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Mitigation of Rayleigh Backscattering in WDM Passive Optical Access Networks

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Abstract*— *Achievement of transmission (full duplex) over single fiber is a challenge for researchers for Wavelength Division Multiplexed Passive Optical Networks. There are many schemes available but they suffer from transmission issues because of using transmissions on the same wavelength with bidirectional transmissions. This results in the reduction of transmission distances between optical fiber terminal equipment and the optical network units. This happens because Rayleigh' backscattering noise and there is a need to reduce that noise substantially. In this research work channels capacity Dense Wavelength Division Multiplexing (DWDM), Passive Optical Networks (PON) are simulated after extensive testing. The main aim is enhancing the capacity over a distance with less bit error rates. This was achieved through the design optimization using Rayleigh' Backscattering elimination technique thus enhancing the performance.

Keywords*— *Rayleigh backscattering, DWDM, PON.

I. BACKGROUND

To begin with, one must comprehend the fundamental ideas of optical fiber networks. Optical fibers offer a great deal of benefits, including lengthy repeater spacing, minimal crosstalk or signal leakage, compact size and light weight, and service security. A glass or plastic fiber that is intended to direct light along its length is called an optical fiber (or fiber). Two methods for light to pass via an optical fiber are by reflection and refraction.

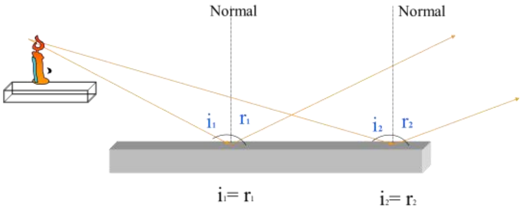


Fig. ***Error! No text of specified style in document.****:*
Total Internal Reflection of Light

The other law is called the Total Internal refraction of Light.

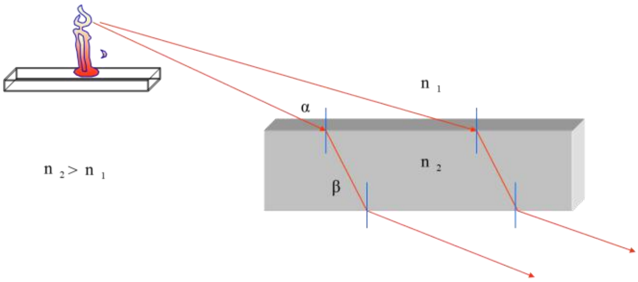


Fig.1: Total Internal Refraction of Light

Optical fiber is basically a glass waveguide. Now we will look at the architectures of optical fiber communications. FITL-Fiber in the loop can have many architectures such as.

- FTB - Fiber to the Building
- FTC - Fiber to the Curb

- FTH - Fiber to Home

Same is shown in the Fig below:

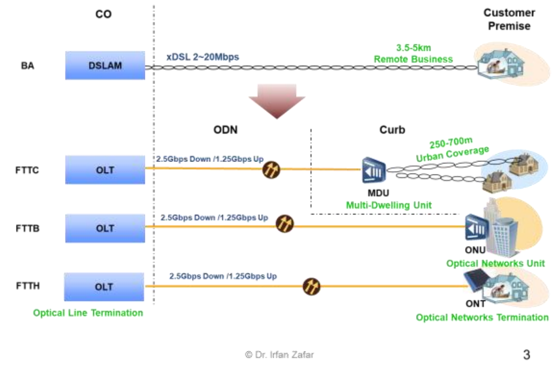


Fig.2: Optical Access Network (OAN) Architectures

OAN consists of the following scenarios:

- FTTB
- FTTC
- FTTH

Once we have studied various scenarios about the network architectures used for optical communications, it is also important to know what we mean by the PON (Passive Optical Networks).

PON features;

- OLT - Optical Line Terminal
- ONU - Optical Network Unit
- ODN - Optical Distribution Network

Typical PON architecture is shown in below Fig:

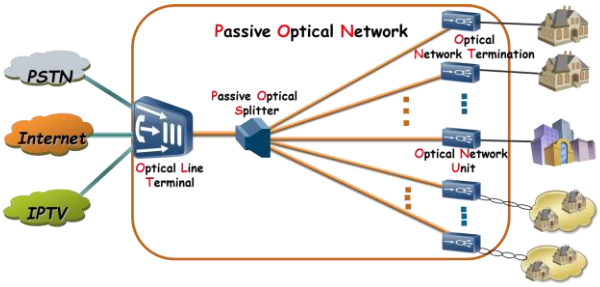
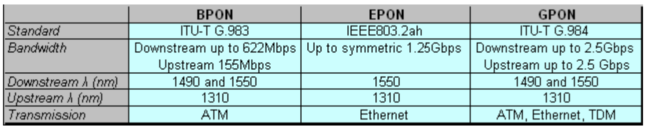


Fig.3: PON Architecture

Shown below are various protocols used for PON.

Table 1: PON Protocols



	BPON	EPON	GPON
Standard	ITU-T G.983	IEEE803.2ah	ITU-T G.984
Bandwidth	Downstream up to 622Mbps Upstream 155Mbps	Up to symmetric 1.25Gbps	Downstream up to 2.5Gbps Upstream up to 2.5 Gbps
Downstream λ (nm)	1490 and 1550	1550	1490 and 1550
Upstream λ (nm)	1310	1310	1310
Transmission	ATM	Ethernet	ATM, Ethernet, TDM

It's also important here to look at the Time Division Multiplexing concept. The below Fig explains the time division multiplexing.

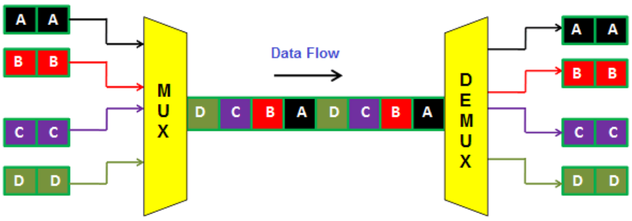


Fig.4: Time Division Multiplexing

The communication is divided into time slots and packets are sent in the allocated time frames. Nowadays TDM-PON standard is generally being used. It divides the users based on the fixed time slots where users share available bandwidth. Because of growing need of multimedia applications, TDM-PON is not effectively achieving high data rate which are necessary for communications [1]. A typical architecture is shown below.

