IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 19, Issue 2, Ser. I (Mar. – Apr. 2024), PP 06-23
www.iosrjournals.org

Simulative Design Of Passive Optical Network (Pon) As A Mobile Communication Backhaul Network

Okeke Remigius Obinna[1], Idigo Victor Eze[2]
[1] Electrical/Electronic Engineering Department, University Of Port Harcourt, Rivers State, Nigeria.
[2] Electronic/Computer Engineering Department, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.

Abstract:
The *current microwave backhaul systems face numerous challenges including issues related to adverse weather conditions, limited capacity, restricted range and latency concerns. In response to the need for enhanced backhaul performance for 4G (LTE) and 5G networks, operators are increasingly exploring Passive Optical Network (PON) technology as a viable solution. PON technology holds the promise of overcoming these challenges by offering unlimited capacity, minimized latency, scalability, and cost-effectiveness. This research's primary aim is to simulate a designedPassive Optical Network (PON) to serve as the backhaul infrastructure for 4G (LTE) cellular networks, focusing specifically on the SMILE mobile communications network located in Port Harcourt. The study encompasses various specific objectives, including the examination of Port Harcourt's geographical characteristics, the identification of SMILE network eNBs and their coordinates, the determination of optimal splitter locations using both manual and automatic/systematic approaches, the assessment of dispersion's impact on downstream and upstream transmissions in relation to network capacity, the calculation of power budgets for both transmission scenarios, the implementation of the designed network configurations in the OptiSystem simulation environment, and a comprehensive comparative analysis of the proposed PON system's performance in contrast to the existing SMILE backhaul system. The results obtained showed average BER of 4.88E-10 and provided 99.99% performance improvement when compared to average BER of existing microwave backhaul technology.*

Index Terms: *PON, Mobile Communication, Passive Optical Network (PON), Upstream, Downstream, Backhaul Network.*

Date of Submission: 01-03-2024 Date of Acceptance: 10-03-2024

I. Introduction

Despite the improvements in mobile communication systems as witnessed by the evolutions, there are still short comings in delivering higher speed data and meeting up excellent performance as promised by each generation of evolution [1]. 3GPP an acronym for 3rd generation partnership project, released LTE technology document in its Release 8 and 9 which is set to provide an increase to both capacity and speed using new techniques for modulation. The standard requirement was specified by the International Telecommunication Union-radio communication sector (ITU-R) and it was named the International Mobile Telecommunication Advanced (IMT-Advanced) specification [2]. Setting peak speed requirement for 4G services at 1 gigabit per second (Gbit/s) for low mobility communication such as pedestrians and stationary users and 100 megabit per second (Mbit/s) for high mobility communication like trains and vehicles [3]. Other requirements for this new access network are high spectral efficiency, high peak data rates, short round trip time and also flexibility in frequency and bandwidth [4].

Backhauling (traffic transmission from cell sites, such as base station/eNodeB, to core networks) of this LTE has witnessed some challenges leading to operators not meeting up to LTE promised deliverables. It is likely very unfeasible for the current microwave backhaul systems of the cellular networks to satisfy the Gigabit promised by 4G networks without promoting latency and poor quality of service (QoS) in the system [5].

Existing backhaul technologies like T1/E1 wire line with maximum bit rate of 155Mbit/s or microwave (with maximum bit rate 620Mbit/s) used by previous generation of networks have not meet the promised deliverables of 4G (LTE) without compromise [6]. To meet the demands of 4G mobile network, a backhaul technology that can support Quality of Service (QoS), cost effectiveness, unlimited capacity is needed. Hence, this research is centered on using Passive Optical Networks (PON) as cellular backhaul for 4G LTE with focus on SMILE mobile communications Port Harcourt. In search of backhaul link that supports quality of service (QoS), unlimited capacity, unrestricted range, high reliability and as well cost effectiveness, a good number of researchers have done tremendous works on improving backhaul networks especially for 4G LTE networks.

(i.) Researchers in [16] pointed out that microwave transmission links encourage speed of rollout especially in green field areas, however noted that limited capacity, poor weather effects, limited range as well as scarce spectrum were its biggest drawbacks as a quality backhaul for 4G LTE networks.

(ii.) In [17], it is also discovered that not only microwave links that are affected by poor weather, limited range and poor capacity, it was noted however from their numerous researches that all radio wave links and all "line of sight" links like WiMAX, mm-wave, Satellite, etc used as backhaul were also having some technical limitations like limited capacity, restricted range, etc .

(iii.) In furtherance, researchers in [17] revealed that in all wired backhaul, only fiber optics has all technical attributes like unlimited capacity, unrestricted range, reliability, scalability required for a good backhaul system. Regrettably, point to point fiber optics deployments tend to be a bit expensive and hence, slow speed of rollout.

(iv.) Researchers in [18] also revealed that Passive Optical Networks PON, which is fiber Optics, reduces the cost of fiber deployments by a reasonable percentage, above 70% depending on the split ratio chosen when used in access network.

II. Passive Optical Network (Pon)

PON technology could be deployed using different concepts, below are some evolutions and available ways and scholarly reviews on deployment of passive optical networks technology based on the transportation scheme and capacity capability.

A-PON an acronym for ATM based Passive Optical Networks, is a PON technology that utilizes ATM cell for its data/signal transportation. A-PON has its works initially developed by Full Service Access Network (FSAN) working group. Later it was transferred to ITU-TSG15. The ITU-TG.983.1 release specifies some certain functionality like its architecture, range, transceiver characteristics and frame structures of A-PON [7]. A-PON consists of an OLT and ONUs which are connected using optical fiber and optical coupler. In the downstream traffic transmission (OLT to ONU), ONU receives a designated cells from the OLT and the transmission is continuous and based on Asynchronous Transfer Mode (ATM) stream at a bit rate of 155.52Mb/s or 622.08 Mb/s with designated PLOAM (Physical Layer Operation, Administration and Maintenance) cells that are inserted into the data stream. On the side of upstream transmission (ONUs to OLT), traffic is in form of burst mode time division multiple access TDMA. ONUs send/transmit their data/information based on the time slots allocated to them and these time slots are generated by the OLT [8]. Figure 1 shows a schematic diagram of a typical A-PON. It showed clearly that the PLOAM cell conveys the upstream time slot allocation information. The ATM transport scheme can support all multimedia services and a bi-directional transmission is achievable with the aid of WDM. In upstream, a burst mode transmission is employed [9]. It uses a wavelength of 1.31μm, likewise a continuous mode transmission at wavelength of 1.55μm is used in the downstream.

In [10], the following upstream and downstream bandwidths were specified for A-PON as listed below. However, ATM- based PON is inefficient for IP traffic.

- 155.52 Mbit/s / 155.52 Mbit/s
- 622.08 Mbit/s / 155.52 Mbit/s
- 622.08 Mbit/s / 622.08 Mbit/s
- 1244.16 Mbit/s / 155.52 Mbit/s
- 1244.16 Mbit/s/ 622.08Mbit/s.

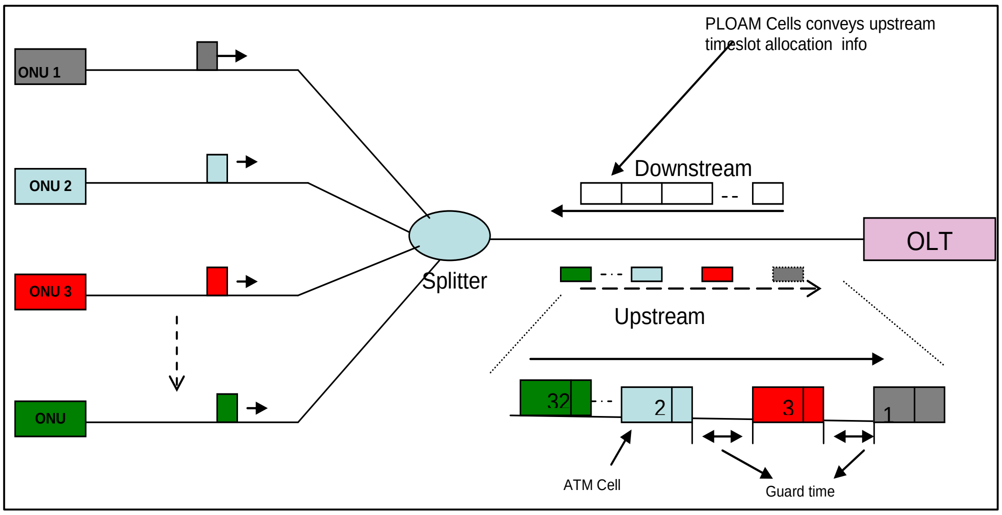

Figure 1: Diagram of A-PON [9]

Broadband Passive Optical Network (B-PON) is another concept of PON defined by ITU-standard (G.983). This concept is used to correct the negative impression that 'ATM-PON support only ATM services'. B-PON is seen to promise the delivery of legacy broadband services and video distribution and is built on the strength of ATM. Like ATM-PON, B-PON Adopts ATM cells for its transportation and employs the Time Division Multiplexing (TDM) techniques in the downstream and Time division multiple access (TDMA) at the upstream transmission directions. A major limitation is the reach as ITU-T specifies 20km as the maximum distance between the OLT and ONU and also 20km for the distance separating the ONU closest to OLT and that farthest from OLT [10].

