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Gigabit Passive Optical Networks: Undetected Signal Tapping

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ABSTRACT

Recently, the customer high demands for increasing bandwidth and high data rates have necessitated the provision of innovative services such as video cameras and high-speed internet. Although Very High-speed Digital Subscriber Line (VDSL) technology addresses the demand for high bandwidth, it has significant drawbacks in terms of long-distance communications and high attenuation. To overcome the attenuation in cables over long distances and also to increase the bandwidth and data rate, the solution is the use of fibre optic networks. These networks are divided into passive and active networks. Among the different optical network choices, Gigabit Passive Optical Networks (GPONs) have acquired popularity due to their energy-efficiency because they use extremely small power to operate effectively. Furthermore, it consumes 95% less energy than copper networks and it offers a very high traffic speed of up to 100 Gbps for subscribers. The purpose of this study is to evaluate the performance of GPONs under varied transmission powers and frequencies while subjected to undetected signal tapping. The recommended approach includes eavesdropping on upstream and downstream networks without detection. This is accomplished by using an optical coupler with predetermined splitting ratios (10:90, 5:95, 2:98 and 1:99) and insertion losses (0.75 dB, 0.4 dB, 0.3 dB and 0.25 dB). Furthermore, the distance between the coupler and the Optical Line Terminal (OLT) is set to 2-10 km. To measure the quality of the intercepted signals before and after the interception, the Optisystem software is used.

1. Introduction

GPON is a point-to-multipoint network technology that provides broadband connectivity to the end-user over fibre optic cable. The word 'Gigabit' in GPON refers to the highest speed it delivers, which is generally 2.488 Gbps downstream (DS) and 1.244 Gbps upstream (US). Keep in mind that this bandwidth is shared by end users. 'Passive', on the other hand, indicates that the optical fibre network is not powered by any electrical equipment. Today, GPON technology is considered to be the most prevalent type of optical fibre connection. In addition, GPON can send data through a single

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optical fibre to up to 64 users, making it the preferred optical network standard for delivering last-mile connections in an efficient and cost-effective way [1-5].

GPONs typically comprise three main components. Firstly, the OLT unit serves as the network manager and is responsible for sending optical data to the end of users through a process called wavelength division multiplexing (WDM) and receiving optical signals carrying video, data and voice from the ONT located at the receiver's end. Secondly, the Optical Distribution Network (ODN) includes passive elements like fibre cables and splitters. The splitting ratio of the splitter varies depending on the number of outputs required by end-users, ranging from 1:2 to 1:64. Lastly, the user end-point of GPON is the Optical Network Terminal (ONT) or Optical Network Unit (ONU), a specialized modem that converts optical signals into electrical signals at the end-user premises [6-8]. This enables broadband access for various devices such as Wi-Fi, TVs, desktops, phones, laptops, etc., as illustrated in Figure 1. The choice between GPONs and active optical networks (AONs) depends on specific requirements and circumstances. The GPON operates on a passive infrastructure, using optical splitters and reduces power consumption and maintenance needs.

