ distance (1850 km) product of 18500 b/s/Hz.km using predistortion algorithm and RRC filtering.

3.6 Conclusion

In this chapter, a Nyquist superchannel with a driver signal adjust algorithm module for wavelength division multiplexing (WDM) system is established. In a driver signal adjust algorithm module, pre-distortion algorithm and RRC filtering has been proposed. Consequently, a proficient utilization of channel spacing method relies on band predistortion, square root raised cosine filtering and FFT to improve the system performance. From the result, it has been observed that in the proposed WDM Nyquist superchannel transmission system the channel spacing between subcarriers for each Nyquist superchannel has been reduced to 26.5 GHz from 32.5GHz without any pre-distortions using pre-distortion algorithm and RRC filtering. Further to improve the spectral efficiency, RRC filtering is used in addition to pre-distortion algorithm and due to this the channel spacing between subcarriers is reduced to 26.5 GHz from 28.5 GHz with reduced ISI. The system has achieved a speed 21 Tb/s with spectral efficiency $\times$ distance product of 18500 b/s/Hz.km using predistortion algorithm and RRC filtering.

CHAPTER 4

HYBRID MODULATION SYSTEM WITH NYQUIST TO INCREASE SPECTRAL EFFICIENCY

1.1 Introduction

In this chapter, the third objective is proposed to design a new architecture of hybrid modulation technique using Nyquist WDM superchannel. The advantage of hybrid modulation techniques with Nyquist superchannel as compared to single modulation (as explained in chapter 3) is that they not only increase the data rate beyond 100 Gb/s for each channel and but also transmit the unicast and multicast data simultaneously. With the help of this technique, multiple users can transmit their data on a single channel at distinct parameters of the signal. To achieve this, a combination of three different modulations (Nyquist DP-16QAM, DPSK, and POLSK) techniques is used with the Nyquist superchannel to improve the system performance. In this design, a BW efficient system is designed in which Nyquist DP-16QAM and POLSK are used as unicast data and DPSK as multicast data transmission. From the proposed design system, the best acceptable BER, the input power, and the Quality factor are analyzed using a hybrid modulation technique for a multicast overlay system, which is best as compared to other existing research works for multicast overlay system. The modulations which are used in unicast and multicast transmit the data at 640 GB/s and 40 GB/s data rate respectively. The total transmission rate of the overall system is 5.1 Tb/s using 8 superchannels of unicast data and 1 channel of multicast data. The proposed system design also provides the efficient use of 0.015 THz bandwidth at high speed transmission rate for each channel. The organization of hybrid modulation techniques with optical Nyquist superchannels as a unicast and multicast overlay system is evaluated in section 4.2. Results and discussions using the hybrid modulation technique with multicast overlay system are presented in section 4.3. The conclusion is given in section 4.4.

1.2 System Set-up

The proposed Nyquist superchannel hybrid modulation design in Optisystem software's [70] as shown in Fig. 4.1 in which six subcarriers are modulated by Nyquist DP-16QAM modulation from 193.1 THz to 193.175 THz frequency and the data is transmitted at 100 Gb/s data rate with 1nsec interval at 15 GHz channel spacing. In the previous researches,

channel spacing was set at 27.75 GHz in hybrid modulation design to achieve high spectral efficiency [72]. In this proposed model, sub carrier channel spacing is further reduced from 27.75 GHz to 15 GHz to improve the system performance and this channel spacing is utilized to transmit more sub-channels efficiently. An M-ary root raised cosine (RRC) filtering is used in Nyquist DP-16QAM modulator with NRZ line coding. RRC filtering is used to utilize the channel spacing more efficiently. After RRC filtering, a continuous light beam that works on conventional mode is modulated with LiNb Mach-Zehnder at 100 Gb/s data rate.

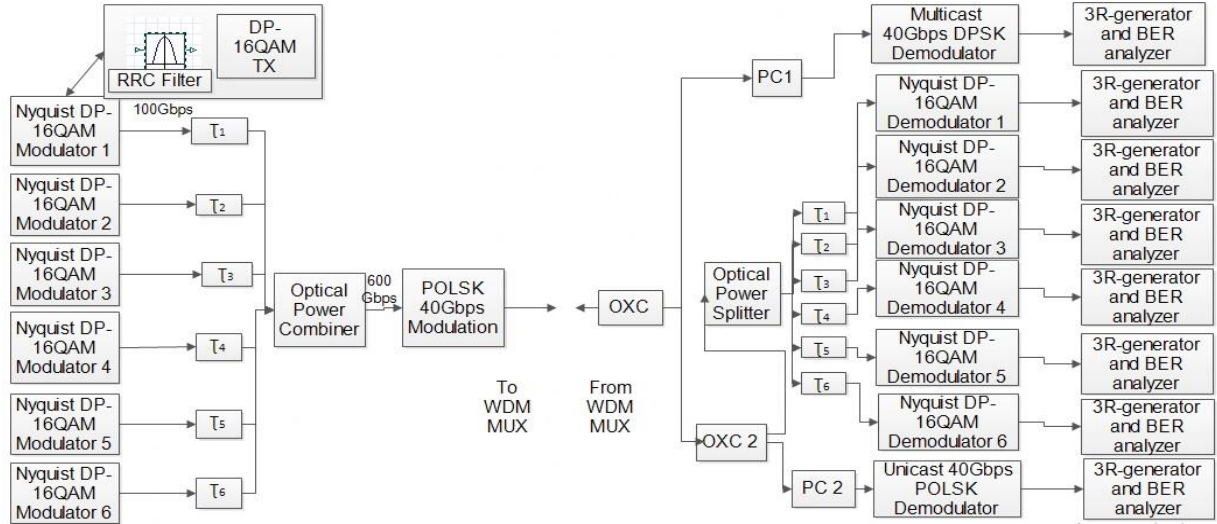


Fig. 4.1 Design of unicast transmission and reception for single subchannel

The six outputs each at 100 Gb/s data rate from Nyquist DP-16QAM are transferred to optical power combiner at 1nsec interval. After combining the signals in power combiner, 600 Gb/s multiplexed signal is transferred to POLSK, in which NRZ modulator is used to drive the 40 Gb/s data rate by PM and is placed between polarization beam combiner (PBC) and a polarization beam splitter (PBS). Further, the generated data at 640 Gb/s data rate at the POLSK modulator output is transferred to WDM multiplexer. As shown in Fig. 4.2, the total eight superchannels each at 640 Gb/s data rate are transmitted to the WDM multiplexer. These eight unicast superchannels are further combined with DPSK modulation at 40 Gb/s data rate for the generation of multicast overlay system. The joint multicast and unicast signal is transmitted to the N re-circulating span and it is comprised of standard single mode fiber (SSMF) with dispersion compensated fiber (DCF) as shown in Table 4.1 and is further amplified by erbium-doped fiber amplifier (EDFA). Table 4.1 describes the parameters of SMF and DCF for design of unicast multicast transmission. The length of SSMF is 42 km and DCF is 8 km at wavelength varies from 193.1 THz to 193.8 THz. To make the system

more precise, white Gaussian noise is inserted in each channel. Subsequently, these eight unicast signals each at 640 Gb/s data rate and 40 Gb/s multicast signal at 40 Gb/s data rate are transferred to demultiplexer and recovered back by the receiver that is shown at the right-hand side of Fig. 4.1. The optical cross coupler (OXC) is used to separate the unicast and multicast data at the receiver side. Further, the polarization controller (PC1) is used to receive the multicast data and OXC2 is used to receive the unicast data by Nyquist DP-16QAM demodulation and PC2 is used to receive the unicast data by POLSK demodulator. The DPSK demodulator which is used to recover back the multicast data consists of mach zehnder interferometer at 2 sec interval and balanced detector. The POLSK demodulator which is used to receive the unicast data consists of PBS and balanced photodiode. In the Nyquist DP-16QAM demodulation, six sub-channels each at 600 Gb/s data rate are separated by optical power splitter and nullify their respective delays. After recovering back the multicast and unicast data, they are transferred to 3R generator and further to BER analyser to observe the system performance of Hybrid modulation with Nyquist superchannel.

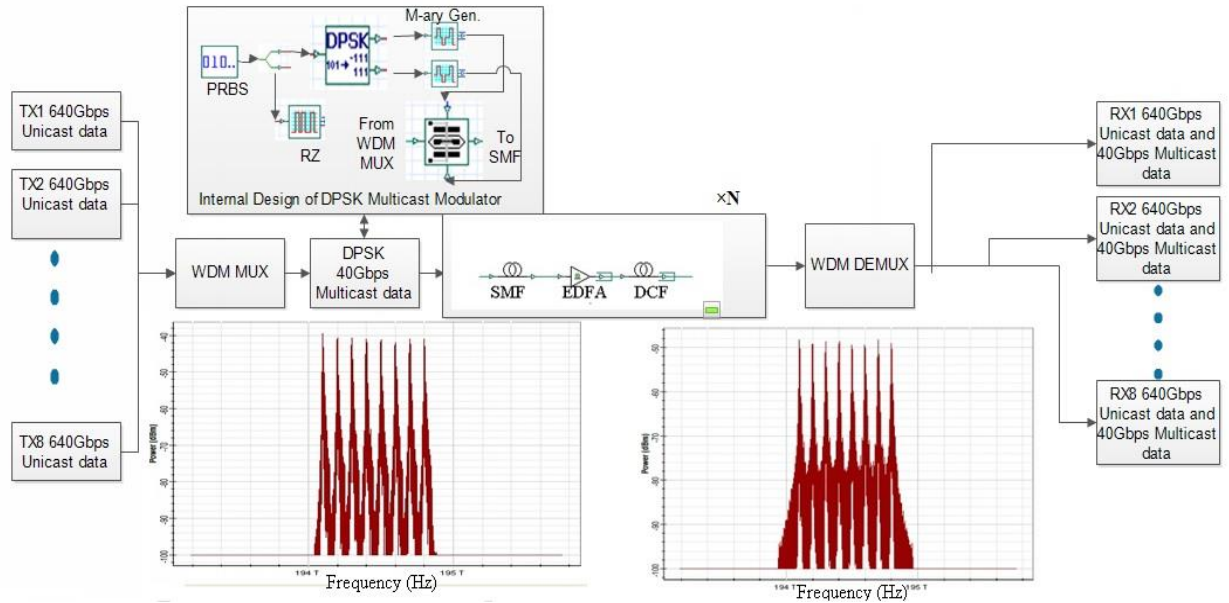
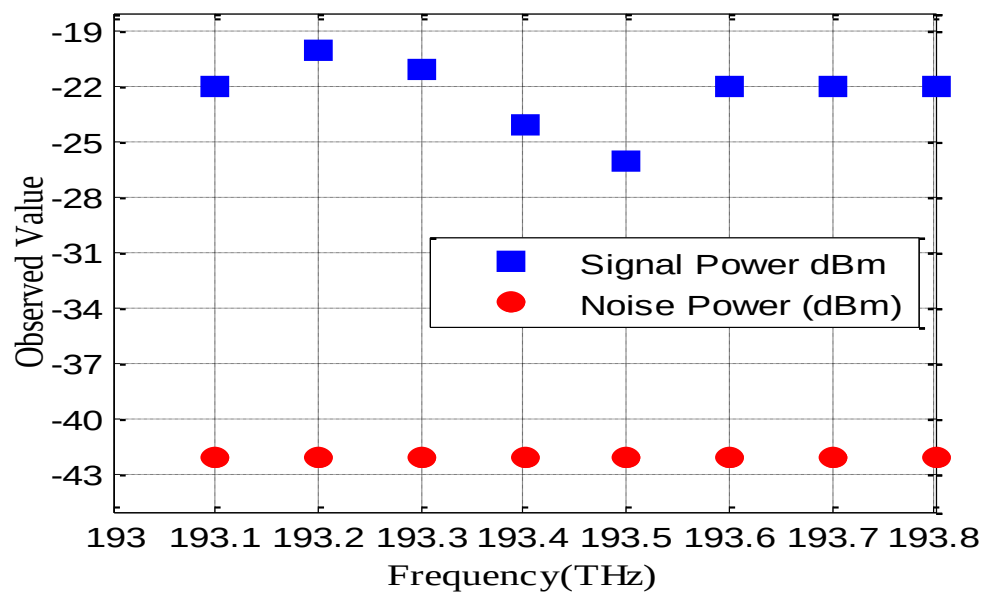


Fig. 4.2 Design of multicast overlay system using Nyquist superchannel as a unicast data and DPSK for multicast data transmission [126]

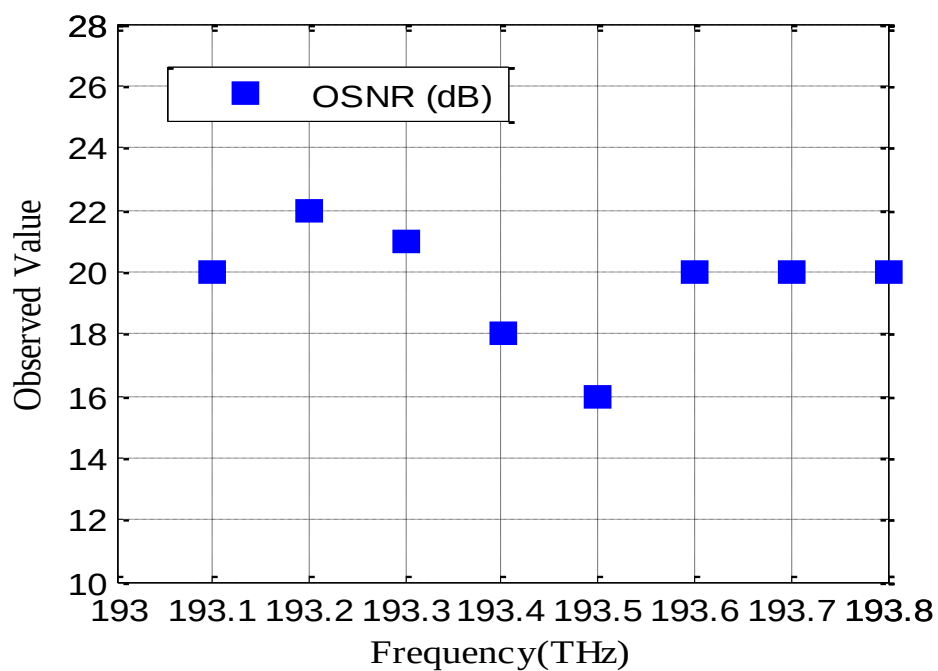
1.3 Simulation Results

The simulation results of a multicast overlay system with hybrid modulation techniques have been analyzed using optisystem version 15 software [126]. The observed value of signal power and noise power at different frequencies is shown in Fig. 4.3(a) for each channel. From

the results, it has been observed that the signal power and noise power are in an acceptable range.



(a)



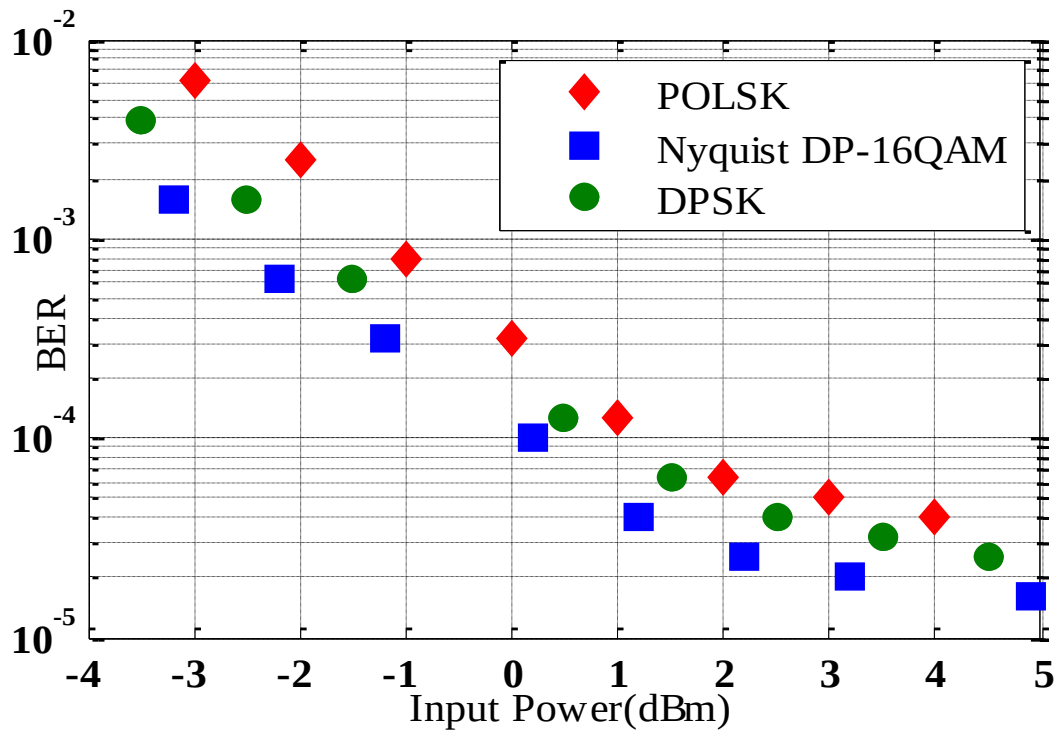
(b)

Fig. 4.3 (a) Observed value of signal power and noise power (b) OSNR of each sub-channel at different frequencies

Table 4.1 Parameters of SMF and DCF for design of unicast multicast transmission

Fiber Type	Fiber Length	Attenuation (dB/km)	Dispersion (ps/nm/km)	Dispersion Slope (ps/nm ² /km)	Effective Area (μm ²)
SMF	42	0.2	17	0.075	70
DCF	8	0.5	-85	-0.3	22

The optical to signal noise ratio for each channel at different frequencies is shown in Fig. 4.3(b). The received OSNR at the receiver end is >16 dB and <25 dB for all used wavelength signal by varying input transmitted power from -4 dBm to +5 dBm as shown in Fig. 4.3 (b) and OSNR is calculated from signal power and noise power as shown in Fig.4.3 (a). There is a dip at central frequency 193.5 THz frequency due to transmitted input power of 1 dBm. For a multicast overlay system with hybrid modulation techniques, targeted OSNR has been analysed for transmission of 5.1 Tb/s data rate.