The concept of Ethernet Passive Optical Network came on board by IEEE 802.3ah in the taskforce called Ethernet in the First Mile (EFM) [10, 11]. For E-PON, Ethernet frame carries all data in encapsulated form and each ONU gets the frame meant for it. The transport protocol in E-PON is based on Ethernet frame and figure 2 shows Ethernet frame structure.

In [10], the speed of E-PON is described as symmetrical and 1Gbit/s with 8B10B block coding and has an operating wavelength of 1490nm downstream and 1310nm upstream for a single fiber and reserving 1550nm wavelength for any expected extensions. A minimum splitting ratio of 1:16 was specified by IEEE 802.3ah. The E-PON supports two different reaches between the OLT and ONU (10km and 20 km). The downstream transmission employs TDM technique while the upstream utilizes TDMA technique. In the downstream transmission, the Ethernet frame is transmitted by OLT and it goes to 1: N splitter which splits according to N (N denotes the number of ONU in the network), and the splitting ratio is between 4 and 64. Each ONU extracts the frame meant for it using the destination MAC address and discards the rest. Figure 2 shows the downstream traffic in E PON. From the diagram, OLT broadcasts many Ethernet frames, on getting to the optical splitter, it sends the same frames to different ONUs and each ONU uses the destination MAC address on the frame to pick the particular frame meant for it.

In the upstream, transmission is between different ONUs to OLT simultaneously and sometimes frames from different ONUs may collide. This has resulted in ONUs sharing the link in either time domain (slots) or using WDM. Ethernet networks can support voice, data, and video and even prioritization and virtual LAN (VLAN) tagging because of its ability to support QoS techniques [11]. In PON, multiple users share single fiber and if any failure occurs in feeder, splitter or OLT, entire user suffers connection problems. To solve this problem, [12] in their work demonstrated video streaming with N: 1 protection of 10G EPON system. Their result showed that uninterrupted service is achievable even during system maintenance using hitless N: 1 PON protection scheme. Its interoperability and cost effectiveness is yet another advantage Ethernet networks is using to get more market among other technologies. Despite known for limited reach and split ratios, an improvement was demonstrated by [12] when 41.3km reach and 128 split 10G EPON system was designed and implemented for commercial broadband access network infrastructure and error free transmission over 130 hours was recorded. Their result proved that N:1 OSU protection with automatic level control semiconductor optical amplifier is a promising approach to practical 10G EPON system that are not only cost effective but also reliable. The major limitation of EPON at the moment is capacity as regards 4G LTE as many researchers in this field are working very hard on the standardization of 100G EPON as shown in the work of [13].

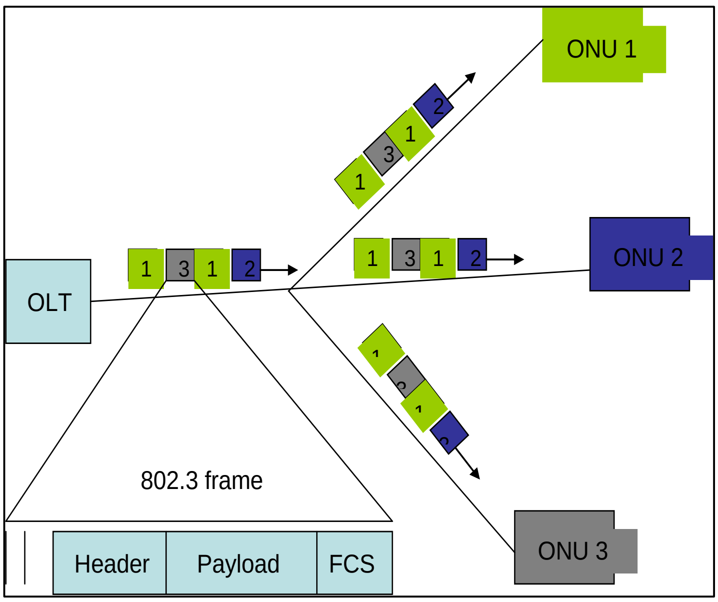

Figure 2: E-PON frame structure.

G-PON is yet another concept of PON developed by ITU-T series G.984 with the intensions of providing high bandwidth requirements for business and residential services. G-PON can utilize either the technology behind Ethernet or ATM in its services, thus, ATM traffics as well as both circuit and packet switched data are being transported by GEM in G-PON frame [10]. In [14] it specifies that G-PON architecture supports a two WDM wavelength schemes for both the downstream and upstream and a reservation of 1550nm wavelength for extension services like analog video services.

Figure 3 specifies the maximum reach of G-PON and also, the reach between two closest and farthest ONUs to the OLT. The diagram also shows the number of splits that can be obtained from G-PON. The G-PON standards specify the following bit rate for downstream and upstream in G-PON [10].
1244.16 Mbit/s / 155.52 Mbit/s
1244.16 Mbit/s / 622.08 Mbit/s
1244.16 Mbit/s / 1244.16 Mbit/s
2488.32 Mbit/s / 155.52 Mbit/s
2488.32 Mbit/s / 622.08 Mbit/s
2488.32 Mbit/s / 1244.16 Mbit/s
2488.32 Mbit/s / 2488.32 Mbit/s.
The ITU-TG 984.2 standards specify a physical medium dependent layer (PMD) parameters.

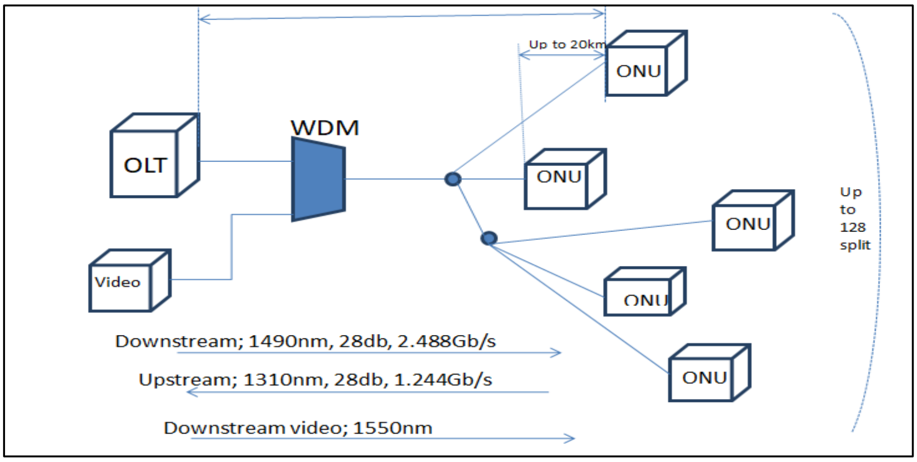

Figure 3: Typical G-PON physical architecture

III. Research Methodology

In this design of Passive Optical Networks as a cellular Backhaul using SMILE 4G mobile Networks as a case study; many factors were put into considerations towards actualizing the work. The work provided relevant information as regards optimizing the splitter location for PON backhaul, using SMILE mobile communication network provider as a case study for the analysis. The analysis used Port Harcourt as a geographical case study. Analytical data for SMILE 4G mobile network in Port Harcourt is generated from network monitor applications (Net monitor). The methods used are as follows:

(i.) Understudy Port Harcourt terrain, identify SMILE network eNBs and their coordinates in Port Harcourt.
(ii.) Computation of Optimal splitter location using ‘manual’ and ‘automatic/systematic’ approaches
(iii.) Dispersion determination for both downstream and upstream transmissions with respect to network capacity and further determine the ranging delays for upstream transmissions
(iv.) Power budget calculations for both downstream and upstream transmission scenarios.
(v.) Implementation of the designed network for both Downstream and upstream transmission in OptiSystem simulation environment.