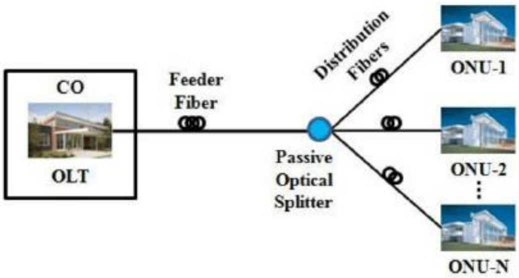


Fig.5: Time Division Multiplexed Passive Optical Network (TDM-PON)

The answer is the deployment of WDM-PON networks, which are the networks of the future that provide each user with a high-bandwidth link between the central office or exchange and the end user in order to achieve full bandwidth utilization [2]. Future high bandwidth networks are expected to use this kind of network. Moreover, DWDM-PON makes advantage of the less expensive ONU [3]. Lastly, efficient use of wavelengths is a crucial prerequisite [4].

A select number of tactics, tools, and attributes are examined and evaluated in order to satisfy the requirements of low-cost ONUs. Injectable Fabry-Perot lasers [5,6,] Reflective semiconductor optical amplifiers [7], and semiconductor optical amplifier with reflective electro-absorption modulators [8] are used to implement the usage of light transmission in order to do this. Temperature management is necessary for transmissions utilizing Fabry-Perot lasers, but [5]. The approach of Reflective Semiconductor Optical Amplifiers is seldom used by researchers [9]. Due to their large bandwidth, semiconductor optical amplifiers used by ONUs result in significant levels of signal interference [10]. Consequently, there is a large degree of Rayleigh Backscattering throughout the transmission process [11].

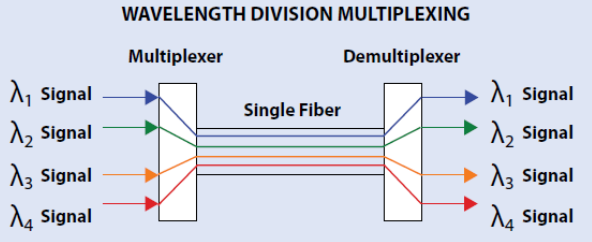


Fig.6: Basic Wavelength Division Multiplexing Technology Diagram

Before reviewing basic requirements of DWDM-PON system, it is helpful to have a look at its origin.

- CWDM is an abbreviation for Coarse Wavelength Division Multiplexing
- DWDM is an abbreviation for Dense Wavelength Division Multiplexing

Essential Components of DWDM are;

- Optical Source
- Optical Multiplexer & DE multiplexer
- Optical Amplifiers
- Supervision of DWDM System

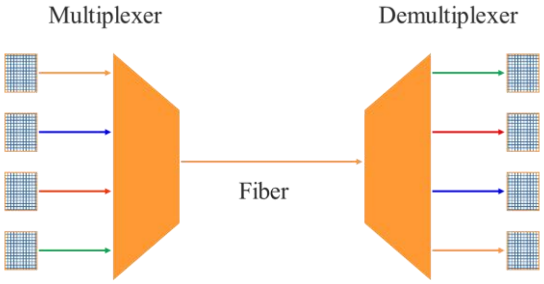


Fig.7: DWDM Multiplexer and DE Multiplexer

Typical Network Element types of DWDM are;

- OADM - Optical Add Drop Multiplexer
- OTM - Optical Terminal Multiplexer
- Regenerator
- OLA - Optical Line Amplifier

A typical DWDM network architecture is shown in the below network drawing.

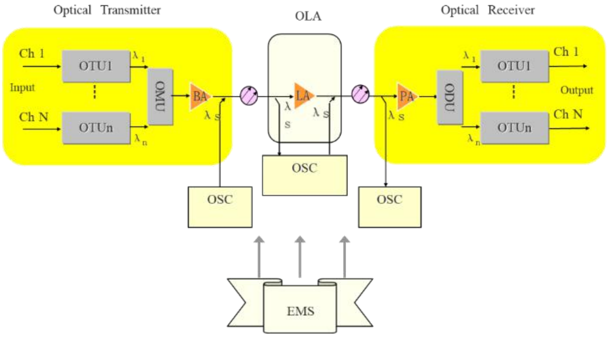


Fig.8: DWDM System Architecture

Common network elements in the DWDM networks are shown below;

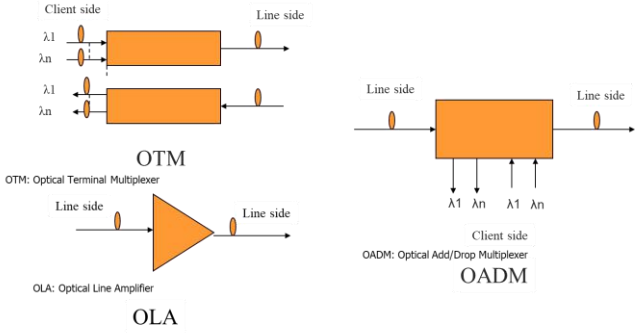


Fig.9: Common Network Elements in DWDM System

Rayleigh Distribution has significant internal loss at low absorption window [12,13, 14, 17].

For taking care needs of DWDM-PON systems (e.g. inexpensive ONU with RB termination produced by reflective transmitters) there is a need to meet the other two requirements of DWDM-PON which includes reducing channel spaces and effective wavelengths usage. Wavelength Shift/Optical Carrier-Suppressed Subcarrier-Modulation avoid RB and obtain the appropriate level of long-distance use [18,19]. However, these methods are extremely complex requiring different modelling techniques [18-20]. Adding Continuous Wave to a remote location is another way [21]. It avoids RB effect and achieves low cost requirement of ONU [4]. Cross-seeding RB uses the elimination process, as introduced recently [22,23] provides a significant reduction in RB, which achieves high wavelength, as well as ONU with low cost. One might conclude that the seed method achieves a complete RB reduction and better performance of Bit Error Rate (BER) in comparison to other ways to reduce RB. It is however achieved by going for high cost of the system [18-23].