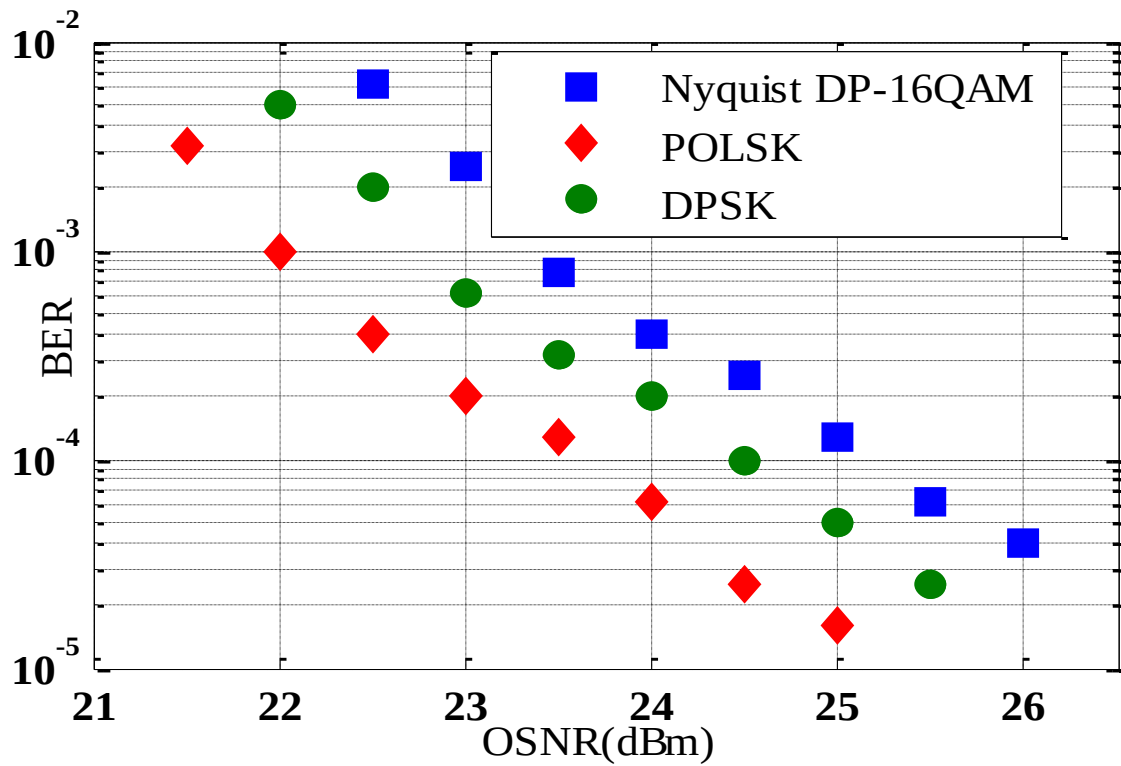


(a)

Fig. 4.4 Results for each super-channel in proposed design system (a) BER with respect to Input Power

Fig. 4.4 (a) shows the result of received BER versus input power for multicast overlay system and it has been deduced that BER varies proportionally with respect to input power. As the input power increases till 5 dBm the value of BER increases and the input power reduces to 0dBm, BER deteriorates.

Fig. 4.4 (b) shows the observed BER with respect to OSNR for each channel of unicast and multicast data transmission and the best OSNR is achieved at Nyquist DP-16QAM instead of DPSK multicast data for multicast data transmission system. In case of Nyquist DP-16QAM for unicast data transmission, the value of the best acceptable OSNR is 26 dBm at BER of 7×10^{-4} .



(b)

Fig. 4.4 Results for each super-channel in proposed design system (b) BER with respect to OSNR

The quality factor with respect to transmission length is shown in Fig. 4.5 for each channel received by unicast data and multicast data and it is analysed that the quality factor of the proposed system declines as we increase the distance due to multicast overlay system in which multicast data is overlaid with unicast data and due to fiber nonlinearities. The Fig. 4.5

shows the Q-Factor versus length for each channel for Nyquist DP-16QAM and POLSK unicast data transmission and DPSK multicast data and observed that the quality factor of the system deteriorates as the distance increases. In the proposed system design the transmission length of fiber is 50 km and the numbers of spans (N) are 10 so the total distance covered by the design system is 500 km.

Singh et al. [70] work demonstrated the multicast overlay system with hybrid modulation techniques with a transmission capacity of 1 Tb/s, using 4 channels of SC-DQPSK at 20 Gb/s data rate and POLSK at 40 Gb/s as unicast data transmission and 40 Gb/s as multicast data transmission. While in the proposed design, Nyquist superchannel with hybrid modulation techniques is used in a multicast overlay system. This work provides total 5.1 Tb/s transmission capacity which is based on 6 sub channels of Nyquist DP-16QAM each at 100 Gb/s data rate with optimized channel spacing of 15 GHz and POLSK modulation at 40 Gb/s data rate as unicast data transmission and DPSK modulation at 40 Gb/s data rate as multicast data transmission, which is improved 55% as compared to Singh et al. [70] work.

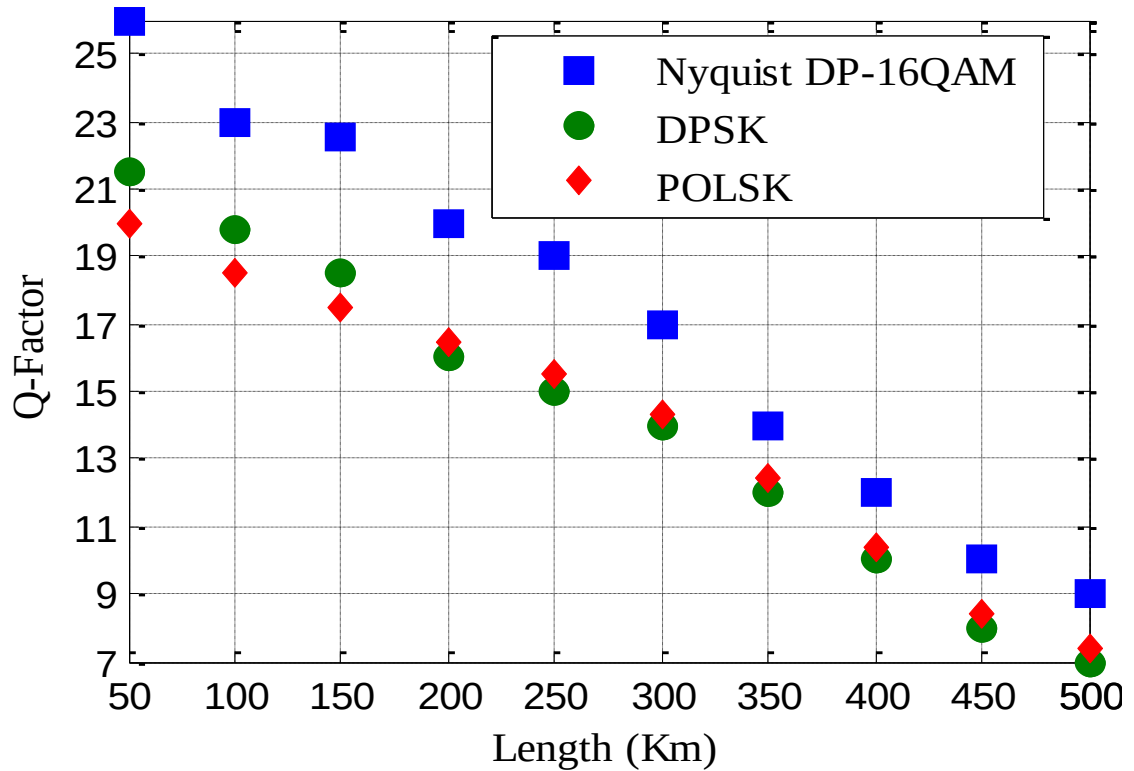


Fig. 4.5 Quality Factor with respect to length for each sub-channel using Nyquist DP-16QAM modulation and POLSK and DPSK modulation

1.4 Conclusion

Here, a multicast overlay system has been proposed and investigated by using 640GB/s unicast data and 40 GB/s multicast data over 500 km distance. In this proposed system, a novel BW efficient Nyquist DP-16QAM modulation with different hybrid modulations (DPSK and POLSK) in multicast overlay system has been investigated. The total transmission rate of the overall system is 5.1 Tb/s using eight superchannels (each at 640 GB/s) of unicast data and one channel (at 40 GB/s) of multicast data. Each superchannel consists of six sub channels of Nyquist DP-16QAM modulation each at 100 GB/s data rate with optimum channel spacing of 15 GHz and POLSK modulation at 40 GB/s data rate for multicast data transmission. The measured Quality factor for all multicast and unicast data signal is more than 7. From the proposed system, the best acceptable BER (7×10^{-4}), the input power (5dBm), and Quality factor (25) is analyzed using hybrid modulation (Nyquist DP-16QAM, DPSK and POLSK) for multicast overlay system, which is best as compared to other existing research works for multicast overlay system.

CHAPTER 5

NYQUIST SUPERCHANNEL SYSTEM USING TRENCH ASSISTED MULTICORE FIBER

5.1 Introduction

This chapter affirms the third objective to enhance the Nyquist superchannel system with Hybrid modulation (NRZ, BPSK and 16QAM) technique to increase the spectral efficiency with a new optimized design of multi-core fiber. So to implement this, a Trench Assisted Multicore Fiber with optimized parameters is designed with this system. A Trench Assisted Multicore Fiber [46] is designed with optimized parameters and further, it is interfaced with the Nyquist superchannel system and hybrid modulation technique in VPI transmission maker software. In this design, channel spacing is reduced at 25 GHz (after coding) from 32.5 GHz (before coding) with five Nyquist superchannels each at 4.224 Tb/s transmission rate and it also covers the transmission distance of 2688 km with the help of trench-assisted multicore fiber (TA-MCF) at altered spans. Now a Nyquist superchannel of 15 subcarriers occupies an optical bandwidth of 375 GHz at 4.224 Tb/s data rate and achieves a spectral efficiency of 11 b/s/Hz. In each Nyquist superchannel, total of 15 subcarriers are transmitted each at a 35.2 Gbaud symbol rate with PM-16QAM hybrid modulation technique without any pre-distortions. With the help of core to core rotation (CCR) scheme, minimum inter-core crosstalk from the neighbouring cores has been observed after WDM/SDM transmission. In the fourth chapter, to improve the data rate using hybrid modulation techniques with Nyquist superchannels, the combined input power from all WDM channels should be more than 1Watt to sustain the optical to signal noise ratio. But such high value of input power [87] produces fiber non-linearities and also the reason for fiber fuses. To reduce such issues, space division multiplexing (SDM) with multicore fiber (MCF) [98] has been introduced that can be easily interfaced with wavelength division multiplexing (WDM) in standard single mode fiber (SSMF). Although using homogeneous and heterogeneous MCF with SDM, the communication distances were limited to shorter ranges only. To overcome all these limitations, Nyquist superchannels along with TA-MCF using hybrid modulation is one of the main ladders to boost the transmission capacity. This chapter is organised as follows. In Section 5.2, the theory and design of uncoupled homogenous TA-MCF coupling with TMC is described. The simulation set up is described in Section 5.3. A mathematical investigation is

explained in Section 5.4. The results are analysed in Section 5.5. The conclusion is described in Section 5.6.

5.2 Design of Homogenous Uncoupled TA-MCF with TMC

In uncoupled multicore fiber, each core arranged suitably so inter-core crosstalk between the cores is small for long haul application. It provides high core density, low attenuation, and large effective area. The Multicore fiber operates between C band (varies from 1550 nm to 1565 nm) and L band (varies from 1565 nm to 1625 nm) and provides high capacity optical access network and high spectral efficiency for SDM applications. Homogenous means multiple identical cores having the same core diameter and same effective area for all cores. But in the case of multicore fiber, crosstalk reduces with an increase in the core to core distance and but the large effective area is required and core density also reduces. So to improve the core density with less crosstalk, a denser core arrangement is required that is known as a trench. A TA-MCF also provides low macro and micro bending losses with less inter core crosstalk. But in TA-MCF coupling is required which can easily couple the data from single cores to multiple cores.

This coupling is provided by two tapered multicore connector which is connected with TA-MCF at the input and output end. It provides well organised coupling as shown in Fig. 5.1 (a) and its internal structural view is shown in Fig. 5.1 (b). While connecting two TMCs, there are some insertion losses that vary from 0.5 dB to 2.8 dB. But these losses are acceptable because the achieved inter-core crosstalk is in an acceptable range and also less than -44dB [99]. The Optimized parameters of uncoupled TA-MCF are shown in Table 5.1.

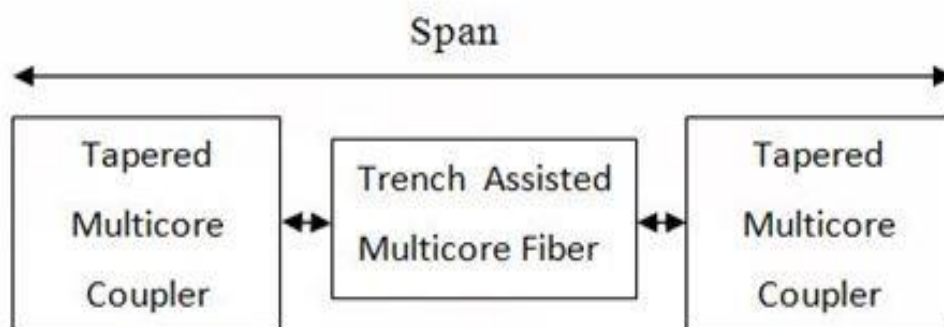


Fig.5.1 Coupling of TA-MCF with TMC

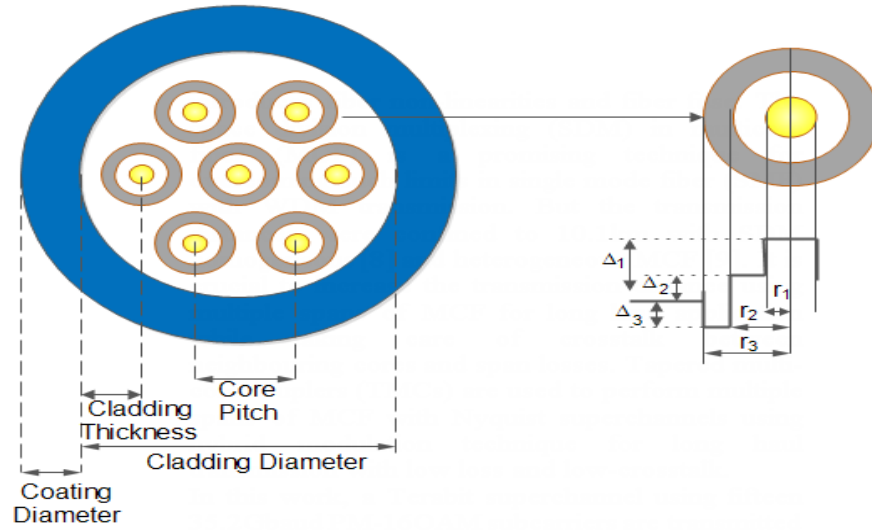


Fig. 5.1 (b) Internal structural view of uncoupled TA-MCF

TA-MCF offers a possible solution to increase the fiber density and overcome the cable size limitation and duct congestion problems. Design and fabrications of several types of MCF have been reported to address the need for high density while maintaining low loss and low crosstalk [83]. The published design of TA-MCF as a reference no. [83] [123] is considered, where the fabrication of TA-MCF for long distance communication is possible. According to the proposed design, the parameters of TA-MCF has been optimized as mentioned in Table 5.1 and these values are set to minimize the inter core crosstalk.