Numbers (i/ii) to (iv) have been extensively discussed in authors’ previous publications [14, 15 and 20]. In this paper, focus is on the network implementation via simulation. The simulation is carried out using OptiSystem simulation tool and various components like Transmitter section, WDM section, Channel /fiber link and the receiver section of the design were integrated and simulated with the view to demonstrate the Bit Error Rate (BER), Quality factor (Q-factor), etc of each eNB in the network.

Upstream/ Downstream Transmission Analysis

In the downstream section of the transmission, there is transmitter, WDM/splitter, Channel/fiber link, receiver sections. The work takes turn to explain each of the sections starting with the transmitter. The transmitter is made up of four units:

a) Pseudo Random Bit Sequence Generator (PRBS)
b) Non – Return -to- Zero (NRZ) Pulse Generator
c) Light Amplification by Stimulated Emission of Radiation (LASER) Diode
d) Mach-Zehnder Modulator (MZM)

The data source produces pseudo random bit sequence which represents the information to be transmitted, followed in the section is the NRZ pulse generator which converts binary data into electrical pulses. Third in this section is the Laser, it could also be Light emitting diode (LED) or Vertical cavity surface emitting laser (VCSEL) depending on what is intended to achieve. Any of the sources uses wavelength of either 850nm, 1300nm or 1550 nm infrared band. Mach-Zehnder modulator (MZM) is the last in the section and it is used to vary the intensity of the light source from the laser in accordance to the NRZ pulse generator output. Figure 4 shows the block diagram of the transmitter unit.

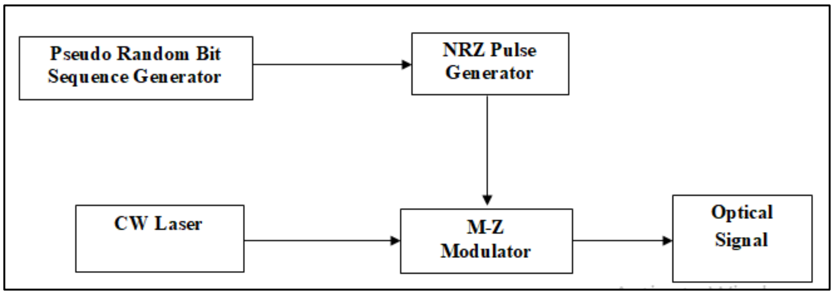

Figure 4: Block diagram of Transmitter section

The required bit rate is 80GB/s for segment A, then there is 10GB/s on each pseudo random bit sequence generator and 3dBm power is lunched into the laser diode. Each optical signal is allocated a wavelength, its frequency starts from 193.1THz through 194.5THz and is spaced 200GHz. Eight of these transmitter units are combined to give 80GB/s in the transmitter section. The signals coming out from the 8x1 WDM mux are allocated dedicated wavelengths, this is displayed in spectrum analyser of figure 5. The output of the mux is fed to SMF which is called the channel/fiber link.

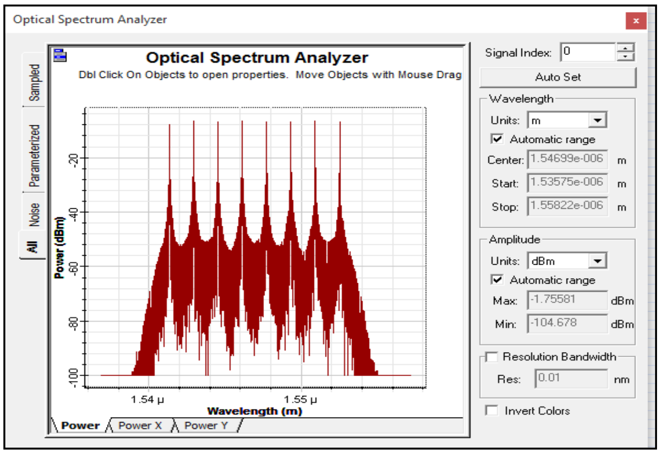

Figure 5: Spectrum Analyser

In upstream direction, ONUs are transmitting to the OLT whereas the OLT receives the signals from various ONUs. WDM transmitters are used in ONU, each ONU is assigned different wavelength, different frequency. Combiners were used in upstream direction instead of splitters as shown in figure 7, here; the combiners combine signals transmitted by four ONUs. Each of the combiners combines separate signals from different ONUs using time division principles. Bessel filter, time delay, optical attenuator and optical fibers of specified lengths are used in the simulation. The filter ensures that only frequency assigned to the transmitter is allowed. Time delay assigns delays to the signal to avoid possible collision in the combiner. The combiner employs time division principles. Hence, signals from the four ONUs are combined.

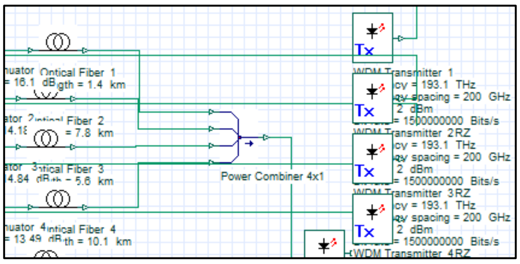

Figure 6: 4x 1 Combiner in OptiSystem environment

Eight number of 4 x 1 combiners were used to combine signals from thirty two (32) ONUs, the output from the 8 combiners constitute the inputs to 8x1 WDM mux as seen in figure 7. The output of the WDM mux became input to DCF and in turn feeds the shared fiber of length 4.8km. Output of fiber feeds WDM demux. The outputs of WDM demux are connected to receiver sections.

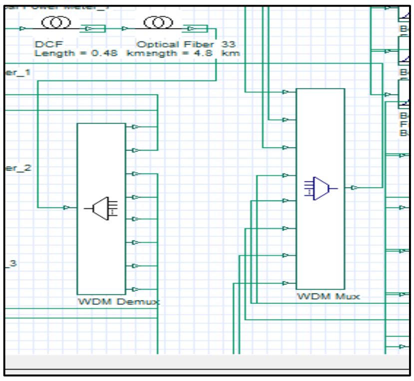

Figure 7: DWM mux, WDM demux, Fiber and DCF in OptiSystem environment

Channel/Fibre Link

The channel in this case is single mode fiber (SMF). The research took time to separate the downstream transmission and the upstream transmission. In each of the transmission directions, SMF is used as the channel. Shared optical fiber length before splitter is 4.8km. Dispersion Compensation Fiber (DCF) was used to compensate for the effect of dispersion in both directions. The Attenuation coefficient of 0.25dB was used to multiply each length of fiber in downstream to achieve the recorded attenuation per fiber length measured in dB/km as derived from the downstream power budget of [20]. Dispersion could lead to pulse spreading and that could limit transmission distances, a dispersion coefficient of 16ps/km.nm was used for both downstream and upstream directions. The effect of dispersion was compensated in this design by using a dispersion compensation fiber (DCF) of length 0.4km with attenuation coefficient of 0.6dB. The DCF has a high dispersion coefficient in the negative domain so as to compensate for the effect of dispersion. Dispersion compensation coefficient of -80ps/km.nm was used.

WDM/Splitter Section

The WDM/Splitter section is made up of WDM and Splitter. Some architecture is made up of Arrayed waveguide gratings (AWG) which is also WDM. In some cases, a combination of both WDM and Splitter is used to achieve greater capacity and it is called Hybrid arrangement. This work considers hybrid architecture to achieve an increased capacity. Figure 8 shows the WDM/Splitter section of this design.

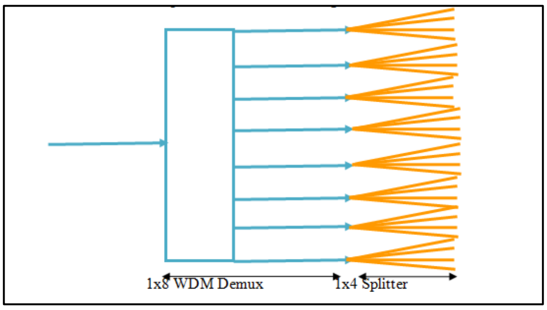

Figure 8: Block diagram of WDM/Splitter section

The channel distribution showing the dedicated wavelengths in frequency domain in the WDM demux is shown in figure 8. The WDM demux and the optical power splitters used in the design have insertion loss of 3.5dB and 6.8dB respectively. The output of the WDM mux used in this design consists of eight port numbering ports 1 through 8 and each carries a dedicated wavelength. The signal from each port goes through a 1x4 optical power splitter. Each optical splitter has four output ports. The information coming out from each wavelength of WDM mux is shared in time domain to the four ports of the splitter output.