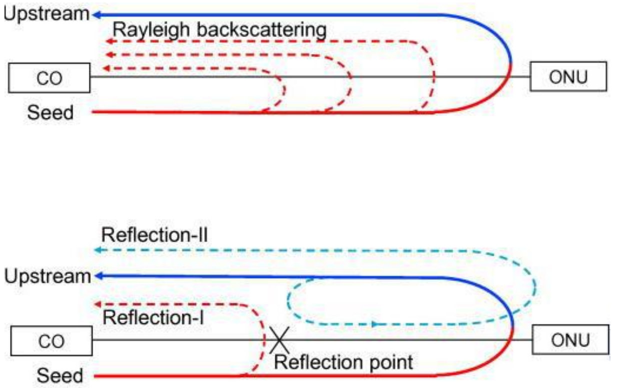


Fig.10: Rayleigh Scattering

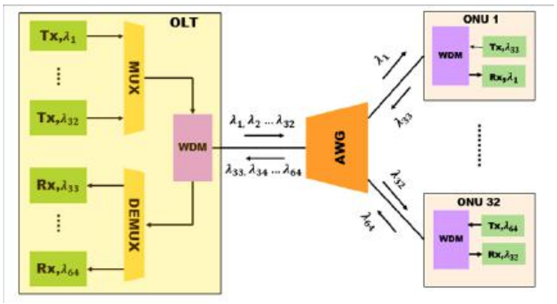


Fig.11: Typical DWDM-PON Architecture

RB reduction by DWDM-PON construction is tested and evaluated in this research. It can be successfully achieved with reasonable channel interruptions. Lower channel upgrade, bit rate improvement, reduction of active components, and storage is the main objective of this function.

Numerous methods for suppressing RB noise and transmitting downstream and upstream on a single cable have been developed by researchers. Using a multi-wavelength source at the service node (ONU), Differential Quadrature Phase Shift Keying for downstream transmission, and Re-modulated On-Off Keying for upstream transmission, RSOA-based WDM-PON techniques reduce RB noise by applying chirping and clipping effects.

Additional methods rely on carrier distributed WDM-PONs, which employ line coding in PON networks together with electrical and in-band optical filtering. Even though various techniques have shown enhanced resilience against RB-induced noise, their effectiveness is diminished due to their extremely complex designs, the need for additional components that come with high deployment costs, and their low receiver sensitivity and data rate limitations for both upstream and downstream transmissions. Therefore, if we want to achieve a cost-effective design, we shouldn't employ Erbium Doped Fiber Amplifier and Dispersion Compensated Fiber. Below is a picture of the architecture.

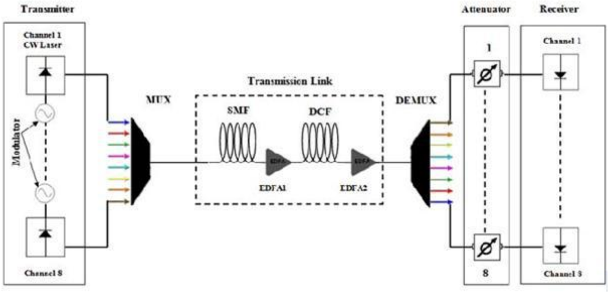


Fig.12: Optical Communication System Block Diagram

II. PROBLEM STATEMENT

In optical Fiber communications, there are issue related to transmission because of the use of same wavelength with bidirectional transmissions resulting in reduction of transmission distances between OF (Optical Fiber) terminal equipment and optical network units as a result of the Rayleigh backscattering noise.

Objectives

The main aim is to enhancing the capacity over a distance with less bit error rates. This was achieved through the design optimization using Rayleigh Backscattering elimination technique thus enhancing the performance. These can be summarized as;

- Performance enhancement/ Capacity enhancement.
    - ✓ Dispersion
    - ✓ Slope

  - ✓ Attenuation Coefficient
  - ✓ Effective core area
  - ✓ Non-Linear index-coefficient (mitigation of RB noise in WDM-PONs).
- Realizing very high capacity DWDM-PON system.
- Enhancing the upstream capacity to 26 km using Single-Mode Fiber.
- Error Rate Reduction.
- Design optimization (effective Rayleigh Backscattering elimination).

Research Questions

- Is it possible to effectively realize high capacity DWDM-PON system?
- How to enhance the upstream capacity to 26 km using SMF - Single-Mode Fiber?
- How to achieve Error Rate Reduction?
- How to come up with a design optimization technique for Rayleigh Backscattering elimination.
- How to achieve system's performance (enhancement/capacity enlargement)?

III. LITERATURE REVIEW

High-definition films and live streaming are among the bandwidth-hungry services that are taking over our lives due to the internet's continued growth and usage. Fiber-to-the-home broadband access networks have been introduced in response to the rapidly increasing demand for high capacity. Passive optical networks appear to be an appealing option for providing high bandwidths to users in between different fiber to the house applications. Because it is constructed point-to-multipoint, the PON system not only delivers high bandwidth but also abundant coverage, decreased fiber transmission, and lower maintenance costs because intelligent network equipment is used.

Higher bandwidth may be supported when wavelength division multiplexing division is combined with PON as opposed to normal PON, as each length of route is allotted to a single subscriber. Other benefits of WDM-PON include its robust network security, high data flexibility, simplicity of management and optimization, and protocol openness. It is widely regarded as the next generation of FTTH and access technology [24–29]. Nevertheless, because point-to-point connections are built, the WDM-PON system must consider certain wavelength transmission to the subscriber area's optical line terminal, central telecom office, and optical network units.

The majority of WDM-PON research is concerned with cost-effectiveness, particularly from the user's perspective where expenses are crucial. Colourless ONUs and numerous WDM-PON loopback access networks have recently been suggested [30–41]. Fabry Pérot laser diodes and semiconductor optical amplifiers are examples of low-level lasers or modulators that are used in many of these systems. Continuous seed light is delivered from the OLT to the ONU and back to the OLT receiver. You can use one fiber [14–41] or two strands [30–33] to receive this round-trip transmission.