Table 5.1 Optimized parameters of uncoupled TA-MCF

Name of parameter	Value
Core to core distance [μm]	45
Center Radius/Trench Core Radius [μm]	5.13/16
Cladding/Coating diameter [μm]	181/302
Refractive Index of Core/Cladding	1.4557/1.4378
Mode Field Diameter [μm]	12.1
Affective Area [μm^2]	112
Attenuation at 1550 nm/1625nm [dB/km]	0.19/0.21

Average Crosstalk at 1550nm (from all neighbouring Cores) [dB] /76.8km fiber Length	-42
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5.3 System Set-up

The System design of Nyquist superchannels with TA-MCF for SDM transmission schematic is shown in Fig. 5.2. It comprises of five optical Nyquist superchannels system with optimum channel spacing and it is transmitted over homogenous TA-MCF that is further coupled with TMC and recovered back by a coherent receiver. In this design, channel spacing is reduced at 25 GHz (after coding) from 32.5 GHz (before coding) with five Nyquist superchannels each at 4.224 Tb/s transmission rate and it also covers the transmission distance of 2688 km with the help of trench-assisted multicore fiber (TA-MCF) at altered seven spans. In each Nyquist superchannel, total of 15 subcarriers are transmitted each at a 35.2 Gbaud symbol rate with PM-16QAM hybrid modulation technique without any pre-distortions. After utilizing the channel spacing, the five Nyquist superchannels are amplified by erbium-doped fiber amplifiers (EDFAs) then transferred on uncoupled TA-MCF having 76.8 km length [100] which is further coupled with TMC. The TMCs provides efficient coupling at the input and output end and also couples the signal received from WDM transmission into SDM transmission. So, five optical Nyquist superchannels can easily travel into the seven cores of uncoupled TA-MCF at first span and then spatially transferred to different cores at each next span. In this design core to core rotation (CCR) scheme helps the signals to spatially rotate in different cores after each span, so the losses can be reduced due to TA-MCF for long distance communication.

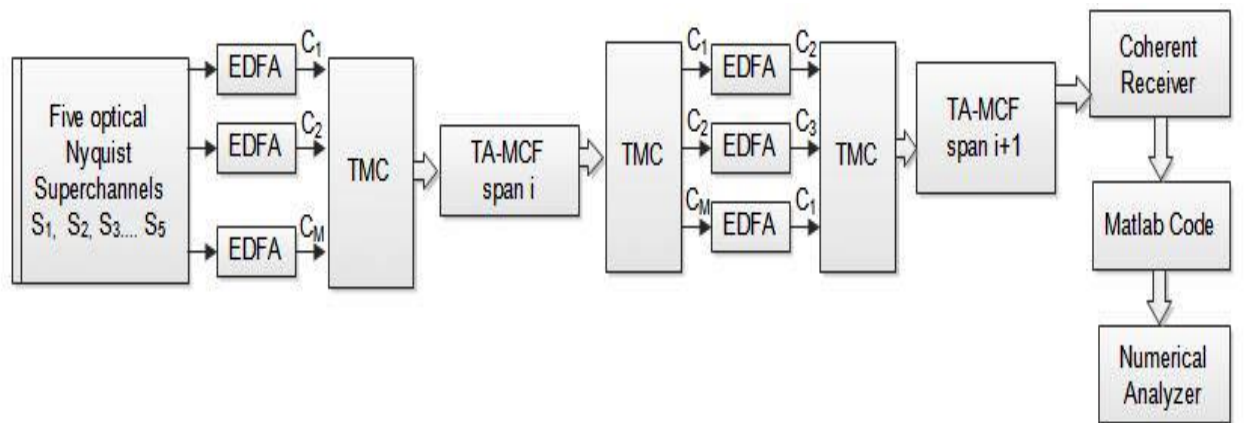


Fig. 5.2 System design of Nyquist superchannels with TA-MCF for SDM transmission [125]

In CCR scheme, Inline erbium-doped fiber amplifiers are used to offer the multiple numbers of symbol de-correlations for each core at the point of signal insertion and then rotation is performed.

At the time of the initial span ($i=1$), the five optical Nyquist superchannels are transferred to the first five cores of uncoupled TA-MCF and at the time of second span ($i=2$), the superchannels are transferred to alternate cores of TA-MCF to reduce inter-core crosstalk. This procedure repeats seven times and at each time channels are transferred to different cores of TA-MCF for each span. This procedure not only minimizes the inter core crosstalk but also decreases the differences of span losses between each core of TA-MCF because at each loop superchannels are transmitted through different cores. The five Nyquist superchannels are received back by a coherent receiver [101]. In the coherent receiver if the output of transfer functions is a rectangular pulse only then it will validate the Nyquist criterion. The internal design of the optical Nyquist Superchannel is shown in Fig. 5.3.

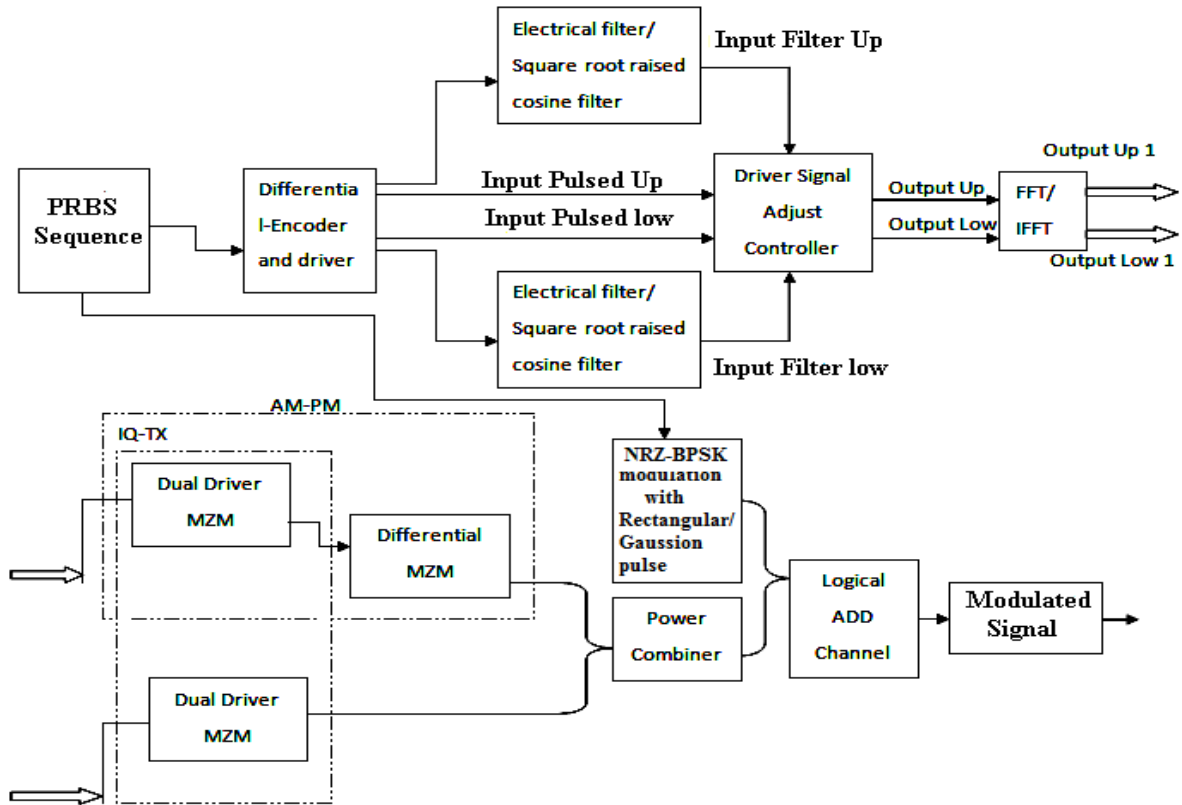


Fig. 5.3 Internal design of optical Nyquist Superchannel

The optical Nyquist superchannel design consists of Pseudo Random Bit Sequence (PRBS), Differential encoder driver, electrical filtering block, Square Root Raised Cosine (RRC) filtering block, driver signal adjust controller, FFT, IFFT, dual driver with differential Mach Zehnder Modulator (D-MZM), power combiner, logical add and combine channel with line

coding (NRZ), modulation, optical In-line amplifier, and fiber loop. The hybrid modulation design is used for optimizing the channel spacing between the optical Nyquist superchannels using line coding and Root Raised Cosine (RRC) filtering.

While optimizing the channel spacing, the intersymbol interferences and band pre-distortions are increases. To remove these pre-distortions (ISI), the scaling coefficient and the driving signal amplitude are adjusted using driving signal adjust controller algorithm. Then finally, FFT correlate with IFFT to reduce the delay generated by external filters.

5.4 Mathematical Analysis

This chapter describes the internal working of the optical Nyquist superchannel system set up with the help of mathematical analysis. With the help of 16QAM modulation, the transmitted data stream is changed into PM-16QAM, in this one superchannel contains fifteen subcarriers. The value of channel spacing between each subcarrier is set to be 35.2Gbaud which is 1.1 times the baud rate. In the PM-16QAM modulation format, the transmitted data utilizes two bits to generate four complex value symbols. As shown in Fig. 5.3, the pseudo-random bit sequence is transferred to a differential encoder and driver block, where encoding is done differently for even (Q- phase) and odd (I-phase) signals.

In-phase and Quadrature-phase symbols (IQ) are represented as [99]:

$$IQ^{z-QAM} = \frac{\sum_{l=1}^{z/2} 2^{(y-l)/2} \left(2^{\frac{I(z-1)y}{z+l}-1} \right) + i \sum_{l=1}^{y/2} 2^{(y-l)/2} \left(2^{\frac{Q(z-1)y}{z+l}-1} \right)}{2^{m/2-1}} \quad (5.1)$$

Where y represents the number of bits per symbol and z is the number of bits ($y=2^z$).

The subcarriers in a Nyquist superchannel are separated by even and odd parts. The Optical Nyquist superchannel reduces the one half of bandwidth in transmission by splitting the signals into even and odd subcarriers. The coder and driver block transmits the four driving signals for PM-16QAM modulation which is symbolized as *Upper/Lower Pulse_{output}* and *Input Filter Up/low*. It helps the dual driver MZM and AM-PM to reduce ISI. If the initial received output from the driver is a rectangular pulse then electrical filtering is used in the frequency domain. In the electrical filtering, a low pass filter with Bessel transfer function is used that is described as [23]:

$$Z(s) = \frac{a_0}{\sum_{i=1}^m a_i s^i}, \text{ Where } a_i = \frac{(2m-1)!}{2^{m-k} K!(m-k)!} \quad (5.2)$$

In eq. (5.2), m represents the order of Bessel filter.

If the received output from the driver is not a rectangular pulse then square Root Raised Cosine filtering is used in the frequency domain which verifies the Nyquist criterion. The Raised Cosine filter routes the In-phase and Quadrature-phase symbols as represented in eq. (5.1) from the driver module with a Bessel filter transfer function. The transfer function of a Raised Cosine (RC) filter is represented as [24]:

$$Z(f) = \begin{cases} 1 & 0 \leq |f| \leq \frac{1-\beta}{2T} \\ 0.5 \left\{ 1 - \sin \left[\frac{\pi T}{\mu} \left(|f| - \frac{1-\mu}{2T} \right) \right] \right\} & \frac{1-\beta}{2T} \leq |f| \leq \frac{1+\beta}{2T} \\ 0 & otherwise \end{cases} \quad (5.3)$$

In eq. (3.3), μ represents the roll-off factor that is used to calculate the requirement of excess bandwidth in the filter. Further, to reduce this excess bandwidth, a square root raised cosine filtering is used by optimizing the channel spacing. The transfer function of square root raised cosine (RRC) filtering is evaluated by taking the square root of eq. (5.3). After RRC filtering, the four driving signals are being acknowledged at the driver signal adjust controller module. The scaling coefficient is used to adjust the amplitude of driving signals. The technique is explained below which helps to improve the scaling coefficient.

Out of four driving signals, two of them are of rectangular shape pulse named as *Upper Pulse_{output}* and *Lower Pulse_{output}* and remaining two signals are the output of square root raised cosine filter named as *Input Filter Up* and *Input Filter low*. The maximum value for rectangular pulse output for upper part and lower part is labelled as [24]:

$$\begin{aligned} maximum_{up} &= dx (Upper Pulse_{output}) \times \left(\frac{\Omega}{V_{\Omega}} \right) \\ maximum_{Lo} &= dx (Lower Pulse_{output}) \times \left(\frac{\Omega}{V_{\Omega}} \right) \end{aligned} \quad (5.4)$$

In eq. (5.4), V_{Ω} represents the input voltage to adjust the output power of Mach-Zehnder modulator from one maximum point to another.

The scaling coefficient for the square root raised cosine (SRRC) filter for its upper and lower part is labelled as [49]:

$$L_{up} = \frac{Input Filter Up}{Max_{up}} ; L_{lo} = \frac{Input Filter low}{Max_{Lo}} \quad (5.5)$$

The supreme value of the scaling coefficient L is labelled as:

$$L = dx (L_{up}, L_{lo}) \quad (5.6)$$

After evaluating the scaling coefficient, scaling is achieved for the upper/lower value of RRC filter output and labelled as [49]:

$$Lower_{Output} = \frac{Lower_{Output}}{L}; Upper_{Output} = \frac{Upper_{Output}}{L} \quad (5.7)$$

$Upper_{Output}$ is distributed by scaling coefficient to minimize the bandwidth of each optical Nyquist superchannel without any distortions. To achieve fast computations, the output of eq. (5.7) drives the FFT/IFFT module and their output is symbolized by Output up/Low1. After the FFT/IFFT module, the predistortions (ISI) are checked in the pair of dual driver MZM block and AM-PM block as shown in Fig. 5.3. The predistortions are verified using the equations [96]. The pre-distortion algorithm is used to remove non-linear ISI distortions that are produced due to MZM and AM-PM. The pre-distortions (Z) are pronounced as [47]:

$$Z = \begin{cases} 1 & \text{then, } Upper_{Output} = 1 \text{ for } Upper_{Output} > 1 \text{ and } \neq 0 \\ & -1 \text{ for } Upper_{Output} < 1 \text{ and } \neq 0 \\ Lower_{Output} & = 1 \text{ for } Lower_{Output} > 1 \text{ and } \neq 0 \\ & -1 \text{ for } Lower_{Output} < 1 \text{ and } \neq 0 \end{cases} \quad (5.8)$$

If predistortions does not arise then

$$Lower_{Output} = Lower_{Output} \times linear\ gain \times \frac{V_{\Omega}}{\Omega}$$

$$Upper_{Output} = Upper_{Output} \times linear\ gain \times \frac{V_{\Omega}}{\Omega} \quad (5.9)$$

In eq. (5.9) $linear\ gain = 10^{gain \times 20}$. After reducing the ISI, the delay can be evaluated and reduced by FFT correlation with IFFT which is produced due to external filter. After removing the pre-distortions, delay (arise due to external filtering) has to be compensated by cross correlating the signals that are $Upper_{Output}$ and $Lower_{Output}$ and its representation are expressed as [48]:

$$\tau_{delay,low} = ifft \left(fft(Lower_{Output}) .* fft(Lower\ pulse_{Output}) \right)$$

$$\tau_{delay,up} = ifft \left(fft(Upper_{Output}) .* fft(Upper\ pulse_{Output}) \right) \quad (5.10)$$

In eq. (5.10), FFT (Fast Fourier Transform) is used internally by the driver signal adjust controller module to convert the signals in block representation from the time domain to frequency domain. FFT is performed on the signals received from the code modulator and used to compensate the delay by cross correlating the signals. In cross correlation, its

maximum value represents that time where the signals are allied together and is represented by maximum value of argument, which is expressed as [48]:

$$\begin{aligned} Upper_{delay} &= abs[argmax_{\tau}(Upper_{output} \times Upper\ pulse_{output})] \\ Lower_{delay} &= abs[argmax_{\tau}(Lower_{output} \times Lower\ pulse_{output})] \end{aligned} \quad (5.11)$$

After the eq. (5.11), in the power combiner, power of allied signals is combined. At this stage, fifteen subcarriers are transmitted in one superchannel with the help of reduced channel spacing (4 GHz). In this design, the logical add channel module is inserted to add the NRZ line coding with BPSK modulation and also need to add Gaussian and rectangular pulse to align the signals optically. The BPSK modulation is used to reduce the ISI at the edge of sidebands of subcarriers.