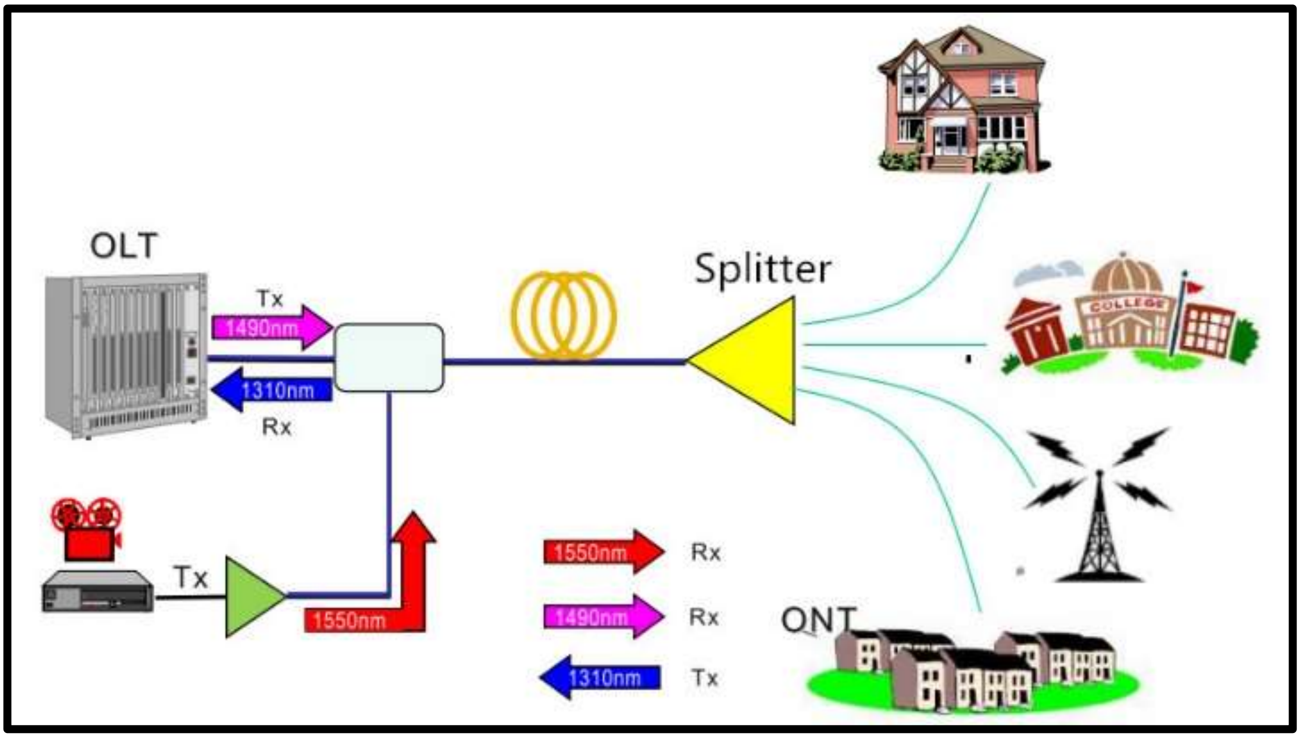


Fig. 1. GPON network architecture [9]

GPON technology has many advantages. First of all, compared with different cabling systems, it can send data across greater distances, up to 20 km. The range of other cabling technologies, including traditional copper, is only roughly 500 m. Secondly, the cost of installing GPON technology is cheaper than that of a copper LAN network. GPON is about 40–50% less expensive. It requires less time to set up and less money to operate. More fibres can be eliminated by using a splitter to divide a single fibre into numerous signals. Unlike copper cables, maintenance is not performed often because it happens rarely, equipment needs less maintenance. Things like this make it highly cost-effective. Lastly, the use of GPON technology provides the network with a high data rate up to 10 GHz and a low attenuation of 0.21 dB/km.

In this paper, undetectable tapping is carried out on the US and DS signals in the GPON network. To accomplish this, an optical coupler is utilized with varying Splitting Ratios (SRs) of 10:90, 5:95, 2:98 and 1:99 and a corresponding insertion loss of 0.75 dB, 0.4 dB, 0.3 dB and 0.25 dB, respectively.

Furthermore, the distance between the coupler and the OLT is adjusted to 5 km, 10 km and 15 km. To evaluate the intercepted signals quality, both before and after the interception, several evaluation parameters are considered. The Optisystem simulator is employed to measure the bit error rate (BER), eye height and quality factor (Q-factor). These parameters serve as indicators of signal quality and provide valuable insights into the effects of interception. Subsequently, the results obtained from these scenarios are compared and the optimal distance from the OLT for undetectable signal interception by users is determined. The contributions of this paper can be highlighted as follows.

This paper demonstrates the prevalence of the GPON technology as the predominant type of optical fibre connection with 1:64 ratios on a single fibre and potential scalability. An innovative method is introduced for the unauthorized interception of optical fibre signals, employing either an optical coupler with a splitting ratio of 10:90. This study highlights the feasibility of signal interception without detecting by using an optical coupler with a splitting ratio 10:90 or by employing an optical amplifier with 2.65 dB gain to the coupler BER ≤ 10^{-10} for the intercepted signal. with a splitting ratio of 5:95 ensuring a satisfactory performance. These contributions highlight the paper's innovative findings and practical implications for the security and vulnerability assessment of GPON networks.