Because it may minimize the number of visible fibers used, which lowers system costs, single-fiber loopback transmission is more appealing than two-string systems. Reusing the visible signal is also something that many people are very interested in [32], [42-46]. It costs more since these arrangements do not require extra seed light. On the other hand, signal-to-noise distortion results from single-fiber bidirectional loopback transmission. Because of the internal structure of the fiber and its fluctuating refractive index, Rayleigh backscattering in fiber cannot be avoided [47]. Therefore, it is crucial to look at the influence of the opposite direction on single-fiber bidirectional WDM-PON network access, as this will aid in system performance monitoring and network configuration optimization.

The adoption of different fixed or mobile-wide services will lead to a large increase in access network users. [49–49]. This is a result of the need for networks to integrate with one another and the elimination of active sites, which will eliminate traffic aggregators and switching areas from service provider access-to-point sites [50]. Because wavelength-division-multiplexing (WDM) passive optical networks can satisfy all of the aforementioned characteristics, they form the foundation of optical access networks [51–52].

Utilizing colourless transmitters at the optical networking units is a major factor in the development of WDM-PON access networks as it lowers expenses and prevents inventory problems. The best methods are to use loop-back techniques to generate colourless ONU transmitters [53], [54]. Nonetheless, using two fibers—one for upstream and one for downstream transmission—is the way to get around these issues.

Likewise, cross-modulation strategies were put forth to boost fiber use efficiency and lessen performance deterioration brought on by Fresnel reflections and Rayleigh backscattering [55–61].

IV. RESEARCH DESIGN

The idea behind the suggested Rayleigh Backscattering noise-resilient design mitigation is that upstream and reflected downstream signals tend to conflict in the frequency range when continuous wave seeding light is employed for downstream communication. In order to create a multi-subcarrier downstream signal and reduce this low frequency interference, the frequency must be modulated onto the downstream wavelength. In this way, the upstream signal carrier is muted, preventing interference with the downstream wavelength reflection.

- Comprehensive simulation analysis of schemes by using latest version of Optisystem will be done by changing various design parameters and studying the related effects.
- Graphical representation of the simulation results will be done while presenting an optimal solution by comparing their parameters including, Dispersion, Slope, Attenuation Coefficient, Effective core area and Non-Linear index-coefficient (mitigation of RB noise in WDM-PONs).

The researcher has come up with a DWDM-PON design as shown in the Fig below:

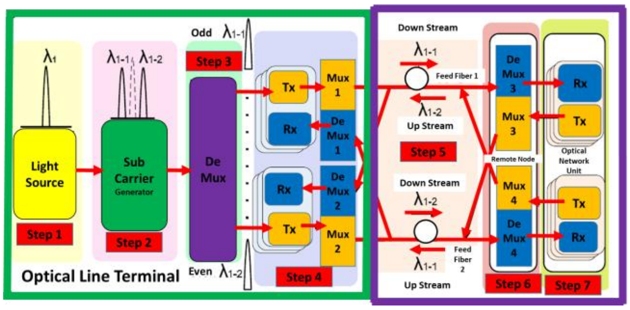


Fig.13: Dense Wavelength Division Multiplexing PON Architecture

The optical Line Terminal is divided into the following stages or steps;

Step 1 = Input Light Source (8 continuous wave light sources with wavelength spacing of 25GHz)

Step 2 = Sub Carriers Generator (16 continuous wave light sources with wavelength spacing of 12GHz)

Step 3 = Subcarriers DE multiplexed (Odd and Even Subcarriers for transmission on bidirectional Fiber Feed 1 and Fiber Feed 2 respectively)

Step 4 = The Even and Odd subcarriers are modulated using On Off Keying Technique (Transmitter Tx and Receiver Rx)

Step 5 = Downstream (from OLT to ONU) and Upstream Transmission (from ONU to OLT). Rayleigh Backscattering elimination.

Step 6 = Remote node consisting of two multiplexers and two DE multiplexers. The Even and Odd subcarriers are modulated using On Off Keying Technique (Transmitter Tx and Receiver Rx)

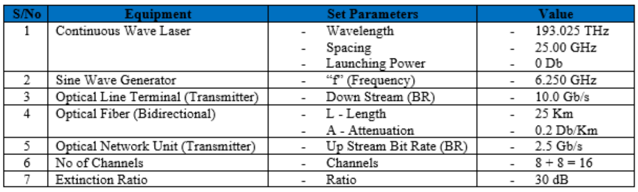
Step 7 = Tx and Rx are used for the demodulation/re-modulation. The Even and Odd subcarriers are modulated/demodulated using On Off Keying Technique (Transmitter Tx and Receiver Rx)

Also, the odd and even Downstream signals are multiplexed to be transmitted through Feed Fiber 1 and Feed Fiber 2 respectively. Rayleigh Backscattering is eliminated at step 5 through the use of cross-seeding technique.

V. PARAMETERS

The following parameters have been set for the analysis of the designed architecture.

Table 2: Set Parameters



S/No	Equipment	Set Parameters	Value
1	Continuous Wave Laser	- Wavelength - Spacing - Launching Power	- 193.025 THz - 25.00 GHz - 0 Db
2	Sine Wave Generator	- “f” (Frequency)	- 6.250 GHz
3	Optical Line Terminal (Transmitter)	- Down Stream (BR)	- 10.0 Gb/s
4	Optical Fiber (Bidirectional)	- L - Length - A - Attenuation	- 25 Km - 0.2 Db/Km
5	Optical Network Unit (Transmitter)	- Up Stream Bit Rate (BR)	- 2.5 Gb/s
6	No of Channels	- Channels	- 8 + 8 = 16
7	Extinction Ratio	- Ratio	- 30 dB

Now we will break down the conceived network architecture into further segmentations. Steps 1-4 relate to Optical Line Terminal and step 7 relates to Optical Network Unit. Steps 5-6 relate to bidirectional fiber transmission through the use of multiplexers and DE multiplexers.

Step 1

In step 1, the first λ is launched at 193.025 THz (0 dB) power from the continuous wave light source. Same goes for the remaining six wavelengths. Furthermore, the system capacity is increased by introducing sixteen subcarriers by reducing the channel spacing from 25 GHz to 12.5 GHz.