After optimizing the channel spacing with the help of the above algorithm, the five optical Nyquist superchannels are transferred to uncoupled TA-MCF which is coupled with a TMC connector using the core to core rotation (CCR) scheme and received back at coherent receiver after seven spans. The average mean value of inter-core crosstalk in homogenous uncoupled TA-MCF is calculated by [103]

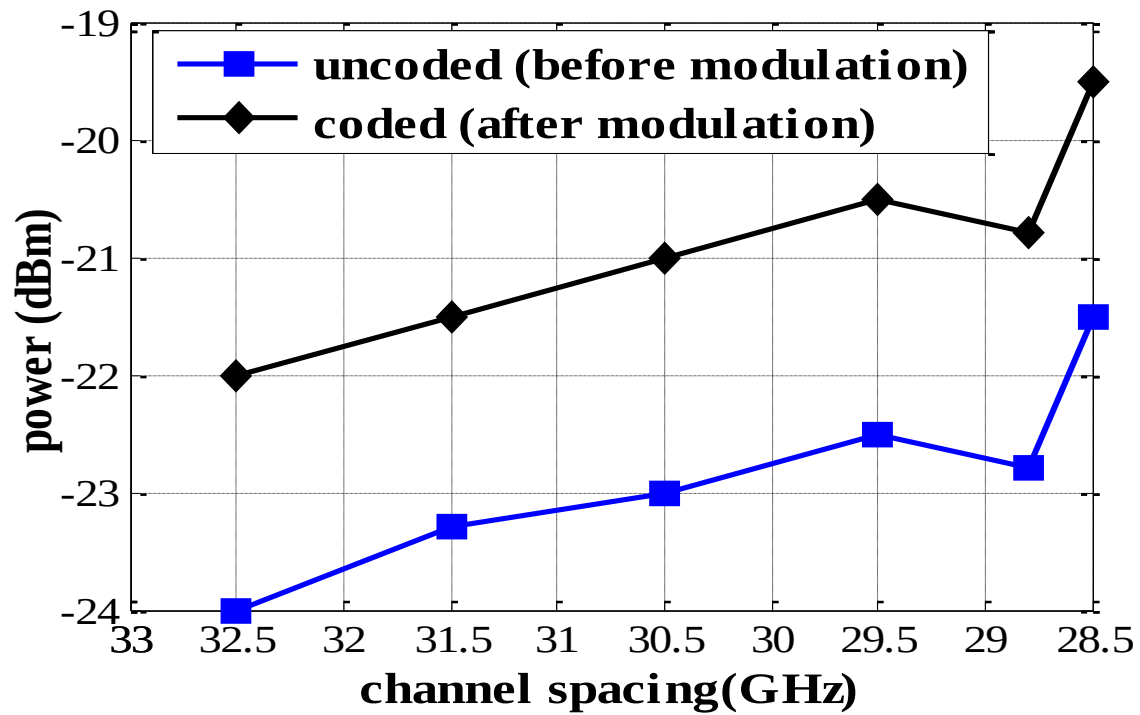
$$XT_{\mu} = \frac{2z^2rl}{\beta\Lambda} \quad (5.12)$$

In the eq. (5.12), z represents the coupling coefficient between surrounding cores and center core of TA-MCF and Λ represents the core to core distance, β represents the propagation constant of each core in TA-MCF, the bending radius and the transmission length is represented by r and l respectively.

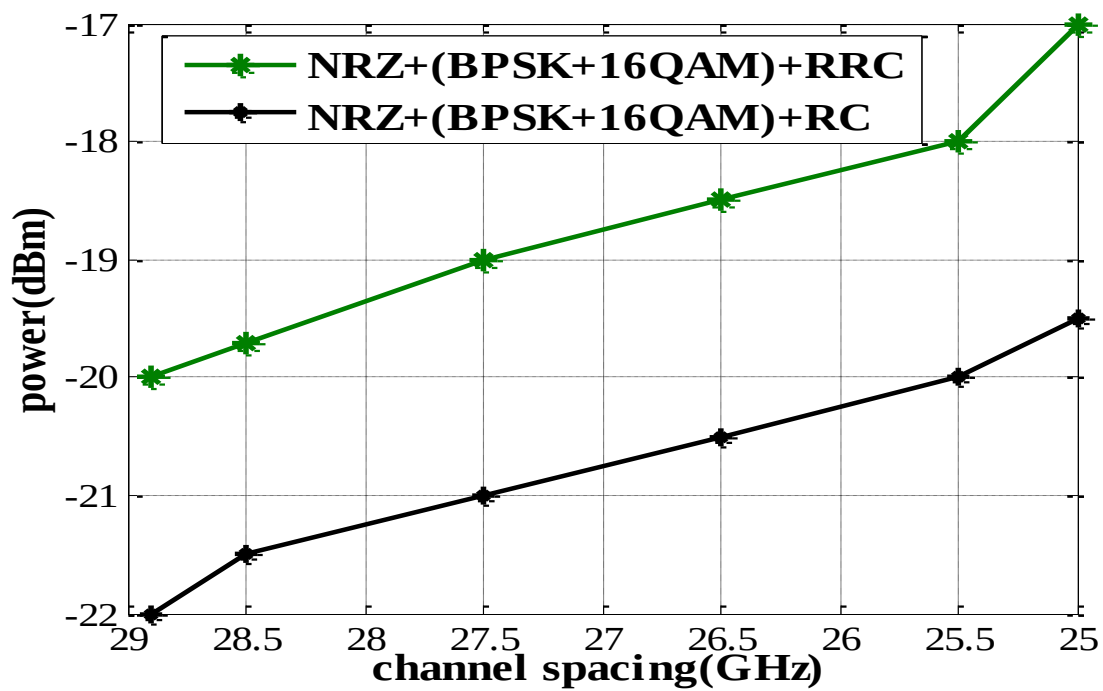
5.5 Simulation Results

The simulation results of designed Nyquist superchannel with optimum channel spacing is shown in Fig. 5.4 with respect to power using VPI transmission maker software version 9.7 [125]. Fig. 5.4(a) shows the deviation of achieved received power after decreasing the channel spacing between subcarriers for each Nyquist superchannel from 32.5 GHz before coding to 28.5 GHz after coding which is done by the above mathematical calculations in chapter 3 for SSMF or as shown in Fig. 3.4(a). Fig. 5.4(b) shows the deviation of achieved received power after further decreasing the channel spacing between subcarriers from 28.5 GHz to 25 GHz with the help of TA-MCF. It is analysed that hybrid modulation with RRC filtering is less profound to ISI. It is also shown that the channel spacing between subcarriers

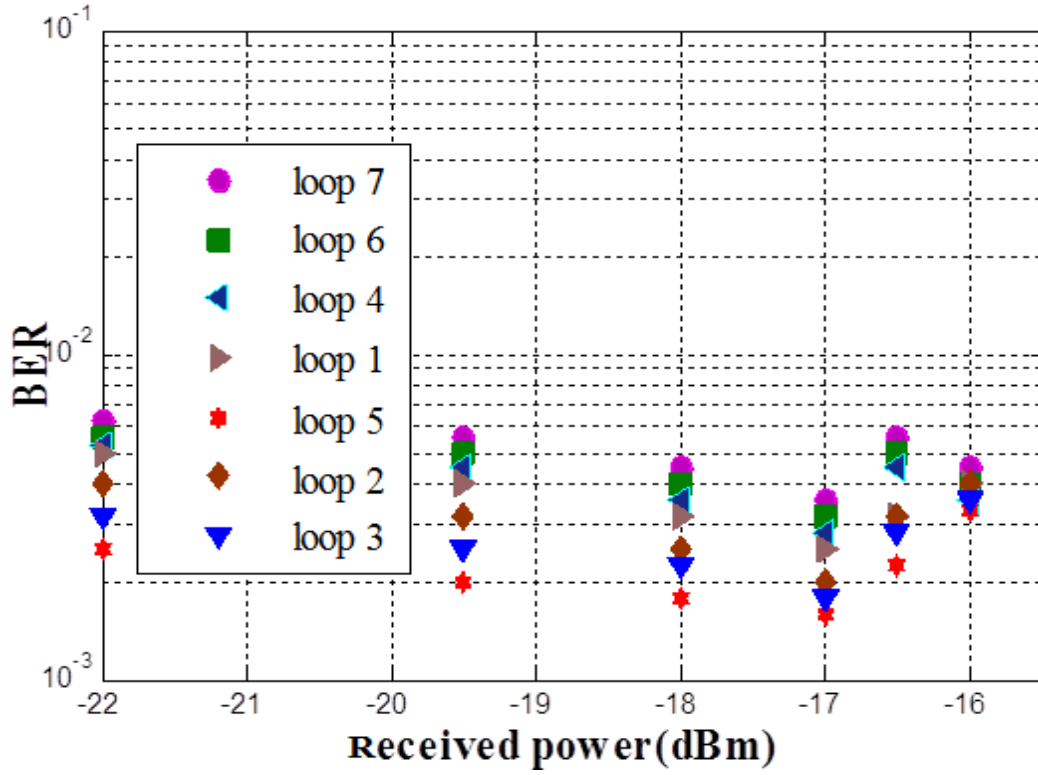
is optimized to 25 GHz with acceptable received power of -17 dBm using the proposed system design. The reduced channel spacing is utilized to transmit fifteen subcarriers through one superchannel.



(a)



(b)



(c)

Fig. 5.4 Nyquist superchannels with optimum channel spacing between subcarriers as a function of power (a) or Fig. 3.4(a) for coded (with modulation) and uncoded (without modulation) data using SSF (b) For hybrid modulation Nyquist superchannel system with RC and RRC filtering using TA-MCF (c) BER performance w.r.t received power for each core in a TA-MCF, measured after each span at the output

The design of static transmitter is used to provide equal powers to all Nyquist sub-bands and BPSK modulation is used for edge Nyquist sub-bands, which has more capability to reduce the intersymbol interference (ISI) from the edges in side bands for the proposed design system. Fig. 5.4(c) indicates the variation of BER with respect to received power after optimizing the channel spacing between subcarriers at 25 GHz. From the result, it is observed that BER from all the cores in TA-MCF is less than the threshold level of forward error correction (FEC). BER with respect to acceptable power is observed after each loop using core to core rotation scheme. It is analysed that the best received BER is dignified at -17 dBm power. It also shows that from all BER values, the best BER is measured at loop 5. Because in the case of loop 5, all the channels will move from the center core to the outer cores and minimum inter-core crosstalk is observed form outer cores. The maximum inter-core crosstalk is produced when channels are transferred from outer core to center core. There are

very small variations in the result of observed BER for all seven cores that indicate the benefit of the core to core (CCR) rotation scheme at every span which balances the variations of BER from all seven cores.

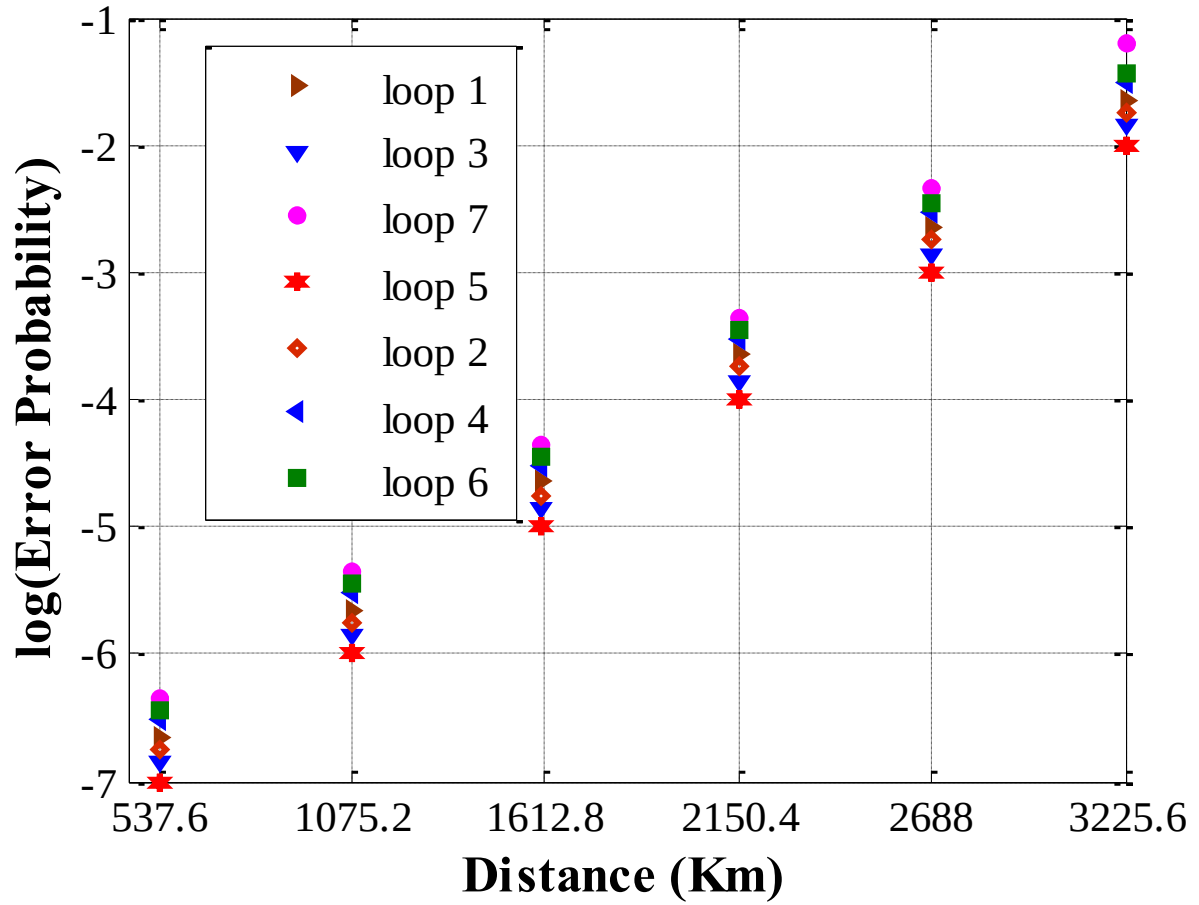


Fig. 5.5 Performances of BER w.r.t distance with the different number of spans for the design of Nyquist superchannels with TA-MCF system

Fig. 5.5 shows the BER performance as a function distance with the different number of fiber spans after transmission of five optical Nyquist superchannels on uncoupled TA-MCF (fiber transmission length=76.8 km). Five optical Nyquist superchannels are transferred through seven loops. It is analysed that the minimum observed acceptable error is at the span number of 35 that covers the 2688 km transmission distance (35×76.8 km) by five optical Nyquist superchannels. This result confirms the SDM transmission of five optical Nyquist superchannels on uncoupled TA-MCF with a benefit of the core to core rotation (CCR) scheme at a transmission distance of 2688 km.