Upstream/ Downstream Receiver Section

The receiver section is made up of Positive Intrinsic Negative diode (PIN), Avalanche photo detector diode (APD) or any diode that produces an electrical signal proportional to the received power level. In some cases, an amplifier is added to take care of attenuation effects by boasting the signal level. Sometimes, regenerators could be used instead of amplifiers, and the job of the regenerator is to boast the signal before being fed to an analyzer. Low pass filter separates the noise, also separates wavelengths outside the preferred range. Finally, an integrated signal processing circuit like Bit error rate (BER) analyzer is added to analyze the delivered signal. Figure 9 shows a block diagram of a typical optical receiver section. Low pass filter is used to allow only the desired frequency components at each case. Optical receivers were used. The receiver sensitivity is -29dBm as obtained from the system downstream power budget, see [20]. Amplifier or regenerators were not used since all loses were accounted for in the power budget.

Integration of Transmitter, Channel/fiber link, WDM/splitter and receiver sections make up the network. Figures 10 and 11 gave a block view of all the sections put together in both segments A and B respectively. The exchange/switch houses the OLT (eNB0) and the OLT in turn accommodates the transmitter section, the splitter is seen to represent the spot after the shared fiber, WDM or optical power splitter distributes/multicasts the signal down to each ONU in the downstream direction. Each ONU represents eNB and BER analyser indicates among other things the bit error rate, Q factor per OLT-ONU pair.

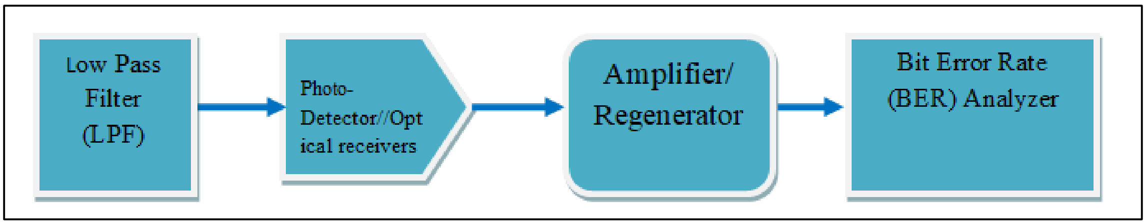

Figure 9: Block diagram of optical receiver section

Block diagrams showing the design of both segments A and B of the network is shown in figure 10 and 11. It consists of one OLT, SMF, DCF, a splitter and thirty two ONUs for a segment. The parameters of each of the components used in this design is as contained in the downstream power budget of [20] and the system/ network architecture showing full network implementation in OptiSystem for segment A and segment B is shown in the figure 12 to 15. Segment A of the upstream or the downstream shows ONU 1 to 32 while Segment B shows ONU 33 to 64.