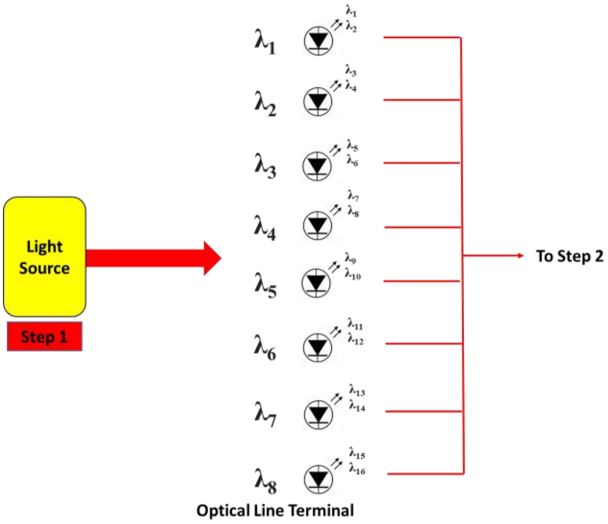


Fig.15: Step 1 – Continuous Wave Light Source (λ1 to λ8)

Step 2

In step 2, the Modulator is fed with 6.25 GHz through sine wave generator and fed into Erbium-Doped Fiber Amplifier.

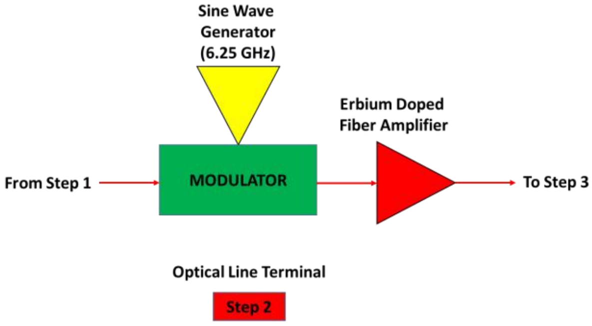


Fig.16: Step 2 – Sine Wave Generator Feeding, Modulator & Amplifier

Step 3

In step 3, a DE multiplexer is used having 0 dB insertion loss. Odd and Even Sub-Carriers are segregated.

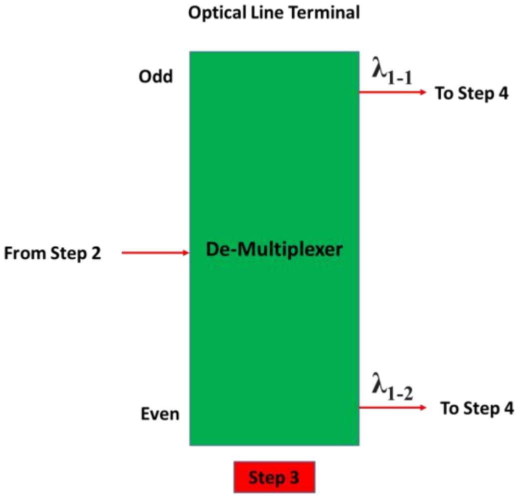


Fig.17: Step 3 – Sine Wave Generator Feeding, Modulator & Amplifier

Step 4

Step 4 has a receiver for the upstream signal. Photodetector with LPF (Low Pass Filter) to demodulate upstream signal is used.

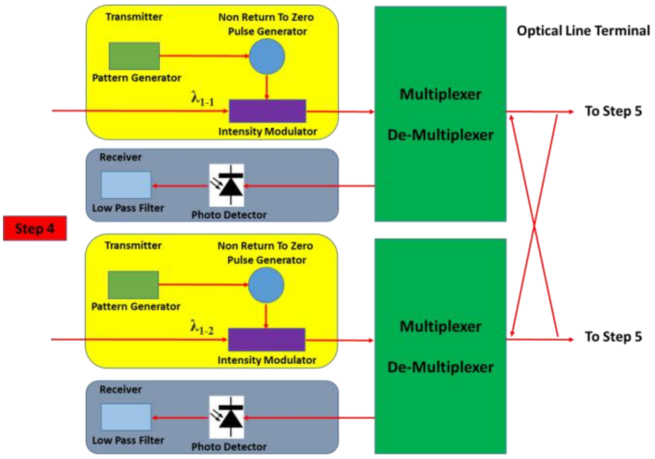


Fig.18: Step 4 – Transmitter, Receiver, Low Pass Filter

Step 5

Bidirectional Fiber Transmission of distance 26 Km is shown below at this step.

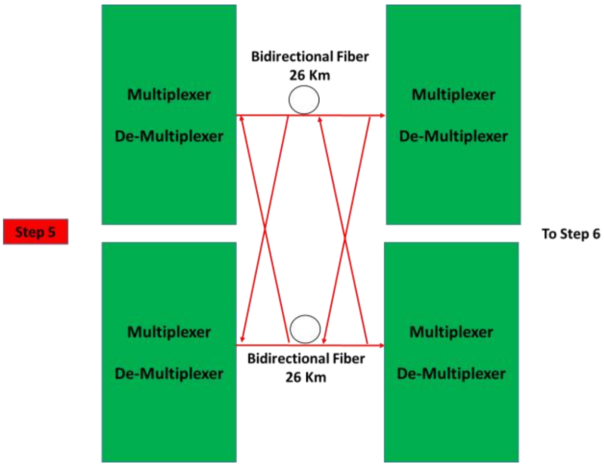


Fig.19: Step 5 – Bidirectional Fiber Transmission (26 Km)

Step 6

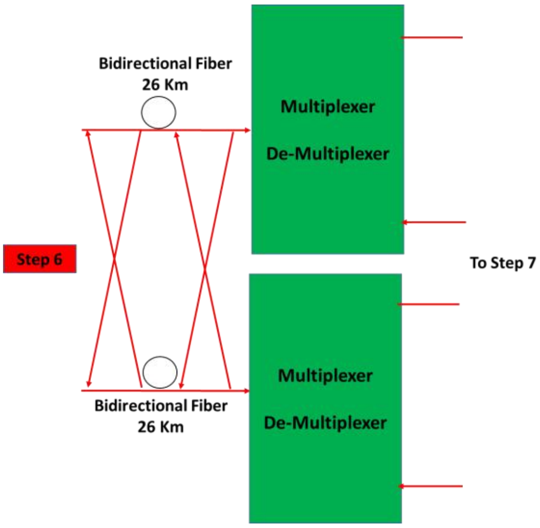


Fig.20: Step 6 – Multiplexing / DE Multiplexing

Step 7

Now we come to the last step of our network architecture design. Transmitters and Receivers are used for demodulation/re-modulation at this step after the received signal.