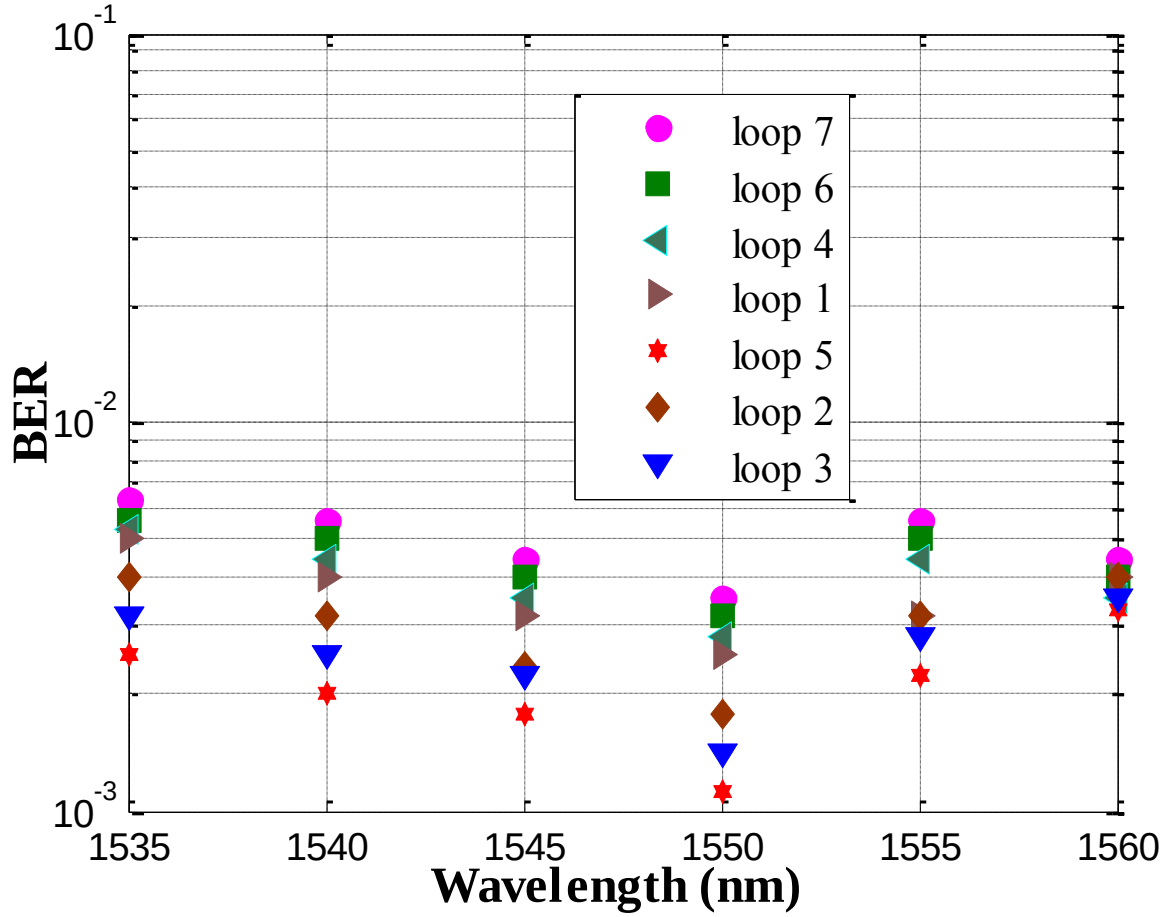


Fig. 5.6 Performance of BER w.r.t the wavelength for all SDM optical Nyquist superchannels after the transmission of 2688 km distance

Fig. 5.6 shows the BER w.r.t the wavelength for all SDM optical Nyquist superchannels after the transmission of 2688 km distance with the transmission data rate of 21.12 Tb/s. It is analysed that the value of best observed BER is 2.9×10^{-3} at a wavelength of 1550 nm that is below the threshold level of FEC. BER is measured after 3R generator instead of 2R generator, because according to the previous research pulse degrades at 2R generator [102]. The acceptable BER variations are less for each span because at each time channels are transferred to differed cores, but an improved BER is observed at span 5 as compared to other spans. Because at the loop 5, channels are transferred from center core to the outer core and acceptable inter-core crosstalk is observed at loop 5 as compared to other loops due to the variations in TMC losses and core losses.

Figure 5.7 shows the inter-core crosstalk variations between neighbouring cores w.r.t output core IDs at the 1550 nm wavelength. The maximum, mean, minimum, and sum of all inter-core crosstalk are analysed from all neighbouring cores.

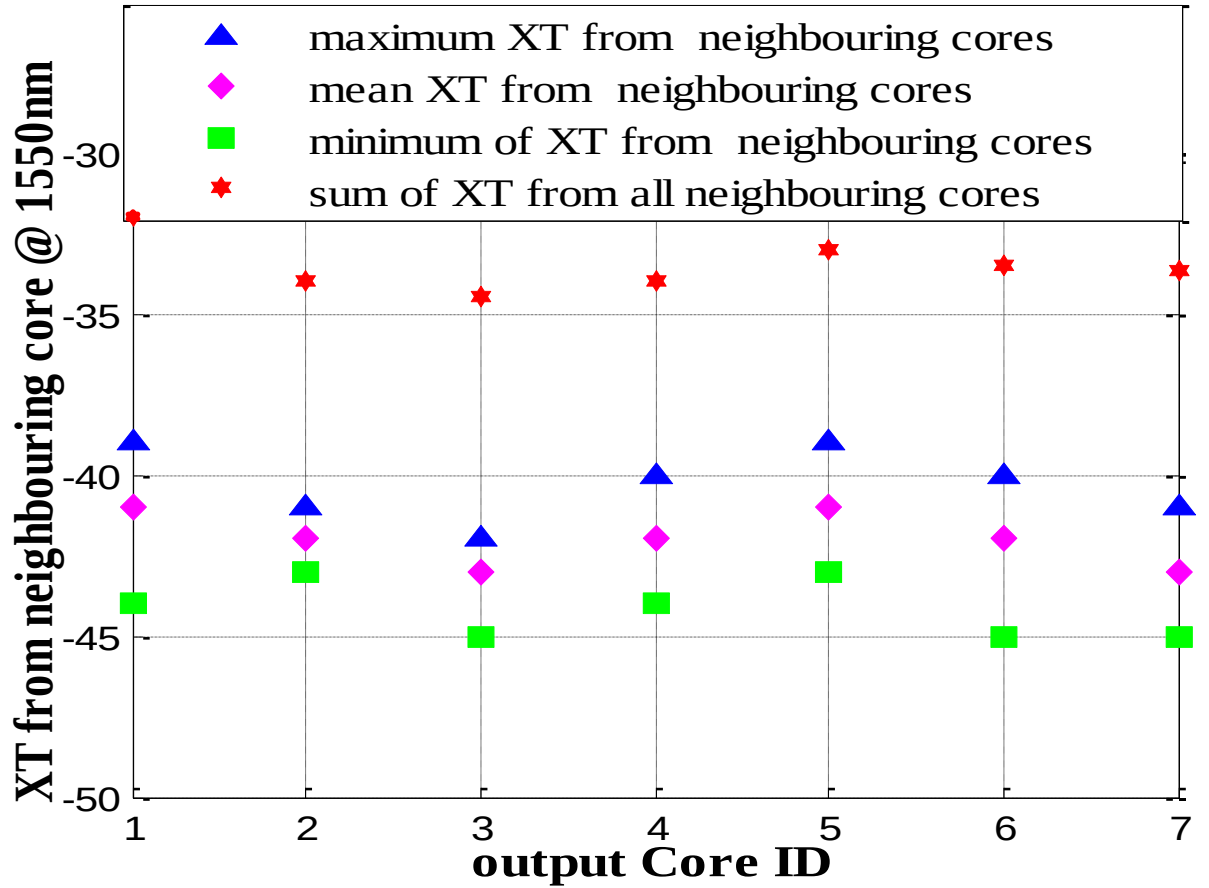


Fig. 5.7 Inter-core crosstalk (XT) between neighbouring cores of uncoupled TA-MCF

It is measured that the range of mean inter-core crosstalk is between -40 dB to -45 dB from all the neighbouring cores. The sum of inter-core crosstalk from all the neighbouring cores is less than -35 dB at the 1550 nm of wavelength. The sum of maximum observed acceptable inter-core crosstalk is -32 dB at the center core (core ID 1) after the transmission of optical Nyquist superchannels at the transmission rate of 21.12 Tb/s at 2688 km transmission distance.

In this chapter, under the thought of simple design and organization, the first need is the transmission of 5×4.224 Tb/s optical Nyquist superchannel with the help of a Hybrid modulation technique (NRZ+BPSK+16QAM+RRC) at optimum channel spacing of 25 GHz between subcarriers. This optimum channel spacing has been utilized to transmit 15 optical subcarriers in one Nyquist superchannel (4.224 Tb/s) with reduced ISI. This has been attained through the system design as shown in fig.5.3 and by mathematical equations described from 5.1 to 5.11. The second target is to transfer these five optical Nyquist superchannels to seven cores of uncoupled TA-MCF fiber with minimum acceptable inter-core crosstalk that covers

the distance of 2688 km. This achievement has been done by the optimized design parameters of seven cores uncoupled TA-MCF mentioned in Table 5.1 beside with the core to core rotation (CCR) scheme. The proposed system has achieved a spectral efficiency (11 b/s/Hz) $\times$ distance (2688 km) product of 29,568 b/s/Hz.km using predistortion algorithm and RRC filtering and TA-MCF with CCR scheme.

5.6 Conclusion

In this chapter, an optical Nyquist superchannel with a hybrid modulation technique is presented to reduce and to utilize the channel spacing. From the measured results, it shows that the channel spacing between subcarriers is reduced from 32.5 GHz to 25 GHz and it has been used to transmit fifteen subcarriers in one Nyquist superchannel with reduced ISI. Five optical Nyquist superchannels, each Nyquist superchannel utilizes the $15 \times$ (35.2 Gbaud) PM-16QAM subcarriers (4.224 Tb/s) that are transferred to seven cores of uncoupled TA-MCF with low inter-core crosstalk and it covers the transmission distance of 2688 km with spectral efficiency of 11 bit/s/Hz. The best system performance is achieved in terms of output power, BER, and sum of maximum acceptable inter-core crosstalk (-32 dB) with the help of proposed system design. Different types of MCF with a different number of cores and modes have been compared in Table 5.2 along with detailed analysis in their references. Table 5.2 summarizes the different design of SM, FM, and MM multicore fiber with a different number of cores. However, FM and MM multicore fiber is used for short distance communication and have a complex structure with MIMO (Multi input-Multi output). Under the consideration of simple design and structure, SM-TA-MCF is designed with achievable 5×4.224 Tb/s data rate at a distance of 2688 km after the utilization of channel spacing. As a result, it is reported that the mean inter-core crosstalk is reduced by using 7 cores TA-MCF in the system.

Table 5.2 Different types of MCF in WDM/SDM transmission systems

Fiber Parameters	Ref. [46]	Ref. [87]	Ref. [85]	Ref. [86]	Ref. [90]	Ref. [88]	Ref. [89]	Proposed work
Core Number	7	19	10	7	7	19	7	7
Mode Type	SM	SM	SM	SM	FM	MM	SM	SM
Cladding Diameter (μm)	150	200	204.4	195	150	318	186.5	181
Core Pitch (μm)	45	35	40.5	49	40	62	46.8	45
Crosstalk/length	-92	-42	-46	-84	-70	-40	-59	-41

@ dB/Km									
Achieved Data Rate (Tb/s)	109	305	Not used	6.28	255	2.05×10^3	112	7.5	10
Distance (Km)	16.8	10.1	3.9	75×14 Loop	1	9.8	76.8	76.8×35 loop	76.8×35 Loop

CHAPTER 6

OPTIMIZED HETEROGENEOUS MULTICORE MULTIMODE FIBER FOR PASSIVE OPTICAL NETWORK

6.1 Introduction

This chapter deals with the fourth objective which is to implement the high speed optical networks in a passive optical network. In this chapter, the optimized design of heterogeneous multicore multimode fiber is used to transmit the signals to multiple ONU's in a passive optical network. Further to reduce the budget loss, a new design of multicore multi-mode fiber is implemented with a passive optical network to eradicate the need for multiple feeder fibers and to implement the results with the help of VPI transmission maker software. Heterogeneous multi-core multi-mode fiber (MC-MMF) is designed for passive optical access networks that efficiently utilize the space division multiplexing (SDM) to reduce the upstream traffic losses and budget losses for optical fiber communication. In heterogeneous MC-MMF, different size of cores with the different number of modes is used. For upstream transmission, an error-free performance is received from 18 modes of heterogeneous MC-MMF in the simulation results. The differential group delay and attenuation per unit length of fiber are also measured at the different number of modes in the design of heterogeneous MC-MMF.

This inspires the researchers towards the optical access networks as heterogeneous fiber provides the largest bandwidth for long distance optical communication [103]. A passive optical network with heterogeneous MC-MM is the best choice for such type of optical access networks. To further enhance the system capacity of a network and spectral efficiency, heterogeneous MC-MMF with space division multiplexing (SDM) is the most favourable technique in optical networks. A space division multiplexing (SDM) is available in two variants that can be used to transfer the information separately over different spatial channels on a single MC-MMF fiber. The first variant is the mode division multiplexing technique with heterogeneous multi-mode fiber [105-106] which transfers the information via different modes. The second variant is multicore fiber with advanced multiplexing [107-109] to transmit the information independently by a separate core with different core multiplexing. By combining these two techniques named MC-MMF, the capacity of fiber is increased and upstream losses are reduced. But in this design, mode coupling [110] is an essential component that provides the coupling from data received from SSMF into MC-MMF. With

the help of mode coupling, splitting losses [111-112] are reduced which helps in further reducing the budget loss.

In this chapter, a heterogeneous MC-MMF is presented which reduces the upstream losses without using multiple feeder fibers and transmits the data over 50km in passive optical access networks. A single heterogeneous MC-MMF can receive the signals from eighteen optical network units (ONUs) in PON with less number of splitters/combiners as compared to SSMF in downstream transmission. An optimized heterogeneous MC-MMF is designed to reduce the upstream losses with minimum acceptable crosstalk.

6.2 System setup

The system setup of PON to reduce upstream losses is shown in Fig. 6.1. It consists of an OLT and number of ONU's. To provide a point to multipoint communication, a multiple single mode fiber is used to transmit the signal from single OLT to multiple ONU's. As shown in Fig. 6.1 (a), in earlier researches standard single mode fiber (SSMF) was used as a feeder fiber which feeds the signal to OLT from different ONUs with the help of single mode combiner. There is a requirement of a large splitting/combining ratio to increase the coverage and a lot of upstream power loss is arisen by optical splitters/combiners which combine and split signals from and to the ONUs at receiver sides respectively. The splitting losses at downlink are unavoidable as it performs many essential functions from OLT to ONUs but upstream losses from ONU to OLT can be reduced by single-mode combiner as shown in Fig. 6.1(a) [105], but it has setbacks in the form of fan out expansion which caused to increase in the total amount of fibers in the network. So, to effectively reduce the number of fibers and upstream combining losses in the proposed design, single MC-MMF is used instead of multiple SSMF as shown in Fig. 6.1(b).

Fig. 6.1(b) shows the proposed MC-MMF in PON which consists of MM coupler, amplifier, combiner, and MC-MMF to reduce the multiple feeder fiber losses. The MM coupler provides the ideal coupling between different modes of MC-MMF. The combiner module combines several single mode optical signals into a multi-mode optical signal and vice-versa. The design of MC-MMF is shown in Fig. 6.1 (c). It consists of 7 cores and 18 modes in which there are three small size cores each having single mode (LP_{01}) and three medium size cores each having 3 modes (LP_{01} , LP_{11a} , and LP_{11b}) and one central core having 6 modes (LP_{01} , LP_{11a} , LP_{11b} , LP_{21a} , LP_{21b} , and LP_{02}). So total numbers of cores are seven and the total numbers of modes are 18 in the design of MC-MMF. The center core (6-modes) having $A_{eff}=71 \mu m^2$ and core dia=11 μm , medium sized core (3-modes) having $A_{eff}=38 \mu m^2$ and

core dia=7 μm and small sized core (1-mode) having $A_{\text{eff}}=28 \mu\text{m}^2$ and core dia=5 μm and cladding dia=181 μm respectively in MC-MMF design. In the design of MC-MMF, the acceptable average crosstalk of medium size core and small size core is -44 dB and -46 dB respectively due to different propagation constant of modes between cores. The large value of effective index difference has been used between non-identical cores to keep the bending losses insensitive and for low crosstalk [107]. At 1550 nm wavelength, differential group delay per unit length(s/m) of fiber is zero at LP_{01} modes, 2 ps at LP_{11} mode, 1.8 ps at LP_{12} mode and 1.6 ps at LP_{02} mode with attenuation per unit length of fiber is 0.2×10^{-3} dB/m at LP_{01} mode, 0.15×10^{-3} dB/m at LP_{11} mode, 0.1×10^{-3} dB/m at LP_{01} and LP_{02} mode respectively.