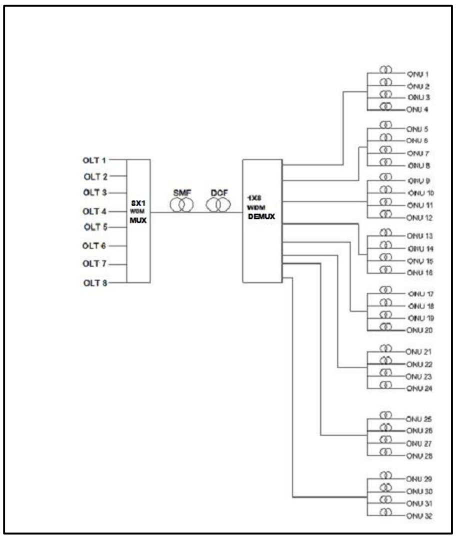

Figure 10: Block diagram of segment A of the network

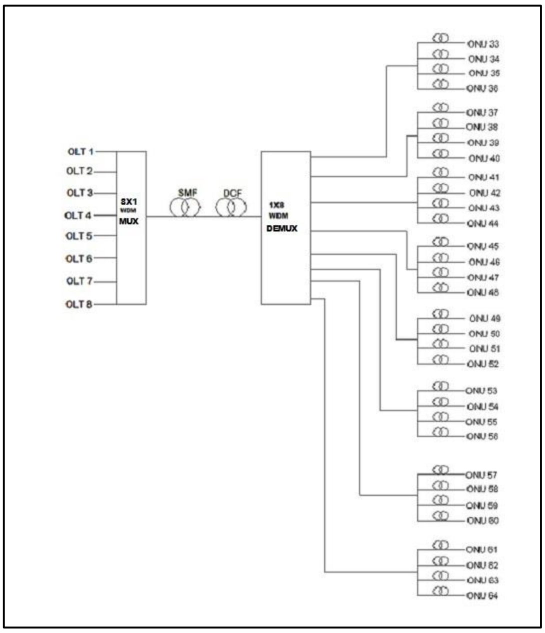

Figure 11: Block diagram of segment B of the network

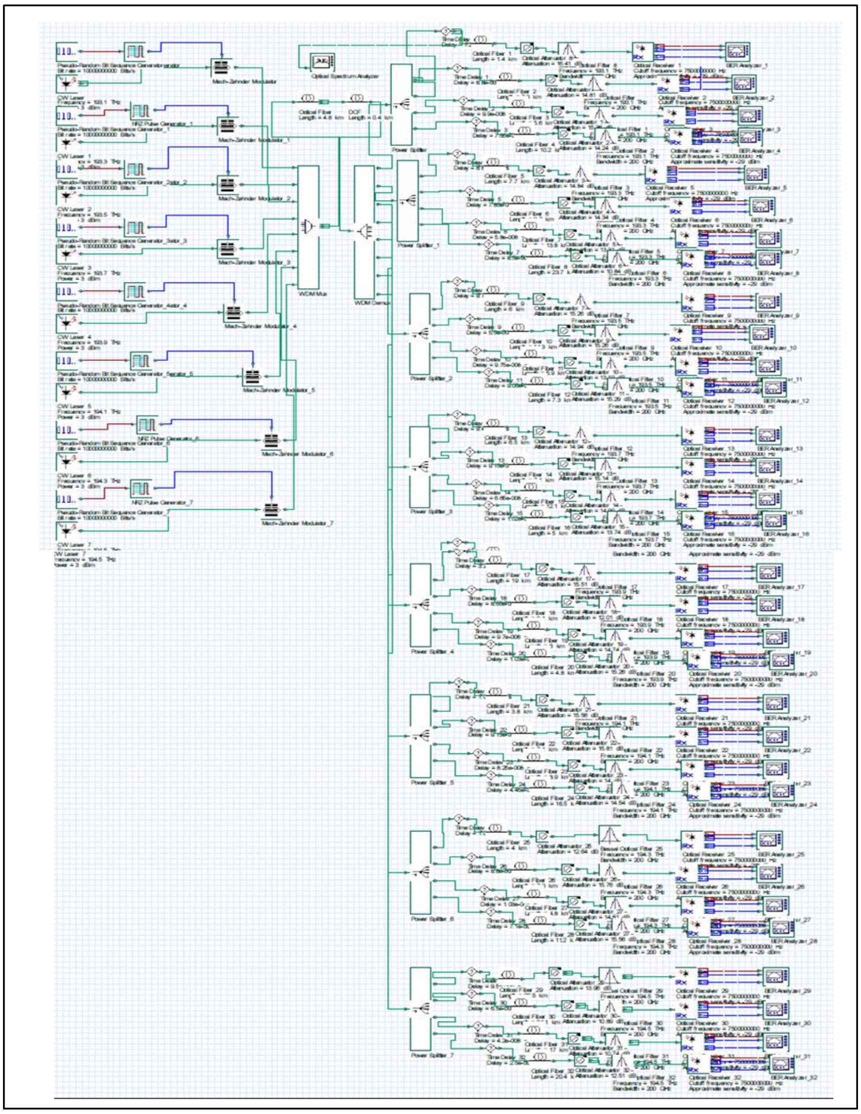

Figure 12: Full Network implementation for Downstream Segment A

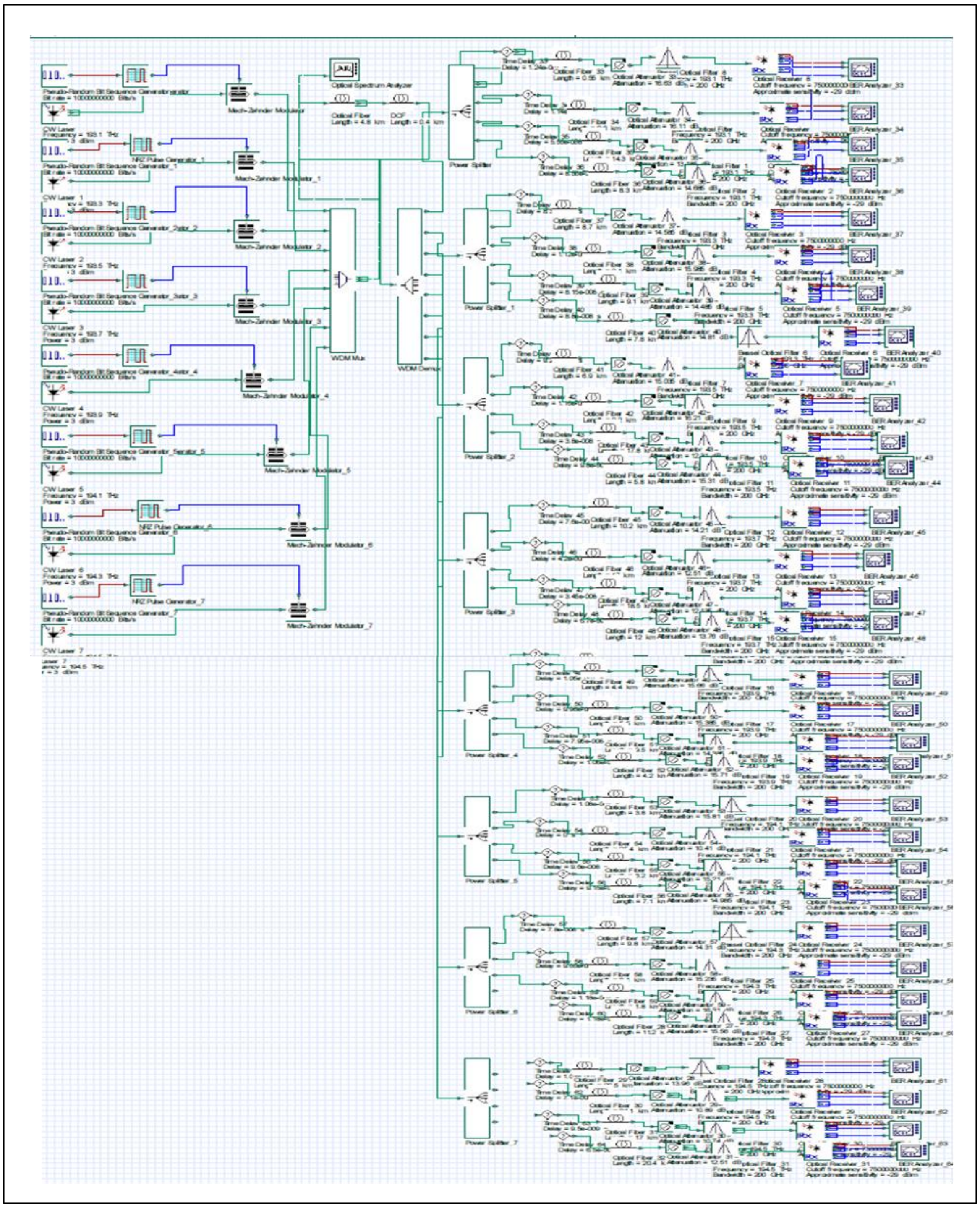

Figure 13: Full Network implementation for Downstream Segment B

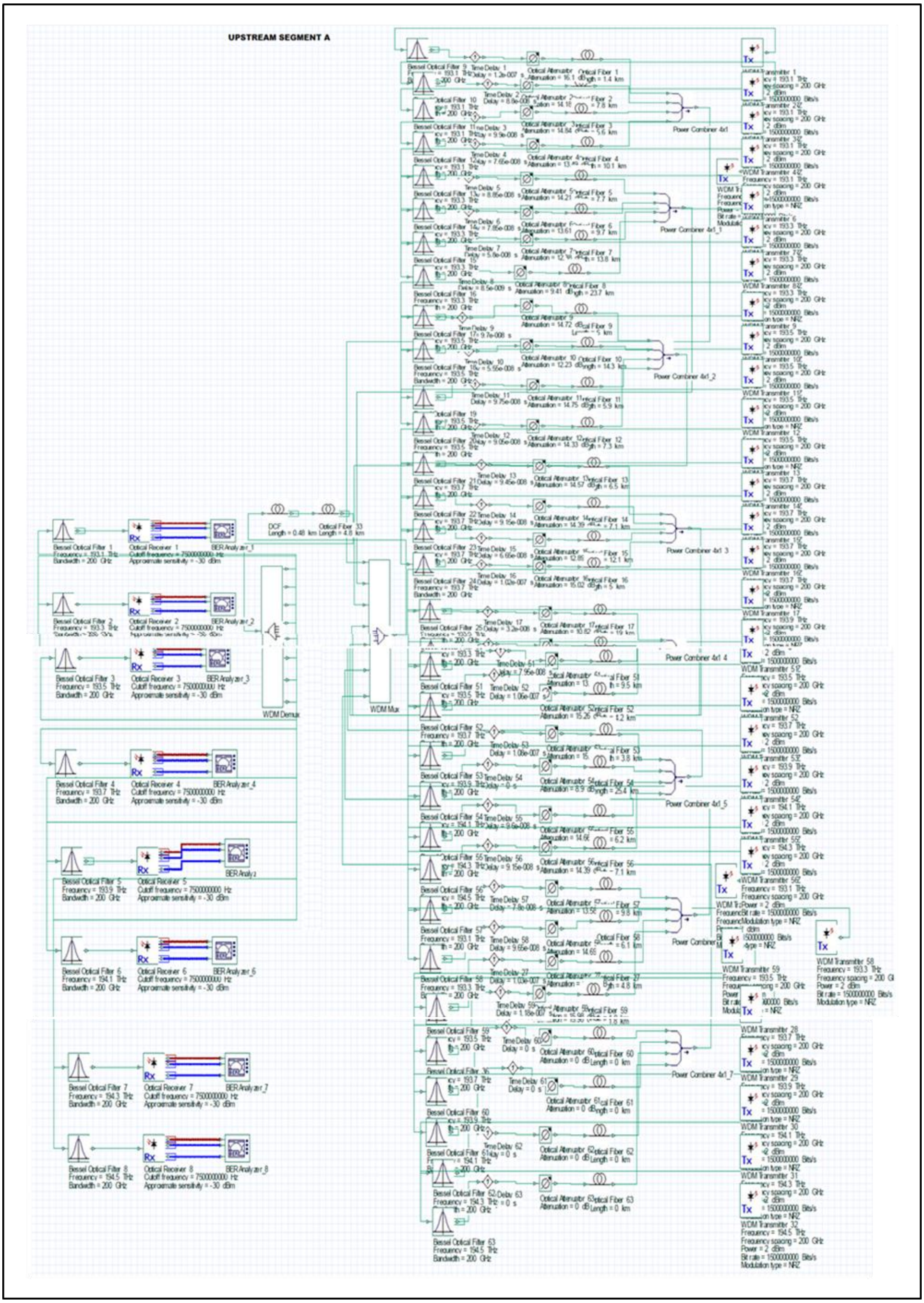

Figure 14: Full Network implementation for Upstream Segment A

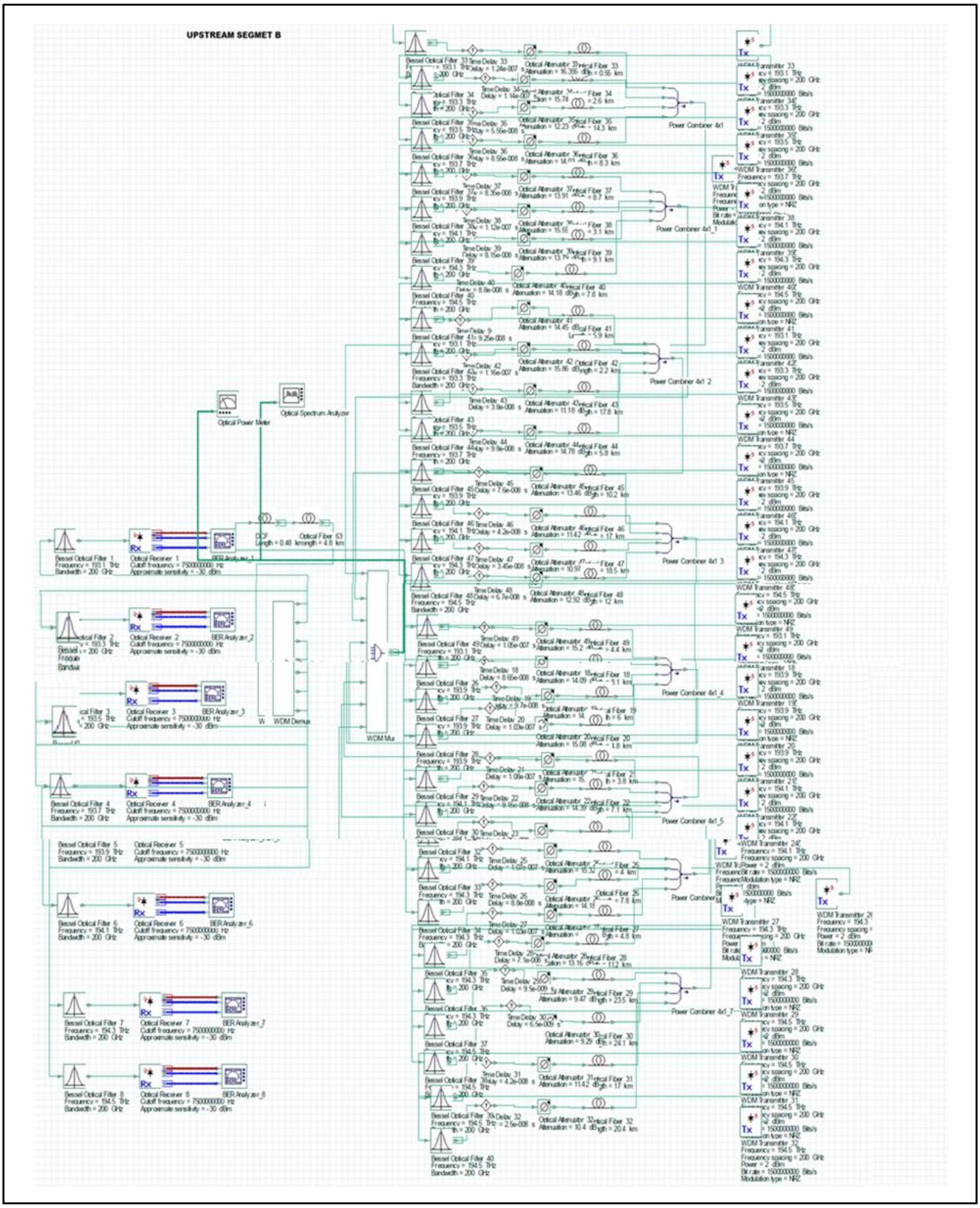

Figure 15: Full Network implementation for Upstream Segment B

IV. Results And Discussion

The simulation results for the downstream transmission are divided into segments A and B just as it was done in the network design. Each result shown represents OLT –ONU pair downstream transmission and it is as shown in a bit error rate (BER) analyser (shown in Figure 16).

The analyser used BER and Q factor to analyse the quality of the backhaul link. BER and Q factor are two important parameters that are used to analyse the results obtained in optical communication system. Bit error rate simply called BER is seen as an indicator to measure transmission quality. In Telecommunication, BER represents the percentage of error per bit transmitted relative to total number of bits received. An example is when one million bits is transmitted and only one bit is in error (10^{-6}), The BER so obtained is said to be E-6.

Also, Quality factor (Q factor) measures the level of noise in a pulse, in other words, it provides a qualitative description of the receiver performance. The larger the values of Q factor, the freer the pulse (received signal) from noise, hence, the smaller the value obtained as BER. According to [14], optical transmission links is classified a quality link if it has a minimum BER of E-9. These explanations of BER and Q factor is used to analyze the results obtained in segment A as depicted in table 1.

Table 1: BER and Q factor results for Downstream segment A

eNBs	BER	Q Factors
eNB 1	3.29E-19	8.86
eNB 2	1.26E-19	8.97
eNB 3	5.84E-16	7.98
eNB 4	8.69E-19	8.76
eNB 5	4.67E-16	8.01