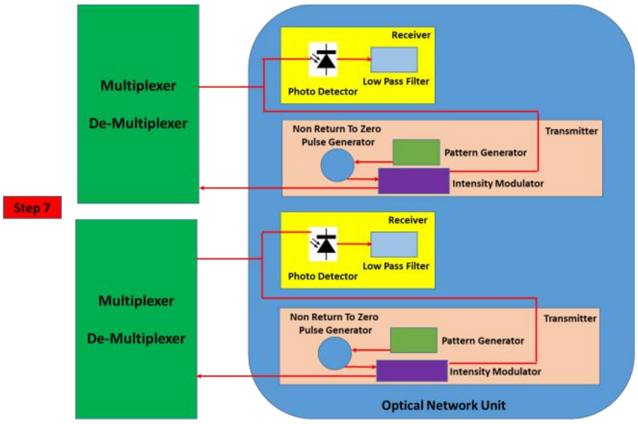


Fig.21: Step 7 – Optical Network Unit Section

Combining the above 7 steps, we get the complete conceived network architecture.

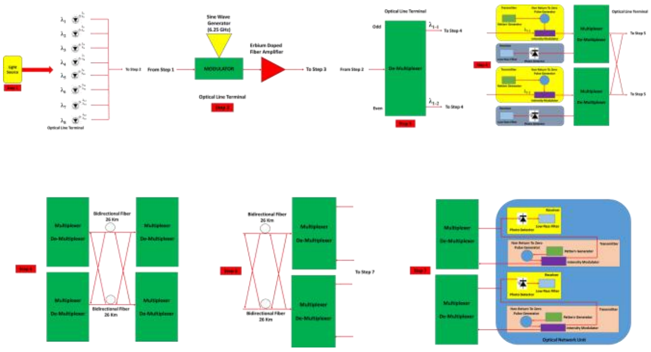


Figure 22: Proposed DWDM-PON System

VI. RESULTS AND DISCUSSION

Results of the simulation will be analysed and discussed. To do the verification of the research goals, evaluations and system tracing will be performed.

- System Trace and Evaluation

Sixteen down-stream channels with a spacing of 12.50 GHz are included in the NS2 simulations. Additionally, eight down-stream "odd" channels and eight "even" channels are included before they are transmitted through fiber feed 1, down-stream odd channel λ1-1 is placed before the optical network unit, down-stream even channel λ1-2 is placed before the optical network unit, up-stream odd channel λ1-1 is placed after the up-stream path, and up-stream even channel λ1-2 is placed after the up-stream path. The simulation details are shown in the Figs below.

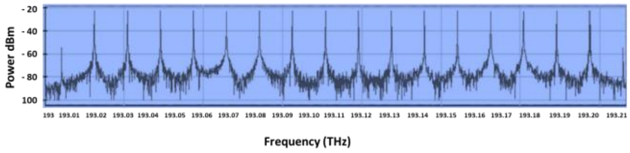


Fig.23: Sixteen (16) Down Stream channels with spacing of 12.5 GHz

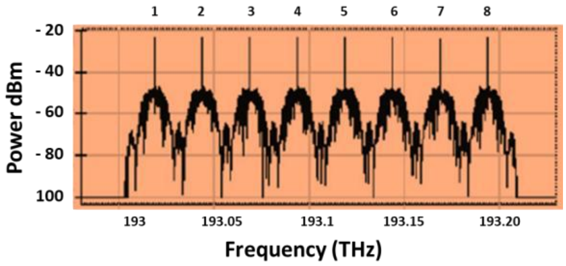


Fig.24: 8 Down Stream odd channels before their transmission through the Fiber Feed 1