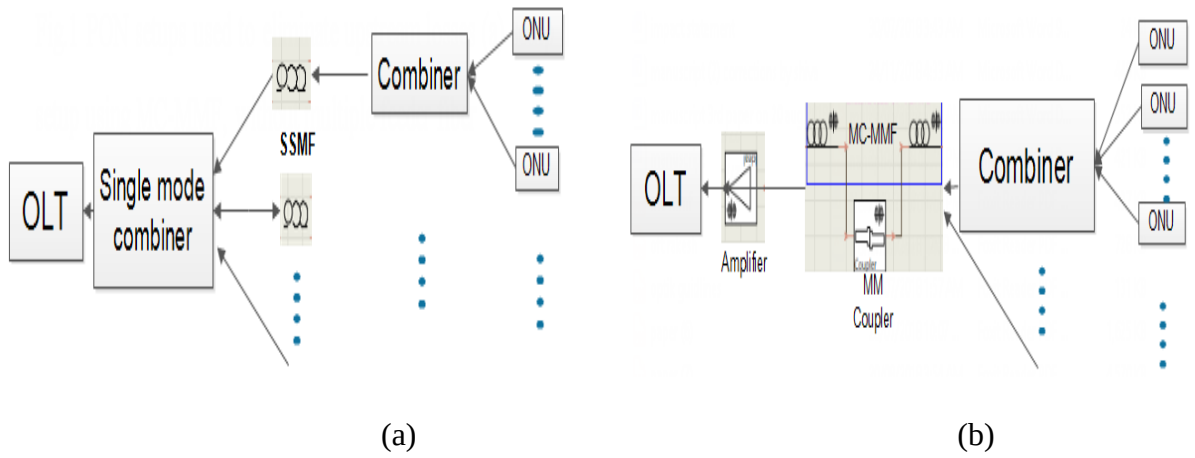


Fig. 6.1 PON setups with low upstream losses (a) setup that requires multiple SSMF (b) setup using MC-MMF, without multiple feeder fibers

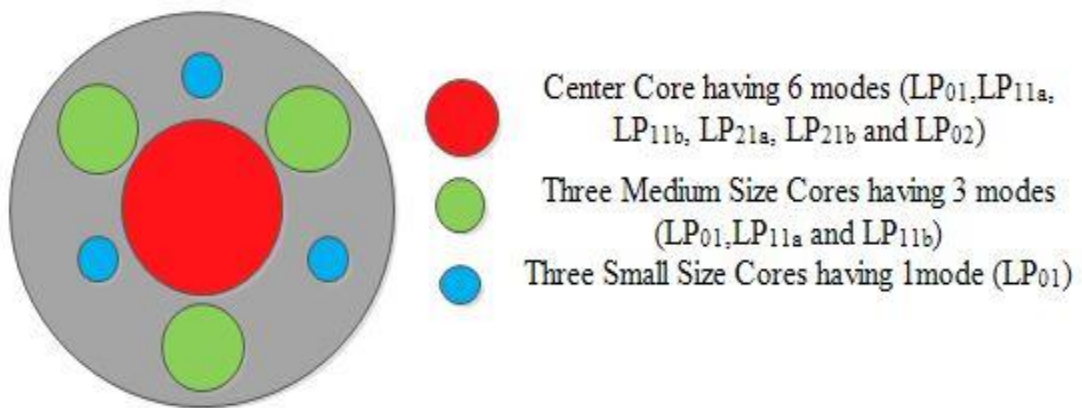


Fig. 6.1 (c) Design of multi-core multi-mode fiber (MC-MMF)

In this chapter, an MC-MMF is substituted as a feeder fiber to eradicate the upstream combining losses and its design is shown in Fig. 6.1(c). It should be noted that the main focus

is not to access the network for long distance communication. Instead, the main focus is to maximize the total information throughput, reduce cost per subscriber, and minimize the budget loss while taking care of low crosstalk in the design of MC-MMF. To reduce the cost and power consumption of the system, Vertical cavity surface emitting lasers (VCSELs)/ photodetectors (PDs) arrays are used at OLT and ONU with MC-MMF in PONs.

6.3 Mode Coupling and Inter-core Crosstalk for MC-MMF

In MC-MMF SDM transmission, it is essential to reduce inter-core crosstalk and to suppress the mode coupling as much as possible between SDM channels. Mode coupling could significantly change the characteristics of the light propagating along with the fiber. From the previous research [113], low mode coupling and its influence have been observed in plastic optical fiber, but it limits the fiber length to a few meters. In advanced research, silica optical fiber has been proposed in which fiber length can enhance to a few 100 m. In the proposed design of MC-MMF, the length of fiber can reach up to 50 km for standard PON at a data rate of 2 Gb/s with acceptable crosstalk and differential group delay. Previously, directional couplers [114], free space phase selective devices [115], and mode group selective photonic lanterns [116] are the methods to excite a certain number of modes. Out of these methods mode group, selective photonic lanterns are the best way to insert a certain number of modes in the passive optical network. In the recent research MTC (mode transfer coupler) is mode selective photonic lantern which converts the single-mode inputs from the standard single-mode fiber into a certain number of modes.

In SDM transmission [117], the coupling between modes (mode coupling) can be suppressed by enlarging the effective refractive index between the modes because phase mismatch between coupled modes becomes larger. For large effective refractive index differences, a high refractive index ratio of core and cladding is required. In the proposed design of MC-MMF, the structure of MC-MMF consists of several kinds of core whose propagation constants are different from each other and it is measured by normalized power [118]. The maximum normalized power transferred between non-identical cores is calculated by power conversion efficiency F [107]

$$F = \frac{1}{1 + \frac{\Delta\beta^2}{(2k)^2}} \quad (6.1)$$

In equation (6.1), $\Delta\beta$ is the propagation constant difference of the fundamental modes between neighbouring cores and k is the coupling coefficient whose value is equal to $2 \times 10^{-3} \text{ m}^{-1}$. F can be decreased by slightly different cores if no bending and twisting.

Further, $\Delta\beta$ is the function of propagation distance and become zero at many positions if the bending radius is smaller than specific threshold value R_{pk} that is given by as below [108]:

$$R_{pk} = \frac{\eta_{eff} D}{\Delta\eta_{eff}} \quad (6.2)$$

In equation (6.2), η_{eff} is the effective index of a core and $\Delta\eta_{eff}$ is the effective index difference between non-identical cores, and D is the core to core distance. Therefore, a large refractive index difference between non-identical cores will be required for pushing the value of R_{pk} towards a sufficiently small range as shown in Figure 6.2.

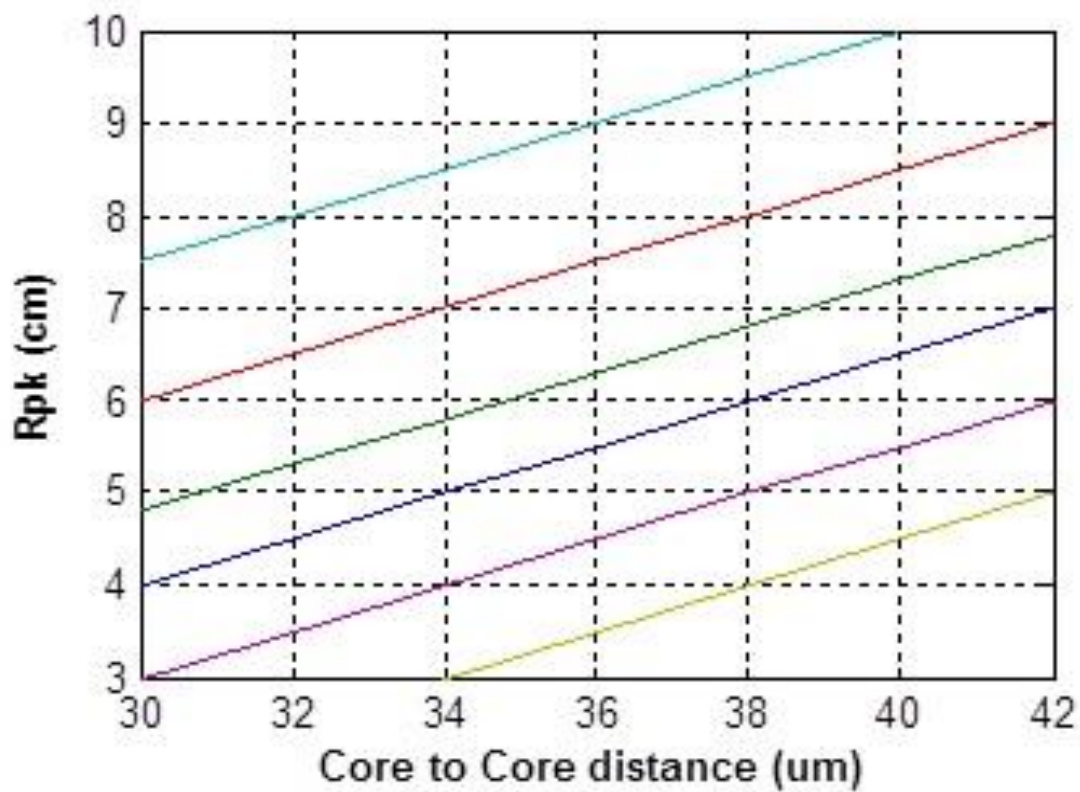


Fig. 6.2 Effective index differences $\Delta\eta_{eff}$ (by solid lines) as a function of R_{pk} and core to core distance D

Fig. 6.2 shows the required effective index difference $\Delta\eta_{eff}$ (by solid lines) as a function of R_{pk} and core to core distance D . It is found that if we try to shift R_{pk} to a bending radius smaller than $38\mu\text{m}$, a $\Delta\eta_{eff}$ value larger than 0.001 would be required between non-identical cores in the design of MC-MMF. So, to suppress the mode coupling and reduce the inter-core crosstalk the following parameters that are mentioned in Table 6.1 are set in the proposed design of MC-MMF. Further, in the proposed design of PON MC-MMF (Fig. 6.4)), a multi-

mode transfer coupler (MMTC) is used inside the combiner block which converts single-mode inputs from standard single-mode fibers (from ONU's) into LP_{01} , LP_{02} , $LP_{11a,b}$, LP_{21} modes of MC-MMF. MMTC couples the three different types of cores with a different refractive index that is mentioned in Table 6.1. With the help of different refractive index differences and different core sizes, we can achieve mode selectivity. To determine the inter-core (core to core) crosstalk, each mode is taken as input.

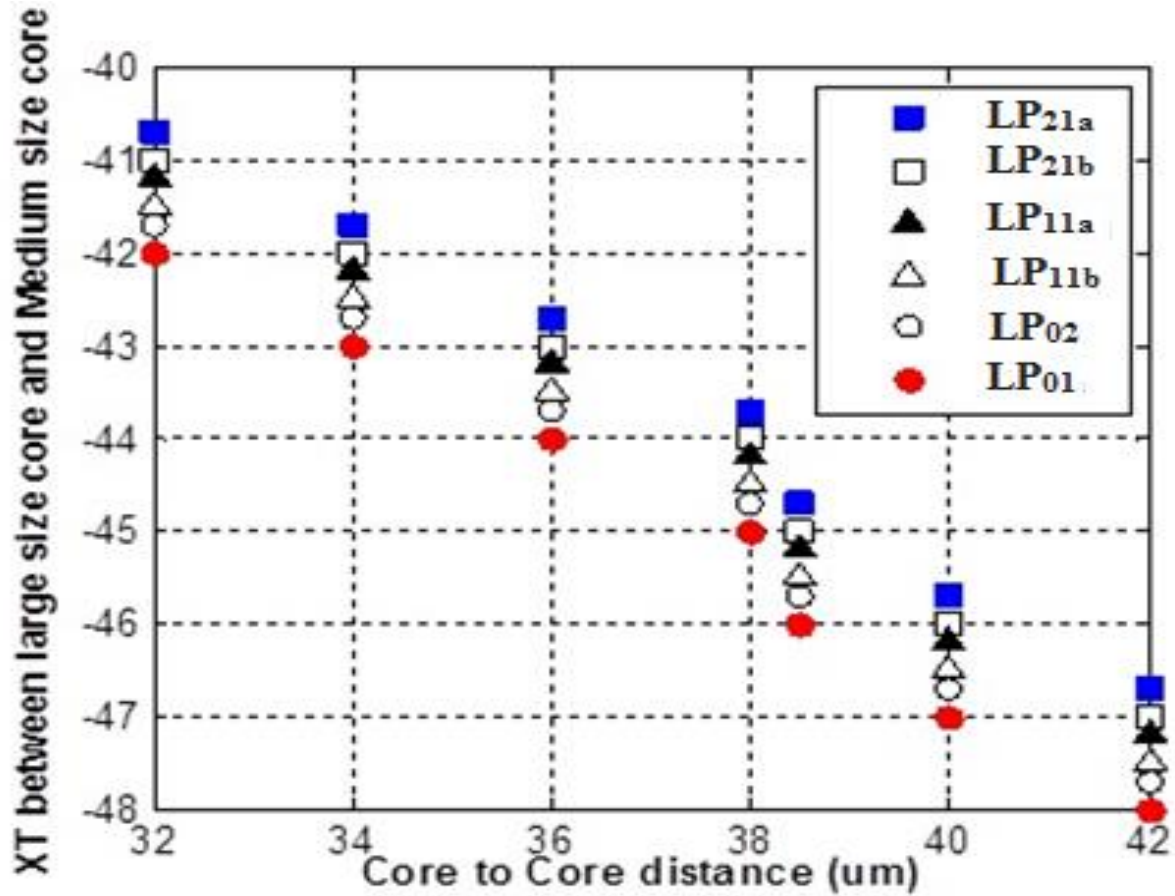


Fig. 6.3 (a) XT between Large and Medium size core with respect to their core pitch

Fig. 6.3 shows the inter-core crosstalk (XT) between different sizes of core with respect to their required core to core distance (core pitch). Fig. 6.3(a) shows the inter-core crosstalk (XT) between large-size core having six modes with core dia 11 μm and medium-size core having 3 modes with core dia 7 μm . From the results, it is observed that to reduce the inter-core crosstalk, the value of the core pitch is set at 42 μm .

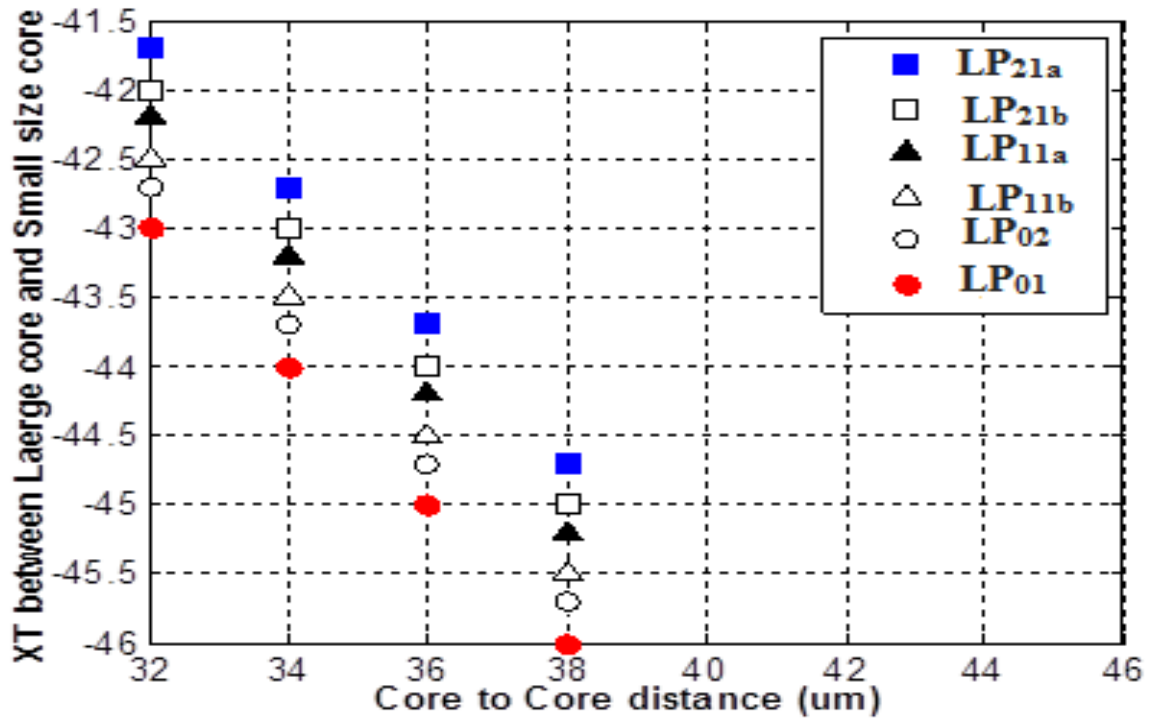


Fig. 6.3(b) XT between Large and Small size core with respect to their core pitch

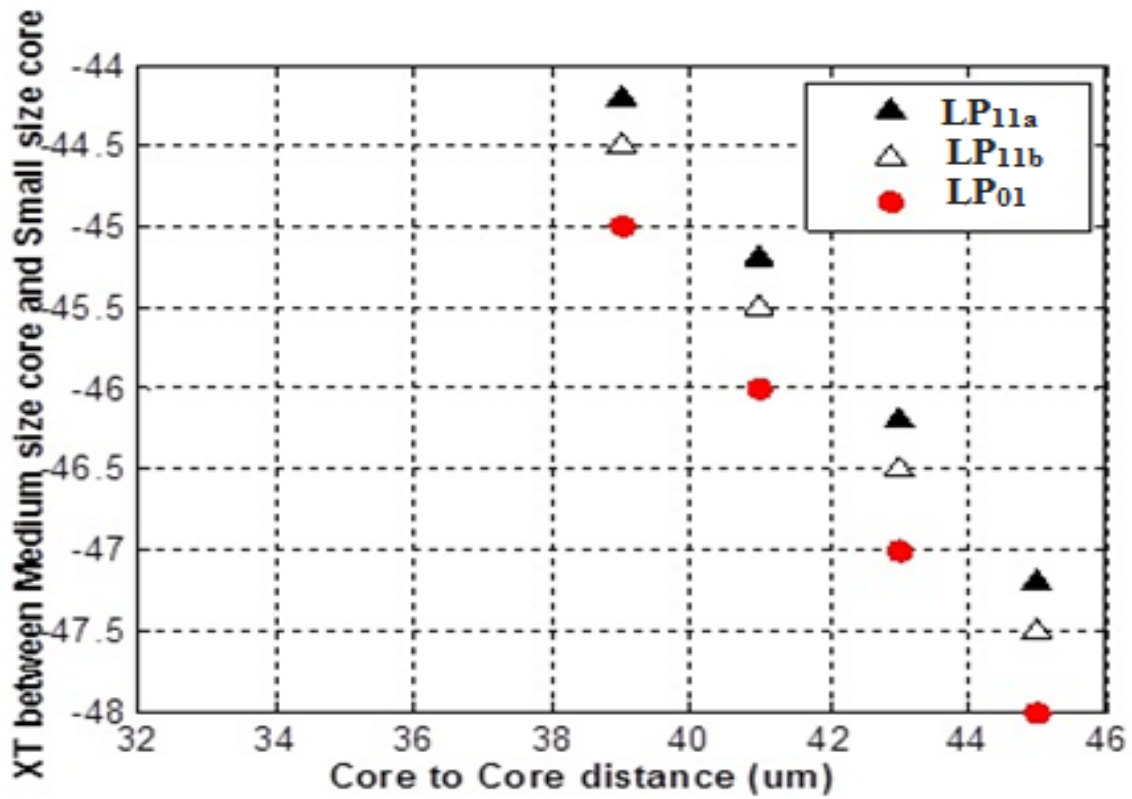


Fig. 6.3(c) XT between Medium and Small size core with respect to their core pitch