eNB 6	6.22E-18	8.53
eNB 7	6.30E-19	8.79
eNB 8	2.16E-14	7.53
eNB 9	4.60E-16	8.01
eNB 10	6.16E-10	6.06
eNB 11	3.29E-29	11.14
eNB 12	1.36E-15	7.88
eNB 13	5.26E-20	9.06
eNB 14	1.31E-16	8.16
eNB 15	6.10E-12	6.76
eNB 16	7.70E-26	10.43
eNB 17	1.94E-08	5.48
eNB 18	6.79E-34	12.07
eNB 19	1.15E-21	9.47
eNB 20	2.92E-18	8.62
eNB 21	3.92E-24	10.06
eNB 22	1.20E-16	8.18
eNB 23	2.58E-21	9.39
eNB 24	7.79E-11	6.37
eNB 25	3.61E-39	13.03
eNB 26	7.36E-15	7.67
eNB 27	1.45E-18	8.7
eNB 28	2.72E-13	7.19
eNB 29	9.18E-09	5.6
eNB 30	1.70E-13	7.26
eNB 31	1.85E-19	8.93
eNB 32	1.45E-14	7.59

The following deductions were made: eNB1 to eNB32 have very low bit error rates ranging from E-39 to E-8. Representing a range of BER classified as high quality link with very low bit error rate. eNB 25 has the lowest BER error per bit. In the same vain, eNB 25 has a Q factor of 13.03. The results so obtained showed that segment A of the transmission link has a very good quality of a backhaul link. Table 1 gave a breakdown of BER and Q factor for each eNB in segment A.

Figure 17 shows the radar plots of BER and Q factor for segment A (eNB1 to eNB32) respectively, the plots represent the results obtained in table 1. The blue lines represent BER whereas the red lines represents Q factor. In both graphs, eNB25 shows very high value for Q factor whereas eNB29 gave lowest value for Q factor. None of the results from all the 32 eNB analysers showed a BER value higher than E-8 which translates to a very good backhaul link.

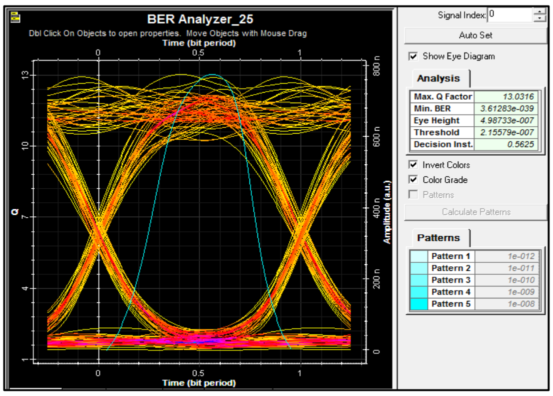

Figure 16: The Eye diagram/BER analyzer for eNB 25

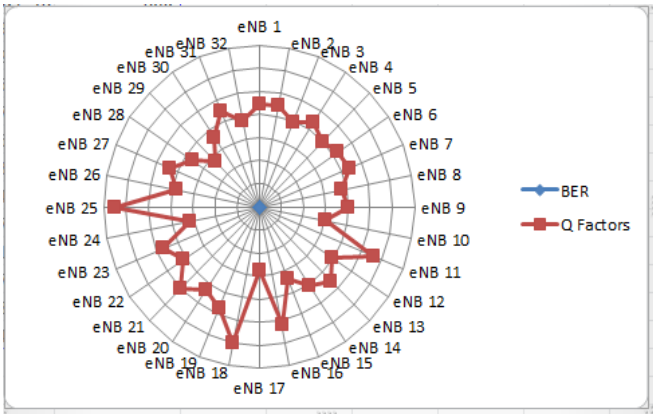

Figure 17: BER and Q factor in Radar plot (Downstream Segment A)

Segment B covers eNB 33 to 59. Provisions were made for possible expansion that is why it covered up to 64 eNBs. From the results obtained, none of BER from all the analysers has a BER value higher than E-13. The eNB 42 has the lowest bit error rate (1.17E-27) and a Q factor of 10.82 whereas eNB 47 has BER of 7.58 x10-13 and a Q factor of 7.06 respectively. The values of BER and Q factor of other eNBs in the downstream segment B is as shown in table 2.