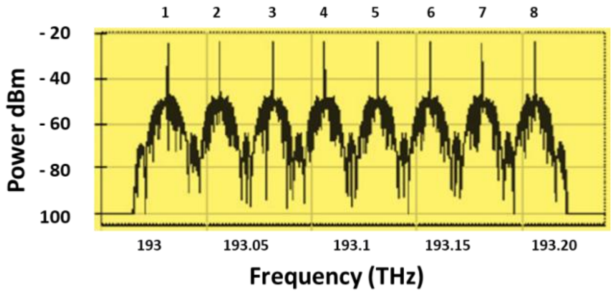


Fig.25: 8 even channels before their transmission through Fiber Feed 2

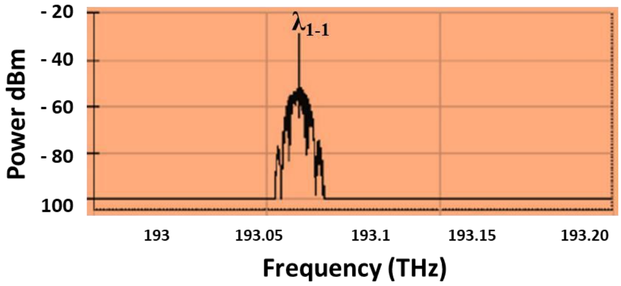


Fig.26: Down Stream odd channel λ1-1 before the Optical Network Unit

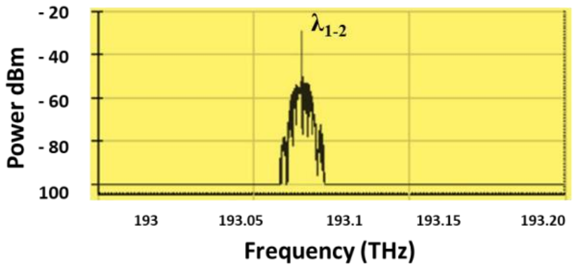


Fig.27: Down Stream even λ1-2 channel before the Optical Network Unit

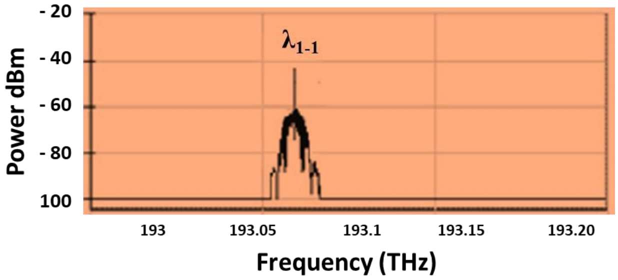


Fig.28: Up Stream odd channel λ1-1 after the Up Stream Path

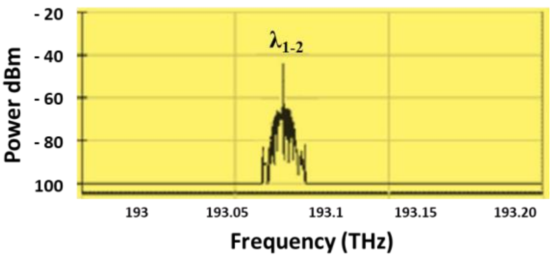


Fig.29: Up Stream even channel λ1-2 after the Up Stream Path

Sixteen Downstream channels have a channel spacing of 12.5 GHz starting from λ_{1-1} at 193.019 THz to λ_{8-2} at 193.06 THz. These sixteen channels were Generated from eight continuous wave light sources having 0 db power using the sine wave generator and the modulator. After the DE multiplexing, even/odd downstream channels are modulated using intensity modulator. These channels are then fed to the downstream modulator in order to come up with cross-seeding (odd/even spectrum) which is then transmitted through feed fibers 1 and 2 respectively. The above simulations depict these scenarios. Transmission takes place over 26 Km through feed fiber 1 after being DE multiplexed before an Optical Network Unit receiver. Signals are then retransmitted back through the upstream path through feed fiber 2. Similar signal analysis is done for the upstream path at the chosen frequencies.

- Eye Diagrams

Eye diagrams (for odd/even channels) after retransmitting path λ_{1-1}, λ_{1-2}, λ_{8-1} and λ_{8-1} is shown below;