As compared to Fig. 6.3(a), there is less inter-core crosstalk due to a lesser number of modes in smaller size core, thus the value of core pitch is reduced from 42 μm to 38 μm in the Fig. 6.3(b). Fig. 6.3(c) shows the inter-core crosstalk (XT) between medium size core having three modes with core dia 7 μm and small size core having single mode with core dia 5 μm . From the results, it is observed that to achieve the acceptable inter-core crosstalk, the required value of the core pitch is to be 45 μm . As compared to Fig. 6.3 (b), to further reduce the inter-core crosstalk (XT) at -48 dB, the value of core pitch required to be increased from 38 μm to 45 μm in Fig. 6.3(c). From the results, it is observed that a smaller distance between cores increases the inter-core crosstalk. The crosstalk from the adjacent cores was required to be smaller than -40 dB with their respective core pitch. The results suggested that core to core crosstalk in the design of MC-MMF is acceptable for SDM transmission. Even though the low crosstalk approach has been demonstrated successfully for MC-MMF transmission, crosstalk suppression for MMTC and MC-MMF is still difficult in general, especially with a large number of modes in different size of the cores. On the other hand, the alternative approach only requires the MC-MMF with low mode differential group delay between modes. As a result, MMTC reduces insertion loss, which is achieved by researchers [119]. Based on previous work [120], trench assisted graded-index is used to reduce the mode propagation delay, and hence it is applied in the proposed work with the cladding trench for low mode differential group delay. With the design parameters that are mentioned in Table 6.1, the acceptable mode differential group delay has been achieved. The material is silica and its refractive index is 1.4585 and the relative refractive indexes of different cores are mentioned in Table 6.1 and the length of fiber is 50 km.

Table 6.1 Optimized optical parameters of MC-MCF

Name of parameter	Value
Core pitch [μm] between Medium size core and Small size core	45
Core pitch [μm] between Large size core and Medium size core	42
Core pitch [μm] between Large size core and Small size core	38

Relative Refractive Index difference Δ_1 between Large size core and cladding	0.8%
Relative Refractive Index difference Δ_2 between Medium size core and cladding	0.41%
Relative Refractive Index difference Δ_3 between Small size core and cladding	0.35%
Cladding/Cladding Trench diameter [μm]	181/302
Refractive Index of Large size Core/Cladding	1.4689/1.4573
MFD* [μm] @1550nm ranged for all cores	9.52 to 9.77
Aeff* [μm^2]	112
Average Crosstalk at 1.55 μm (for all Outside Cores) [dB] /50km fiber Length	-42

The presented results are obtained by using the simulation software named as VPI transmission maker version 9.7. According to the previous research, the affective area has also set for each core for achieving minimum acceptable differential loss [121]. From the simulation results, at 1550 nm wavelength, differential group delay per unit length(s/m) of fiber is zero at LP_{01} modes, 2 ps at LP_{11} mode, 1.8 ps at LP_{12} mode and 1.6 ps at LP_{02} mode are achieved with attenuation per unit length of fiber is 0.2×10^{-3} dB/m at LP_{01} mode, 0.15×10^{-3} dB/m at LP_{11} mode, 0.1×10^{-3} dB/m at other remaining modes respectively. This fiber design can support MC-MMF transmission to reach up to 50 km for standard PON data rate of 2 Gb/s in presence of mode crosstalk.

6.4 Principle of MC-MMF PON

Fig. 6.4 demonstrates the first MC-MMF with PON integrating with SSMF to reduce the upstream combining losses. To form a real PON network, two stages of splitters are designed in the system. In the downstream transmission, SSMF and 3 splitters are used to transmit the signals to ONUs. In upstream transmission, MC-MMF, amplifier, and Combiner module (Splitter/Combiner) is used to transmit the signals from ONU to OLT. The combiner module also provides ideal coupling between mode numbers and corresponding ONU port in which

the signal from the i^{th} ONU port is mapped to the i^{th} mode of MC-MMF as shown in Table 6.2.

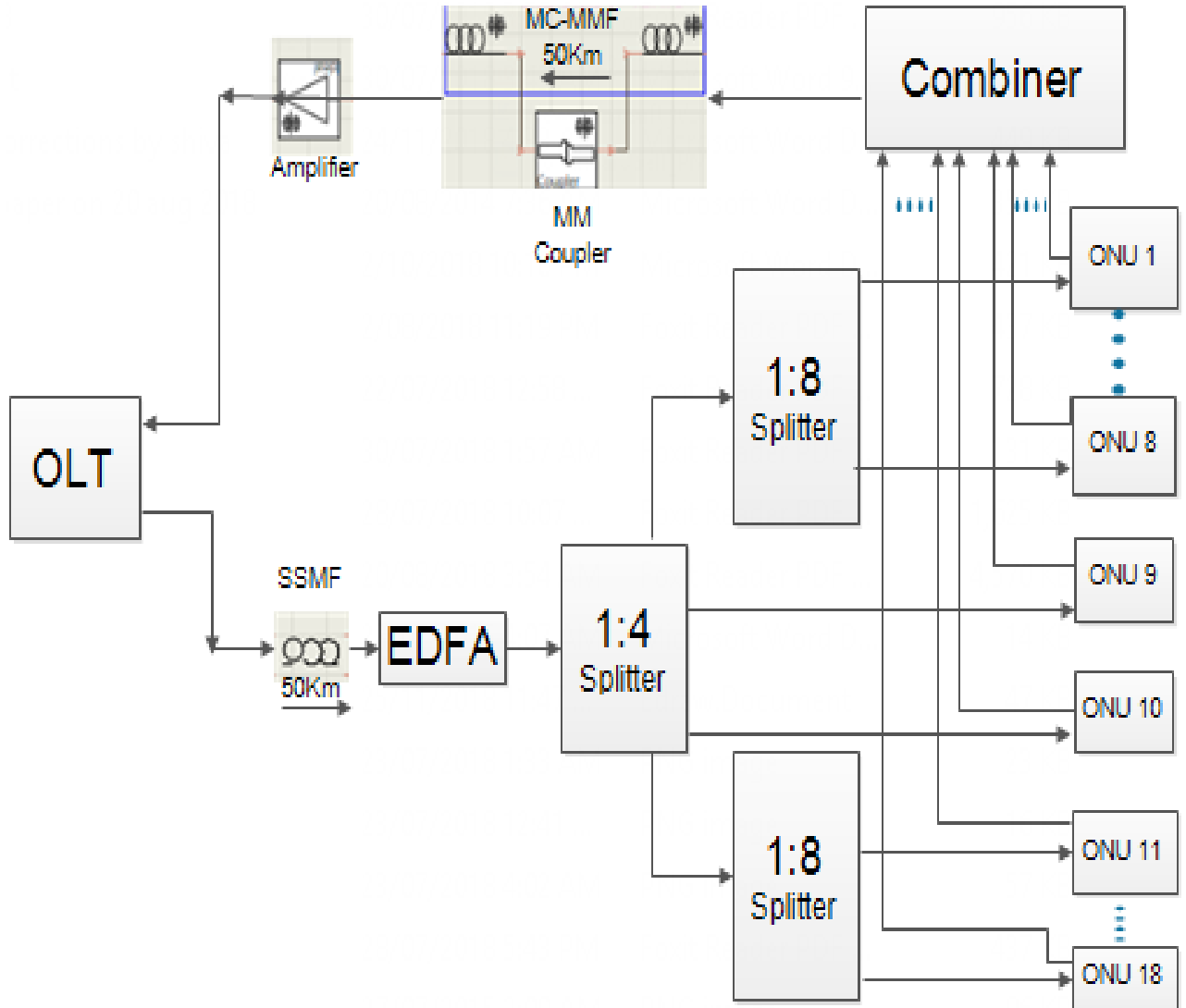


Fig. 6.4 System setup using MC-MMF for upstream transmission and SSMF for downstream transmission [125]

In the downstream transmission, the signals from 1:4 splitters are directly transmitted to ONU9 and ONU10, due to this the high power is consumed as compared to the other ONUs. So, high power of ONUs is used in two ways, Firstly in the upstream transmission, the output of high power ONU's (9 and 10) is connected to the LP_{21b} and LP_{02} modes of the center core through the combiner to reduce the power penalties as compared to LP_{01} modes [112]. Secondly, in downstream transmission, more distance can be kept at ONU 9 and ONU10 as compared to other ONUS to equalize the power of each ONU. If downstream signals are

transported through MC-MMF then we have to use a circulator and few other modifications are also required at the OLT part.

Table 6.2 How the ONU'S are connected to MC-MMF

Core Type	No. of Modes	Connected ONU
Center Core having 6 modes	LP ₀₁	ONU1
	LP _{11a}	ONU2
	LP _{11b}	ONU3
	LP _{21a}	ONU4
	LP _{21b}	ONU9
	LP ₀₂	ONU10
3-Medium Size Core each having 3 modes	LP ₀₁	ONU5 to ONU7
	LP _{11a}	ONU8,ONU11 to ONU15
	LP _{11b}	
3-Small Size core each having single mode	LP ₀₁	ONU16
	LP ₀₁	ONU17
	LP ₀₁	ONU18

In this proposed set up, the main motive is to reduce upstream combining losses by eliminating the need of multiple feeder fibers. So, in this proposed setup, MC-MMF is attached to ONUs for upstream data transmission in the passive optical network. For the uplink, signals from different ONUs are combined into the combiner module and transmitted over 50 km MC-MMF and then they are further amplified by the amplifier with Noise Figure equals to 4 dB for all 18 modes. In this design, One MC-MMF can accept the signals from 18 ONUs and can transfer the signals through its 18 modes. One MC-MMF is used instead of multiple SSMF receiving the signals from different splitters and further transferring them to OLT. The losses for different modes in such special fibers, having multiple cores are calculated by solver fiber measurement multimode block in the VPI transmission maker

software. This block can easily calculate the attenuation loss and differential group delay per unit length(s/m) of fiber for different modes having multiple cores.

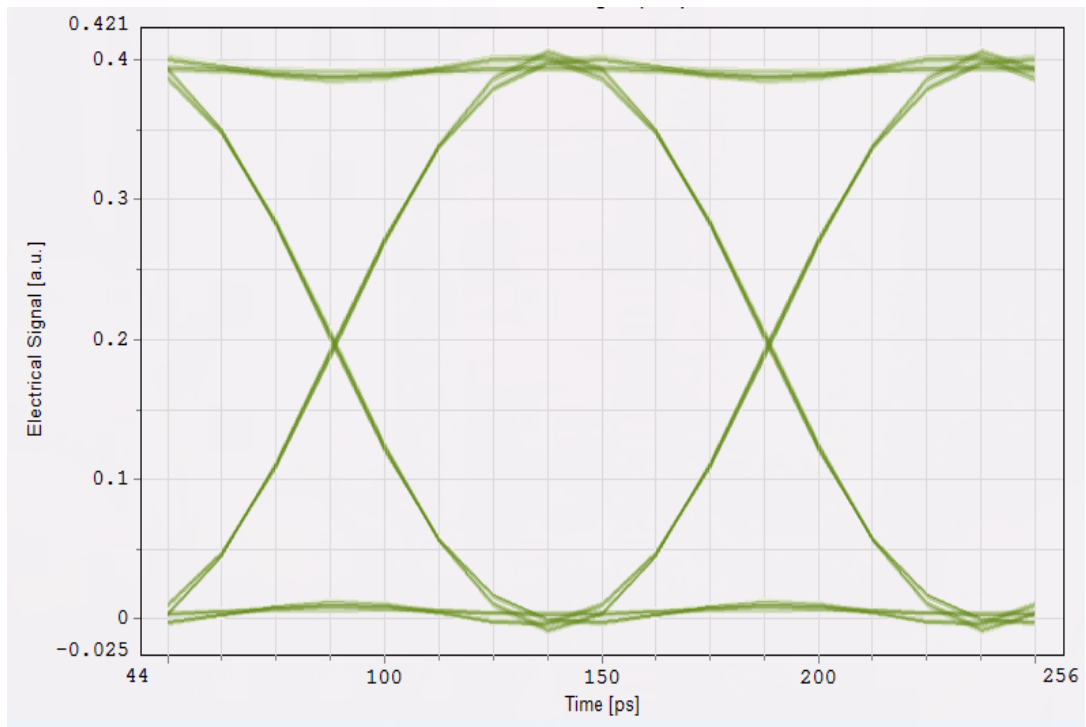
The total link losses for upstream and downstream transmission are described in Table 6.3. In the downstream transmission for SSMF, attenuation is 15 dB after 50km transmission, and for one 1:4 splitter and two 1:8 splitters losses are 6 dB and 18 dB (total=24 dB) respectively. So, total link losses are 39 dB for downstream transmission at 1490 nm wavelength. In upstream transmission at 1550 nm, total average link losses of 6 modes of MC-MMF are 18.5 dB in the center core of MC-MMF. For outer cores, the average of link losses of 12 modes is 20.75 dB. The achieved average acceptable core to core crosstalk between the cores of MC-MMF is less than -44 dB.