The results as shown in table 2 are plotted in figure 19. It shows the distribution of Q factor and BER per eNB in radar graph representation of figure 17. According to Figure 19, all the eNBs in the radar plot of segment B have very low bit error rate and corresponding Q factor. The eNB 42 showed highest Q factor translating lowest BER (Eye diagram shown in Figure 18). Accordingly, all the BER analysers on this segment B demonstrated qualities of a good backhaul link.

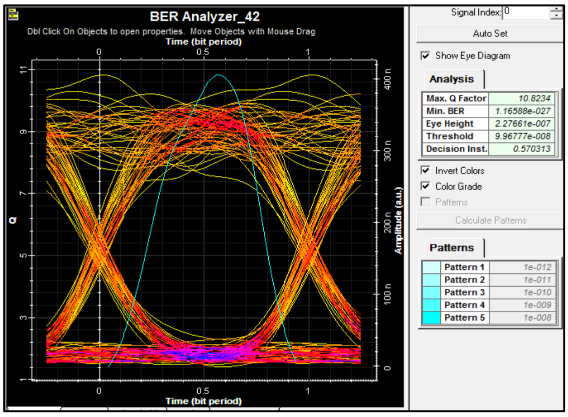

Figure 18: BER Analyzer for eNB42

The simulation results for the upstream transmission are also divided into segments A and B just as it was done in the network design. The assigned ranging delays from [21] ensured no collision at the OLT since multiple eNBs (ONUs) were sending to OLT. Each analyser used BER and Q factor to analyse the quality of signals coming from multiple eNBs. As discussed, BER and Q factor are two important parameters that are used to analyse the results obtained in optical communication system. Segment A of the upstream showed BER analysers when ONU 1 to 32 were transmitting.

As stated, upstream transmission is when eNBs are transmitting to the OLT. Table 3 showed BER and Q factor values as obtained from the 8 BER analysers.

All the eight analysers showed very low error per bits with values ranging from E-18 to E-25 and Q factors 8.52 to 10.32 respectively. The values of BER and Q factors obtained are typical of a good optical backhaul system. The radar graph of figure 20 clearly shows that error per bit on each analyser is relatively infinitesimal while Q factor values are high. Again, the result showed a good optical backhaul system.

Segment B results of the upstream as obtained when ONU 33 to 59 are transmitting are as shown in the BER and Q factor as obtained from each of the eye diagrams results from all the eight analysers which have been collated in Table 4. This shows that error per bit from the signals transmitted were very insignificant.

Table 2: BER and Q factor results for Downstream segment B

eNBs	BER	Q Factor
eNB 33	1.47E-18	8.69
eNB 34	7.08E-20	9.03
eNB 35	2.02E-15	7.83
eNB 36	1.66E-15	7.86
eNB 37	3.74E-17	8.32
eNB 38	1.01E-19	8.99
eNB 39	3.83E-23	9.82
eNB 40	5.88E-19	8.81
eNB 41	2.14E-24	10.11
eNB 42	1.17E-27	10.82
eNB 43	1.01E-13	7.33
eNB 44	3.87E-18	8.58
eNB 45	2.68E-18	8.62
eNB 46	2.11E-15	7.83
eNB 47	7.58E-13	7.06
eNB 48	3.43E-15	7.76
eNB 49	8.08E-16	7.94
eNB 50	5.88E-19	8.8
eNB 51	5.79E-19	8.8
eNB 52	6.37E-20	9.05
eNB 53	8.66E-21	9.27
eNB 54	2.36E-13	7.21
eNB 55	6.28E-17	8.25
eNB 56	2.42E-22	9.63
eNB 57	7.43E-17	8.24
eNB 58	9.43E-16	7.93
eNB 59	4.61E-17	8.29

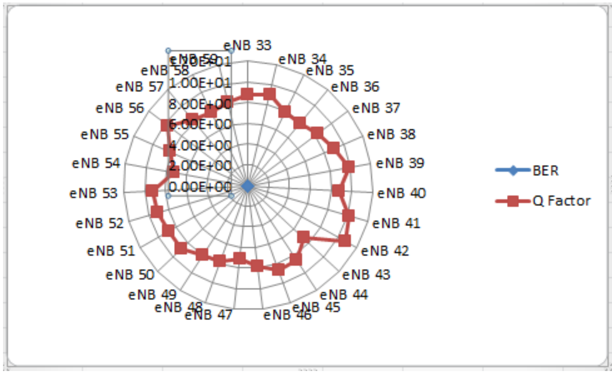

Figure 19: BER and Q factor in Radar plot (Downstream Segment B)

Table 3: BER and Q factor results for segment A (Upstream)

BER ANALYSERS	BER	Q FACTOR
BER ANALYSER 1	1.37E-19	8.97
BER ANALYSER 2	1.02E-21	9.48
BER ANALYSER 3	7.01E-18	8.52
BER ANALYSER 4	4.15E-24	10.04
BER ANALYSER 5	3.28E-23	9.84
BER ANALYSER 6	8.68E-21	9.25
BER ANALYSER 7	1.12E-21	9.46
BER ANALYSER 8	2.29E-25	10.32

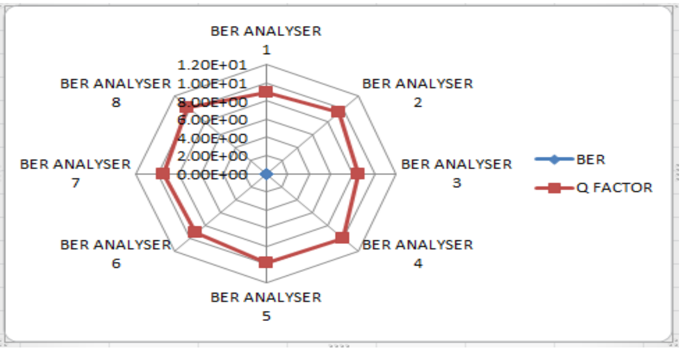

Figure 20: BER and Q factor in Radar Plot (Upstream Segment A)

Table 4: BER and Q factor results for segment B (Upstream)

BER ANALYSERS	BER	Q FACTOR
ANALYSER 1	8.30E-17	8.23
ANALYSER 2	1.61E-17	8.42
ANALYSER 3	2.91E-21	9.37
ANALYSER 4	7.02E-22	9.53
ANALYSER 5	1.53E-21	9.44
ANALYSER 6	2.45E-22	9.63
ANALYSER 7	2.40E-22	9.63
ANALYSER 8	4.46E-25	10.25

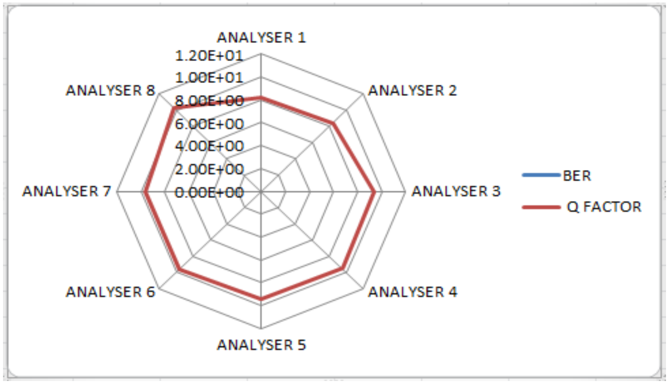

Figure 21: BER and Q factor in Radar Plot (Upstream Segment B)

Radar Plot in Figure 21 shows the results as obtained from table 4. The Blue lines represent BER for each analyser. Analyser 8 is seen as the link with the least error per bit, this is because it has the highest Q factor of value 10.25 and BER value of 4.46E-25, and this represents an optical link with infinitesimal error per bit and translates to a high quality backhaul link. Same analyses go to analysers 1 to 7 of figure 21. This demonstrates a quality backhaul system.

Finally Table 5 shows performance of the existing SMILE 4G LTE microwave transmission link and that of the developed Passive Optical Network backhaul system. Also shown on table 5 is the average BER value of each of the links.