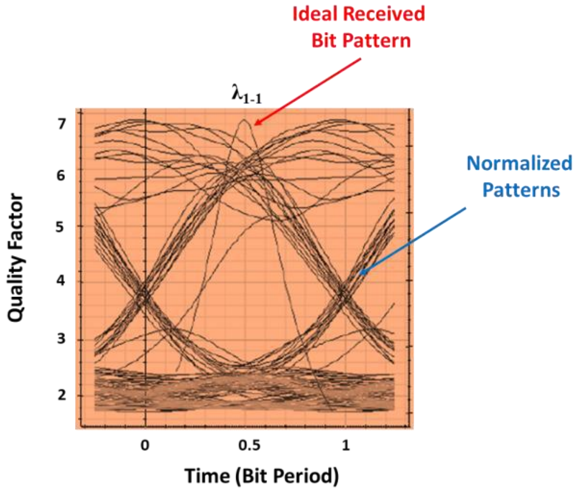


Fig.30: Eye Diagram λ1-1

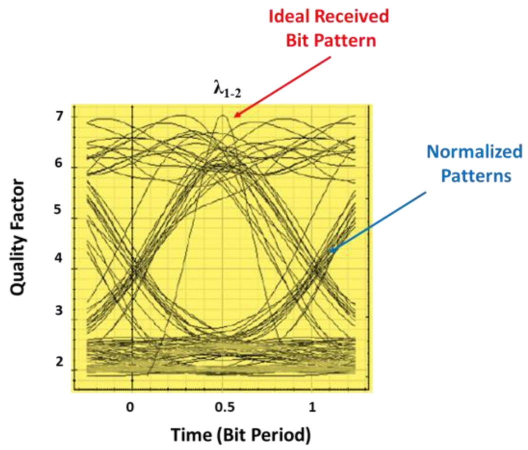


Fig.31: Eye Diagram λ1-2

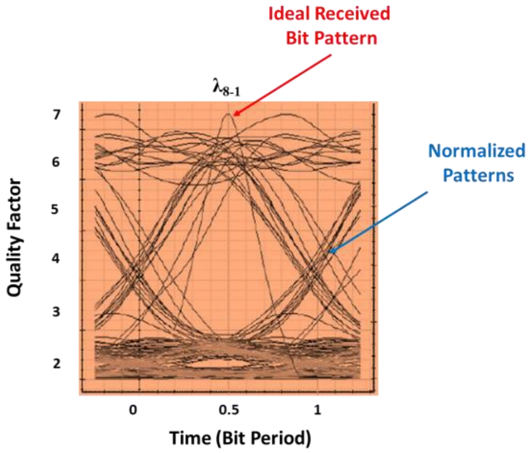


Fig.32: Eye Diagram λ8-1

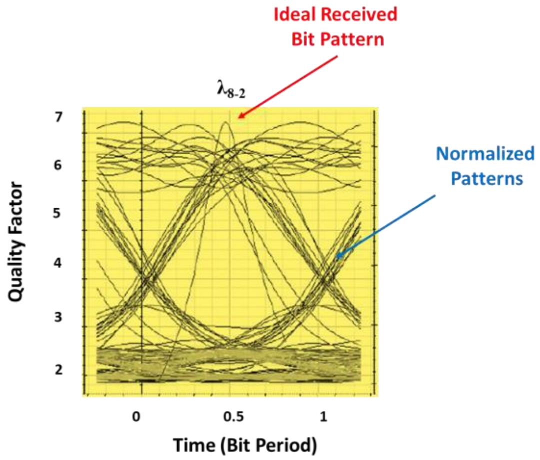


Fig.33: Eye Diagram λ8-2

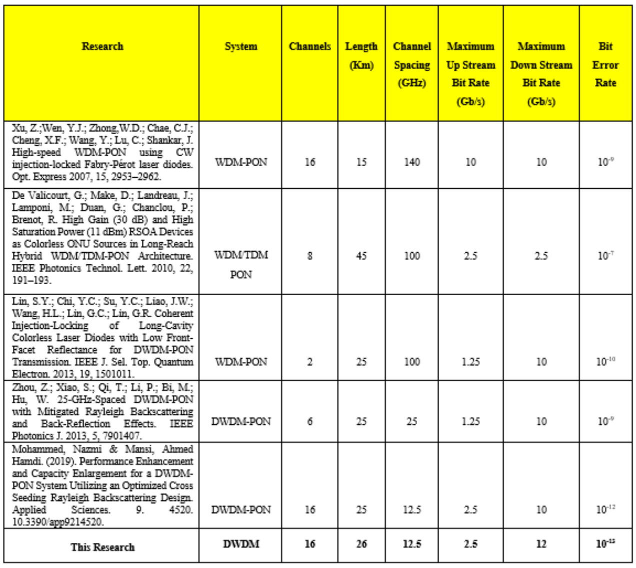
The channel with the lowest simulated bit error rate, λ1-1 of 10-13, has a quality factor of 6.79, whereas channel λ1-2 of 10-14 has the highest simulated bit error rate, with a quality factor of 7.01. For the remaining channels, an average bit error rate of better than 10-13 can be seen. In Fig., the blue line denotes normalized patterns while the red line represents the ideal received bit pattern.

Eye Diagram gives a qualitative analysis of the signals. It gives an understanding of system performance by depicting the channels imperfections. Signal-to-Noise Ratio can also be ascertained through visual approximations in addition to the jitter, skew, rise time, fall time, bit error rate and quality factor etc.

- Results Comparison

The below table shows the previous studies in comparison to the latest research done by this researcher to come up with a better model.

Table 3: Comparison Between Related Studies



Research	System	Channels	Length (Km)	Channel Spacing (GHz)	Maximum Up Stream Bit Rate (Gb/s)	Maximum Down Stream Bit Rate (Gb/s)	Bit Error Rate
Xu, Z.;Wen, Y.J.; Zhong,W.D.; Chae, C.J.; Cheng, X.F.; Wang, Y.; Lu, C.; Shankar, J. High-speed WDM-PON using CW injection-locked Fabry-Pérot laser diodes. Opt. Express 2007, 15, 2953–2962.	WDM-PON	16	15	140	10	10	10^{-9}
De Valicourt, G.; Make, D.; Landreau, J.; Lamponi, M.; Duan, G.; Chanclou, P.; Brenot, R. High Gain (30 dB) and High Saturation Power (11 dBm) RSOA Devices as Colorless ONU Sources in Long-Reach Hybrid WDM/TDM-PON Architecture. IEEE Photonics Technol. Lett. 2010, 22, 191–193.	WDM/TDM PON	8	45	100	2.5	2.5	10^{-7}
Lin, S.Y.; Chi, Y.C.; Su, Y.C.; Liao, J.W.; Wang, H.L.; Lin, G.C.; Lin, G.R. Coherent Injection-Locking of Long-Cavity Colorless Laser Diodes with Low Front-Facet Reflectance for DWDM-PON Transmission. IEEE J. Sel. Top. Quantum Electron. 2013, 19, 1501011.	WDM-PON	2	25	100	1.25	10	10^{-10}
Zhou, Z.; Xiao, S.; Qi, T.; Li, P.; Bi, M.; Hu, W. 25-GHz-Spaced DWDM-PON with Mitigated Rayleigh Backscattering and Back-Reflection Effects. IEEE Photonics J. 2013, 5, 7901407.	DWDM-PON	6	25	25	1.25	10	10^{-9}
Mohammed, Nazmi & Mansi, Ahmed Hamdi. (2019). Performance Enhancement and Capacity Enlargement for a DWDM-PON System Utilizing an Optimized Cross Seeding Rayleigh Backscattering Design. Applied Sciences. 9. 4520. 10.3390/app9214520.	DWDM-PON	16	25	12.5	2.5	10	10^{-12}
This Research	**DWDM**	**16**	**26**	**12.5**	**2.5**	**12**	$\mathbf{10^{-13}}$

It is to be noted that the main difference between this researchers cross-seeding technique used and the other techniques relate to the DWDM-PON system requirements. Researchers achieved higher upstream and downstream rates but the transmission distances were limited and restricts the ability to use more channels. Every used technique as shown in the above table has its drawbacks hence there was a need to come up with an optimal design based on the architecture. Rayleigh backscattering leads to severe degradation in the performance.

To solve these issues and increase usage efficiency, the researcher developed the cross-seeding system. The network architecture has been created with this research effort to minimize Rayleigh backscattering.

VII. CONCLUSIONS

- Summary

- This research contribution simulated enhanced cross-seeding-based DWDM-PON system with channel as per ITU-T G.694.1 defined standard for Dense Wave Division Multiplexing for Passive Optical Networks.
- Channel spacing of 12.5 GHz is used.
- Enhanced performance characteristics/parameters were targeted for this research work.
- The performance characteristics included the following.
    - Enhancing downstream channel capacity
    - Enhancing Up-Stream bit rate.
    - Minimizing active components in network
    - Maintaining and improving BER Performance.
- Based on researcher's design enhancement, conceptualized DWDM-PON has achieved the following.
    - Record of 16 channels,
    - Upstream capacity 2.50 Gb/s over 26 km of transmission.
    - Average BER of 10^{-13}.
- Comparison among researcher's studies was done. This is for ensuring validity of proposed system.

- Contribution to Knowledge

The study contributed to increasing the number of channels to sixteen while enhancing the upstream capacity covering a larger distance which was 25 Km previously thus enhancing it by 1 Km more with improved bit error rate which was previously 10^{-12} and now it has come to 10^{-13}.

- Limitations of the Study

This scheme can be further improved if the amount of data which was analysed is enhanced to get better results.

Future Recommendations

The network architecture should be further improved in the future work by integrating different techniques on different segments of the optical fiber network by breaking it down thus reducing the Rayleigh backscattering further.

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