Table 6.3 Total Link Losses

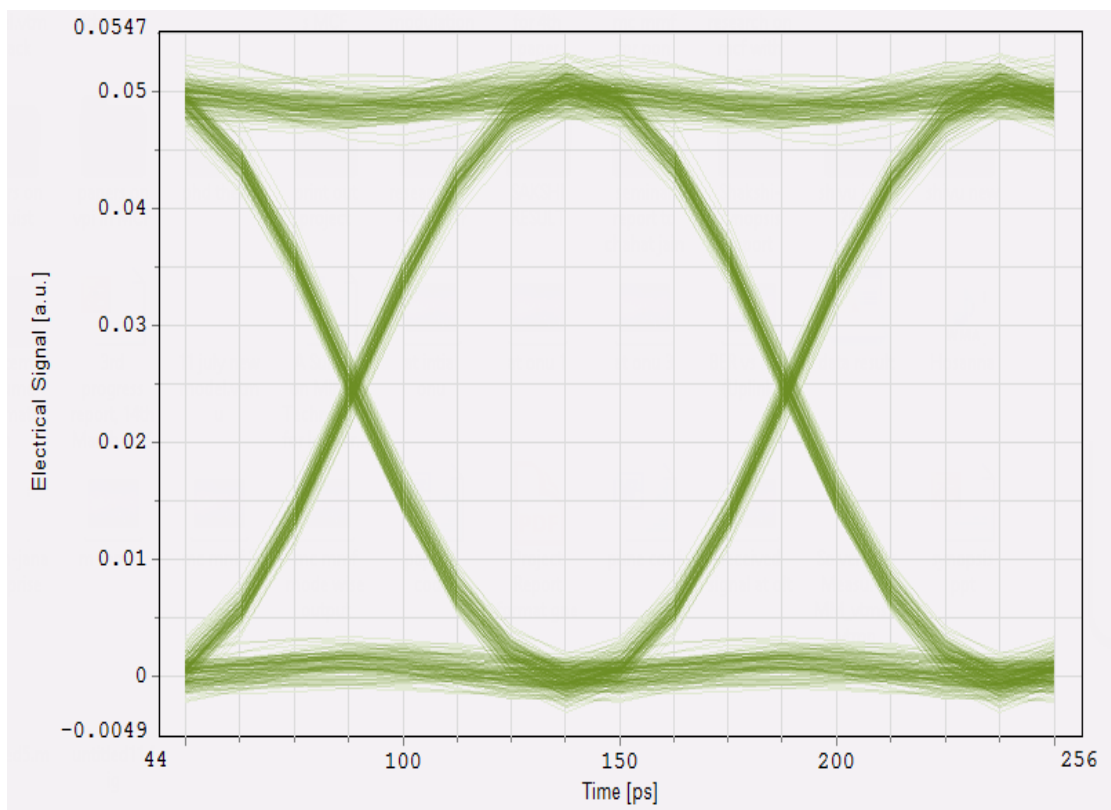
Fiber	Attenuation (dB/km)	Attenuation for (dB) 50km	Splitter/Combiner	Total Link Loss (dB)
SSMF Downstream(1490nm)	0.3	15	24	39
MC-MMF(Center Core- averaged) Upstream (1550nm)	0.13	6.5	12	18.5
MC-MMF (Outer cores- averaged) Upstream(1550nm)	0.175	8.75	12	20.75

6.5 Simulation Results

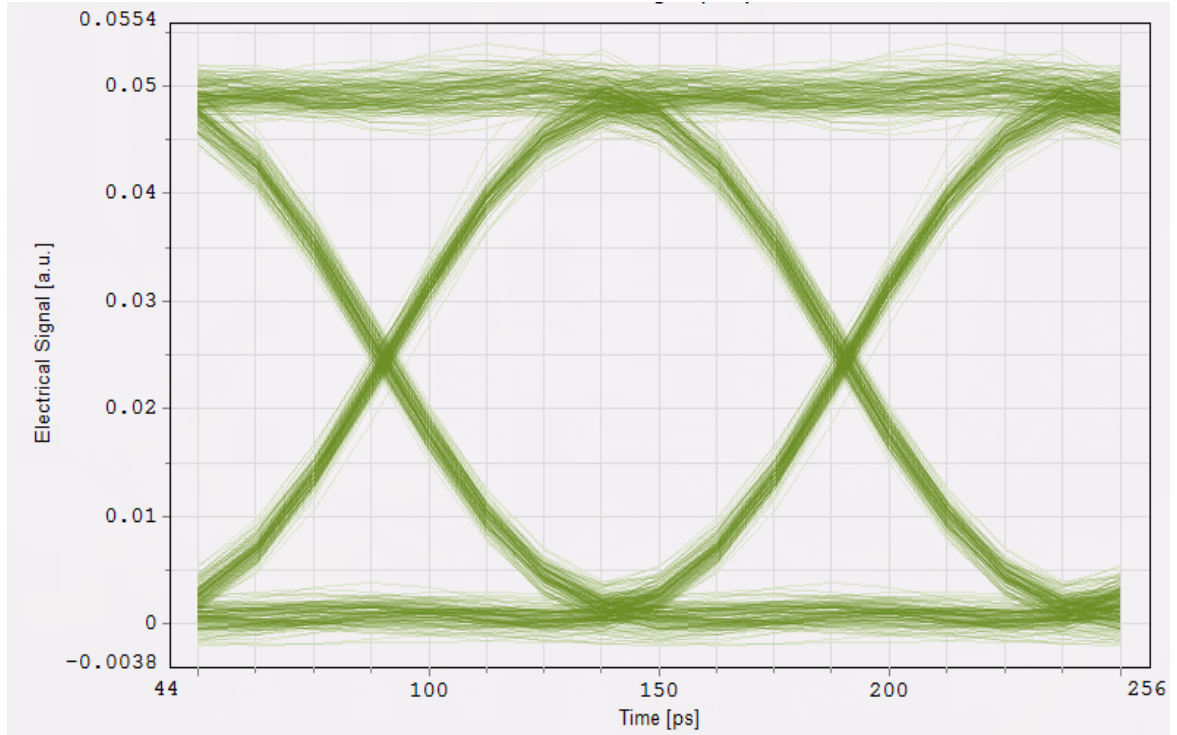
The performance of the proposed system has been evaluated in terms of BER and eye diagrams. Fig. 6.5 shows the upstream transmission performance through 6 different modes of MC-MMF at the center core. The eye diagram for each mode of the center core is shown after 50km transmission. Best results are achieved at LP_{01} mode in the center core of MC-MMF as shown in Fig. 6.5(a). The LP_{11} and LP_{21} have slightly degraded performance as shown in Fig. 6.5(b) and Fig. 6.5 (c). The eye diagram of LP_{11a} and LP_{11b} as well as LP_{21a} and LP_{21b} are almost the same.



(a)



(b)



(c)

Fig. 6.5 Received upstream signals at center (Large size) core of MC-MMF having 6 different modes (a) at LP01 mode (b) at LP11 mode (c) at LP21 mode

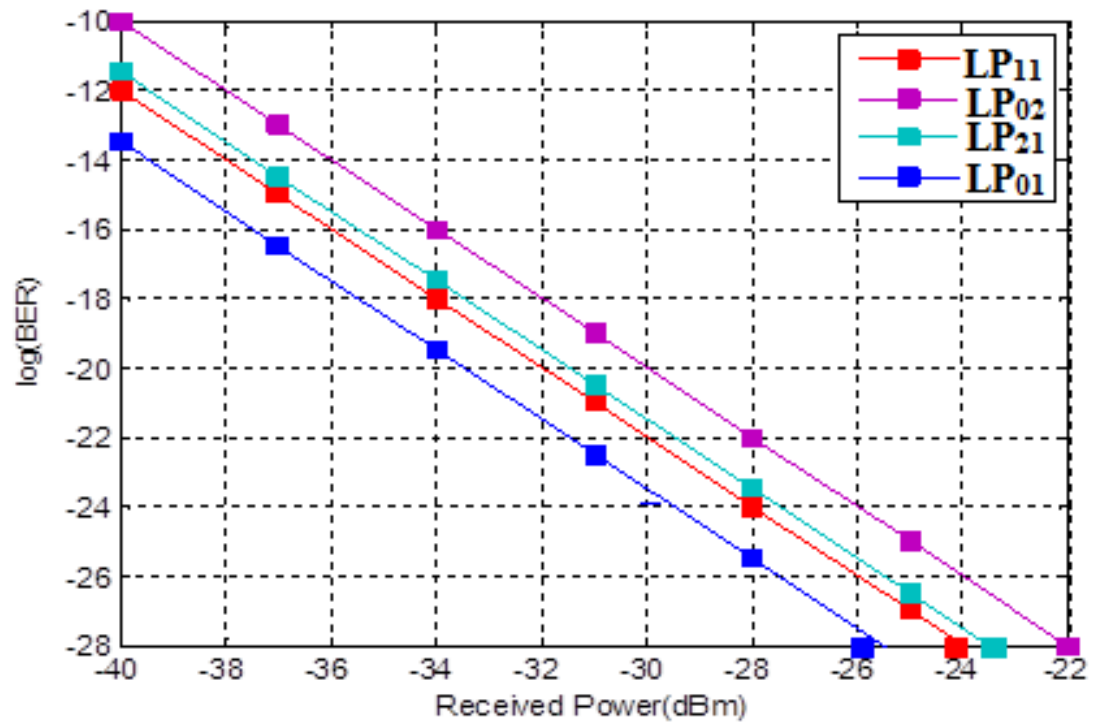


Fig. 6.6 BER (Large size core or center core) as a function of received power

The performance of received BER as a function of received power at different modes of the center core in the design of MC-MMF is shown in Fig. 6.6. The LP11, LP21, and LP02 modes exhibit the power penalties of 2dB, 2.5dB, and 4dB respectively as compared to LP01 mode due to stronger crosstalk and imperfect matching between the modes. When all cores operate, at 1550nm for upstream transmission, BER performance is slightly degraded by about 0.5dB (at BER of $< 10^{-9}$) and 0.3dB for medium size cores and small size cores respectively as compared to the center core. We attribute these penalties due to differential group delay per unit length of the fiber. But, these penalties are acceptable because the achieved BER is $< 10^{-9}$ for all the modes which are noble enough for successful communication.

6.6 Conclusion

In this chapter, for the first time, the MC-MMF for PON is used to reduce the total link losses for upstream traffic. The parameters of MC-MMF are optimized according to mode coupling and inter-core crosstalk effects. The optimized MC-MMF is used in the system for upstream data transmission. The total link losses are reduced to -20 dB with average acceptable crosstalk of -42 dB in PONs network and achieved BER is $< 10^{-9}$ for all the modes for 50 km transmission distance using MC-MMF in addition to combiner module as compared to downstream transmission. Simulation results also show that the upstream transmission performance of the proposed system through different modes of MC-MMF and the system has achieved the best BER at LP01 mode as a function of received power. The MC-MMF for a hybrid passive optical network, efficiently utilizes the space division multiplexing (SDM) to reduce the upstream traffic losses and to reduce the cost per bit of fiber optic transmission. From the fundamental science point of view, this proposed MC-MMF system with SDM in PON research is different from available MDM FM PON in terms of its simple design, cost per bit of fiber optic transmission, and high capacity to survive the upstream losses. Also, this system has a broad impact in submarine, terrestrial and access networks areas where high power fiber delivery, upstream losses are major issues.

CHAPTER 7

CONCLUSIONS, RECOMMENDATIONS AND FUTURE SCOPE

7.1 Conclusion

The thesis focuses on the performance analysis of the Optical Nyquist superchannel with hybrid modulation techniques. The main intention of this thesis is to provide optimum channel spacing between Nyquist superchannels without any distortions. To implement this, the driver signal adjust algorithm has been proposed which utilizes the channel spacing to transmit more number of subcarriers in one Nyquist WDM superchannel without any intersymbol interference. For the requirement of high speed transmission rate along with optimum bandwidth, the modulation and multiplexing techniques are being evaluated from time to time to fulfil the user demands. In previous researches to improve the data rate using Nyquist WDM superchannels, the total power should be 1 W for all WDM channels to maintain the OSNR. But such high power requirement produces fiber non-linearities and causes fiber fuses. Thus to overcome such limitations, WDM is used in addition to SDM through homogeneous and heterogeneous multicore and multimode fiber. Hence, Nyquist superchannels using hybrid modulation technique along with homogeneous and heterogeneous multicore and multimode fiber is one of the major achievements to enhance the system performance. The main results obtained from this study are as follows:

1. Firstly a driver signal adjust control algorithm is proposed that enables the transmitter to remove the predistortions. Both calculation and simulation results demonstrate that the pre-distortion algorithm is very effective to utilize the channel spacing by removing pre-distortion effects. Besides pre-distortion algorithm, the RRC filtering is also used in a system to further reduce the channel spacing between subcarriers and to utilize that channel spacing for transmitting more number of subcarriers in one Nyquist superchannel. Then, it evaluates the scaling coefficient according to the raised cosine filtering by going through m-Quadrature amplitude modulation (m-QAM) mapping and finally, it compensates the delay by using the convolution with Inverse Fast Fourier Transform (IFFT) and FFT. Due to this, the channel spacing reduces from 32.5 GHz to 26.5 GHz and which is further utilized to improve the spectral efficiency of 10 bit/s/Hz significantly. This proposed system has achieved a speed of 21 Tb/s with spectral

efficiency (10 bit/s/Hz) $\times$ distance (1850 km) product of 18500 b/s/Hz.km using predistortion algorithm and RRC filtering. The proposed Nyquist superchannel system with driver signal adjust algorithm has a broad impact in access networks areas where high system capacity, spectral efficiencies are major requirements.

2. To further increase the data rate up to 100 Gb/s for each channel and to simultaneously transmit the unicast and multicast data, the Nyquist superchannel system with hybrid modulation techniques is analysed. This system comprises of Nyquist dual polarization quadrature amplitude modulation (DP-16QAM), polarization shift keying (POLSK) modulation and differential phase shift keying (DPSK) modulation. With the help of this technique, multiple users can transmit their data on a single channel at distinct parameters of the signal. The multicast overlay system transmits a total of 5.1 Tb/s data rate using 8 $\times$ 640 GB/s unicast signal and 40 Gb/s multicast signals. Also, the proposed design Nyquist DP-16QAM modulation offers efficient utilization of 0.015 THz bandwidth for transmission of each channel at the high data rate. The major advantage of Nyquist superchannel system with hybrid modulation techniques is that it not only increases the speed of the overall system but it also increases the number of users at the same time. Also with the help of hybrid modulation techniques, multiple users can transmit their data on a single channel at distinct parameters of signal to secure the data from eavesdropping.
3. A novel trench assisted multicore fiber (TA-MCF) structure is proposed to further increase the spectral efficiency, where different Nyquist superchannels are transmitted using the core to core rotation scheme. By using Nyquist superchannel with hybrid modulation techniques, 15 subcarriers (each at 35.2 Gbaud) are transmitted with reduced channel spacing of 7.5 GHz over seven cores TA-MCF without any distortions. The total five superchannels (each at 4.224 Tb/s) are transmitted that cover the distance of 2688 km at 21 Tb/s data rate. The parameters of the TA-MCF structure are optimized to cover the long distance for Terabit transmission of Nyquist superchannels with -32 dB acceptable inter-core crosstalk using the core to core rotation scheme for SDM/WDM transmission. The proposed system has achieved a spectral efficiency (11 b/s/Hz) $\times$ distance (2688 km) product of 29,568 b/s/Hz.km using predistortion algorithm, RRC filtering, and TA-MCF with CCR scheme.
4. To optimally access the network a multicore multimode fiber (MC-MMF) is demonstrated in passive optical network. MC-MMF is used in PON due to low inter core crosstalk as compared to TA-MCF. Also, while designing the proposed MC-MMF system with passive optical network, upstream losses are found to be less. A single MC-MMF

transmits the signals for upstream data transmission without multiple feeder fibers. It can also accept the multiple signals from multiple ONU's in PON with lesser number of splitter/combiners. The simulation results reported that with proposed MC-MMF system, the total link losses are reduced to -20 dB with average acceptable crosstalk of -42 dB in PONs network and achieved BER is $<10^{-9}$ for all the modes for 50 km transmission distance. The MC-MMF for a hybrid passive optical network, efficiently utilizes the space division multiplexing (SDM) to reduce the upstream traffic losses and to reduce the cost per bit of fiber optic transmission. From the fundamental science point of view, this proposed MC-MMF system with SDM in PON research is different from available MDM FM PON in terms of its simple design, cost per bit of fiber optic transmission, and high capacity to survive the upstream losses. Also, this system has a broad impact in passive optical access networks areas where high power fiber delivery, upstream losses, switching and routing issues are major problems.

7.2 Recommendations

- ❖ In order to handle the demand of high data rate Internet traffic in multimedia like smartphones etc. and to deal with the video streaming problems, the motive of the next upcoming optical transmission system is to enhance the transmission rate, system capacity and transmission distance. To achieve these, the Nyquist WDM superchannel is a renowned technique in which multiple optical Nyquist carriers are routed independently by decreasing the channel spacing of each subcarrier. It is recommended in long haul optical communication systems where high speed data rate in Tbps and high spectral efficiency is required.
- ❖ Featuring distinctive simplicity with reduced intersymbol and inter-channel interference and low power consumption, the proposed Nyquist WDM transmission system can be used in a passive optical access network to fulfil the demand of high capacity systems at optimum channel spacing.
- ❖ The proposed Nyquist WDM transmission system with a Hybrid modulation technique and with multicore multimode fiber is recommended in submarine networks. For example TE-subcom has started the ground work toward a high channel count, low spectral efficiency to each channel by providing optimum power to each channel.
- ❖ For terrestrial networks, where the power is the readily available and the main issue is routing and switching of the networks to allow the communication with multiple numbers of

end users. At this stage, the Nyquist superchannels with multi core multimode fiber are recommended to reduce the need for multiple feeder fibers and to reduce the splitting losses.

❖ For access networks that are price sensitive and key requirement is a low cost passive optical network with a long reach and less splitting ratio. To avoid upstream losses with the constraint of power budget, multimode combiners are recommended with the proposed design system.

7.3 Scope for Future Work

- ❖ The research on the Nyquist WDM transmission system with the Hybrid modulation technique is quite an open area that obliges the utilization of components efficiently in order to cope up with the cumulative demand of high speed data rate and high capacity crunch up to 10^{18} bytes per second.
- ❖ In future, not only higher order modulations and advanced multiplexing are required, but parallelly the requirement of high OSNR needs to be reduced. Thus, utilization of channel spacing is a major concern that can be worked upon in the upcoming researches. The optimum channel spacing also provides progress in high capacity-per fiber, reduces the cost-per-unit, and provides improvements in spectral efficiency.
- ❖ As the requirement of high input power produces the fibre non-linearities and causes fibre fuses. To reduce such limitations, space division multiplexing (SDM) in homogeneous and heterogeneous MCF can be used along with Nyquist superchannels and can be recommended in TE-subcom submarine networks.
- ❖ With further optimization, the proposed Nyquist superchannels with multimode transfer couplers can be used for accessing the long reach networks with multiple numbers of users like in optical access networks and terrestrial networks etc.

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