Table 5: BER for both SMILE Microwave link and that of Developed PON link

eNBs	BER on Microwave Link	BER on the Developed PON Link
eNB 0	7.55E-05	8.95E-19
eNB 1	3.25E-05	3.29E-19
eNB 2	6.42E-05	1.26E-19
eNB 3	8.20E-04	5.84E-16
eNB 4	6.38E-05	8.69E-19

eNB 5	7.46E-05	4.67E-16
eNB 6	4.60E-03	6.22E-18
eNB 7	9.36E-04	6.30E-19
eNB 8	3.71E-05	2.16E-14
eNB 9	8.61E-04	4.60E-16
eNB 10	7.24E-05	6.16E-10
eNB 11	4.85E-05	3.29E-29
eNB 12	6.48E-04	1.36E-15
eNB 13	4.72E-04	5.26E-20
eNB 14	5.44E-05	1.31E-16
eNB 15	9.32E-05	6.10E-12
eNB 16	4.47E-05	7.70E-26
eNB 17	5.89E-04	1.94E-08
eNB 18	7.67E-05	6.79E-34
eNB 19	4.81E-03	1.15E-21
eNB 20	6.29E-04	2.92E-18
eNB 21	6.23E-05	3.92E-24
eNB 22	4.84E-04	1.20E-16
eNB 23	4.22E-04	2.58E-21
eNB 24	8.46E-05	7.79E-11
eNB 25	3.54E-04	3.61E-39
eNB 26	6.18E-05	7.36E-15
eNB 27	7.05E-05	1.45E-18
eNB 28	4.49E-05	2.72E-13
eNB 29	6.17E-04	9.18E-09
eNB 30	3.21E-03	1.70E-13
eNB 31	4.33E-05	1.85E-19
eNB 32	6.20E-05	1.45E-14
eNB 33	3.09E-05	1.47E-18
eNB 34	8.16E-05	7.08E-20
eNB 35	6.11E-05	2.02E-15
eNB 36	5.59E-04	1.66E-15
eNB 37	7.02E-05	3.74E-17
eNB 38	2.43E-03	1.01E-19
eNB 39	3.19E-04	3.83E-23
eNB 40	6.15E-05	5.88E-19
eNB 41	4.13E-04	2.14E-24
eNB 42	8.14E-05	1.17E-27
eNB 43	7.34E-05	1.01E-13
eNB 44	5.15E-05	3.87E-18
eNB 45	7.01E-05	2.68E-18
eNB 46	3.36E-04	2.11E-15
eNB 47	1.89E-03	7.58E-13
eNB 48	4.66E-04	3.43E-15
eNB 49	5.12E-04	8.08E-16
eNB 50	3.65E-03	5.88E-19
eNB 51	7.10E-05	5.79E-19
eNB 52	8.31E-05	6.37E-20
eNB 53	4.14E-04	8.66E-21
eNB 54	7.43E-05	2.36E-13
eNB 55	6.02E-05	6.28E-17
eNB 56	8.05E-05	2.42E-22
eNB 57	4.26E-04	7.43E-17
eNB 58	4.88E-05	9.43E-16
eNB 59	9.13E-05	4.61E-17
AVERAGE BER VALUE	**5.52E-04**	**4.88E-10**

For the microwave, the average BER value is 5.52e-4 whereas, Passive Optical Network backhaul link has average BER of 4.88e-10. The average BER value for the microwave indicates that for 10000 bits transmitted, there could be a single error or a single bit loss. However, for the developed PON backhaul system, the average BER of 4.88e-10 indicates that for every 10giga bits (10000000000 bits) transmitted, there is/could be a single bit error. In figure 22, a linear distribution of BER of SMILE existing microwave link and that of the developed PON network as contained in table 5 is plotted. The graph showed that the BER values of the developed PON network is lower compared to its existing microwave link and hence a better transmission Network. Similarly, figure 23 showed a radar representation of BER values of table 5. It revealed that BER values for the developed PON network are smaller than that of the existing microwave link and hence, a higher quality backhaul network.

Comparing the average BER for both systems, the performance improvement seen using the developed PON network is calculated as follows:
Percentage Performance improvement;
(Pi) = (SAB-PAB)/SAB x100
Where SAB = SMILE Average BER Value = 5.52e-04
PAB = PON Average BER value = 4.88e-10
Substituting value into equation 4.2,
Pi = (5.52 e-04 - 4.88e-10)/(5.52e-04) x 100 = 99.99%, hence PON provided 99.99% performance improvement.

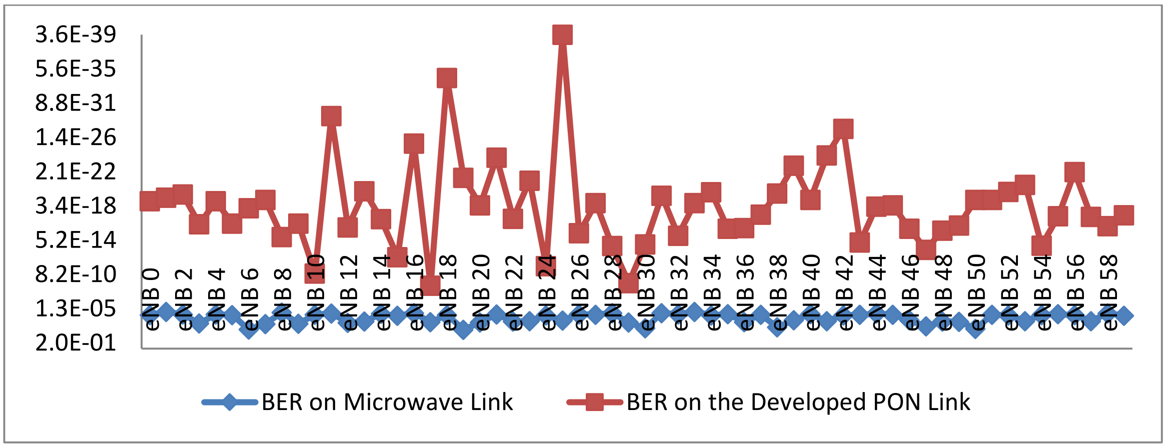

Figure 22: BER distribution on existing SMILE network and that of developed PON Network

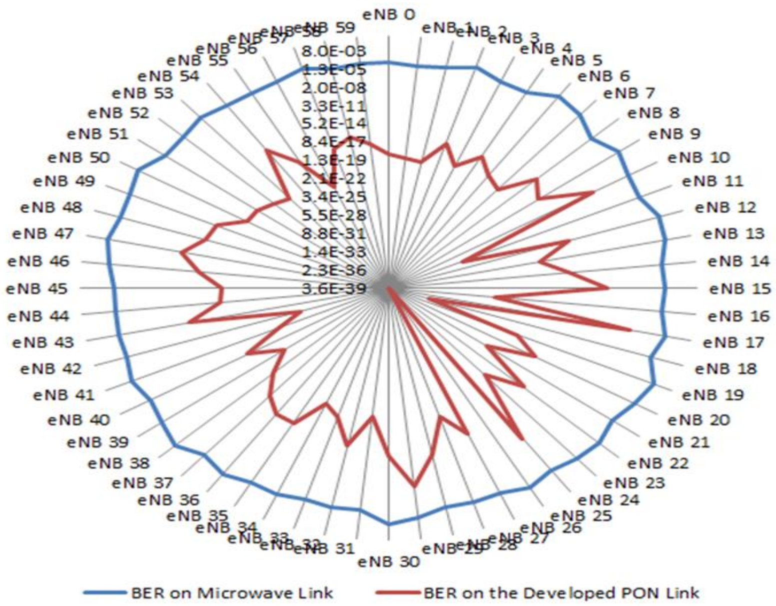

Figure 23: Radar representation of BER on SMILE Microwave and the developed PON system

V. Conclusions

This research employed the use of Passive Optical Network (PON) as a cellular backhaul for 4G LTE network using SMILE 4G networks Port Harcourt Rivers state Nigeria as a case study. Effectiveness of the developed PON network was validated using OptiSystem simulation tool. The simulation demonstrated that both downstream and upstream transmissions are implementable and results displayed in BER analysers showed average BER value of 4.88e-10 and Q factor values obtained were used to characterize the viability of the developed system as a quality backhaul network for 4G LTE. Finally, Performance of the existing SMILE microwave backhaul network was compared with the developed PON model and the developed PON network showed 99.99% improvement over existing SMILE microwave link.

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