2. Literature Review

Spurny *et al.,* [10] introduced a collaborative research study with the objective of addressing the issue of information disclosure within the optical fibre infrastructure. Their investigation encompasses an examination of both passive and active components of the infrastructure, with a focus on evaluating diverse attack scenarios. Similarly, Furdek *et al.,* [11] conducted a comprehensive analysis aimed at gaining a thorough understanding of the potential security concerns prevalent in present and upcoming optical networks. Their research emphasized the identification and elucidation of possible attack methods that exploit vulnerabilities inherent in these networks. Domb *et al.,* [12] explored innovative ideas and approaches for enabling secure optical data transmission, thereby surpassing the limitations of existing methods and technologies. Maslo *et al.,* [13] undertook a study from the physical layer perspective, with a primary focus on the security issues surrounding optical networks. Their research encompassed an examination of various forms of attacks and the proposal of protective measures against tapping and passive data analysis at the physical level of the optical network. Furthermore, they introduced an enhanced security mechanism, termed enhanced security of Dynamic Bandwidth Allocation (DBA), designed to counteract specific threats. This mechanism incorporated a recognition stage crucial for the detection and mitigation of any anomalous activities observed among ONUs. Once an attacker was identified, appropriate sanctions were enforced to discourage any further attempts and restore equity among the ONUs. This particular approach was previously investigated by Atan *et al.,* [14]. In the specific context of ODNs, a notable contribution was made by Malina *et al.,* [15] who introduced an innovative and resilient security solution. Their approach focused on ensuring secure mutual verification and key establishment between OLT units and end units (i.e., ONUs) within the ODN. This solution was designed to enhance the overall security of the ODN. Furthermore, Saltykov *et al.,* [16] introduced a novel approach aimed at monitoring and detecting unauthorized intrusion and eavesdropping in optical fibre access networks [17-19]. Their research also involved the development of a comprehensive framework for evaluating vulnerability and risk factors in potential malicious tapping scenarios. More studies are utilized using more modern technologies, including computer applications [20-22].

These studies significantly contributed to the research field of optical network security by examining various critical aspects, including attack scenarios, vulnerabilities, protective measures and mitigation strategies. By providing valuable insights and a deeper understanding of the security challenges faced in optical communication systems, these findings serve as a foundation for the development of more robust and secure optical networks.

3. Methodology and Optisystem Simulation

We initially established the fundamental parameters that significantly influence the performance of optical networks, namely the Optical Signal-to-Noise Ratio (OSNR), Q-factor and BER. The OSNR is a crucial metric that indicates the strength of the signal in the network and it can be effectively represented by the height of the eye diagram. The height of the eye diagram corresponds to the level of noise that the signal can tolerate, where a greater height indicates a stronger signal. The OSNR, through output and input power, can be mathematically expressed as in Eq. (1) [23-26]:

$$\text{OSNR}= (P_{out}/P_{in}) \tag{1}$$

The OSNR is given by the average output power to noise power. To measure the quality of the signal, we use the OSNR as follows in Eq. (2):

$$Q = \text{OSNR} + 10 \log (B_0/B_e) \tag{2}$$

Where, $B_0$is the photodetector's optical bandwidth and B_e is the receiver filter's electrical bandwidth. As a result, the relation between the quality factor and eye height is indicated in the calculations below in Eqs. (3) – (6):

$$\text{Q}= (\mu_1\text{-}\mu_o)(\sigma_1 + \sigma_o) \tag{3}$$

$$\text{Eye height} = (\mu_1 - 3\sigma_1) \text{ - } (\mu_0 + 3\sigma_0) \tag{4}$$

$$\text{Eye height} = (\mu_1\text{-}\mu_\circ) \text{ - } 3(\sigma_1 + \sigma_0) \tag{5}$$

$$\text{Eye height} = (\sigma_1 + \sigma_0)\ (\text{Q - 3}) \tag{6}$$

Where, μ_1 and μ_0 are the mean voltage values of ones and zeros respectively. However, σ_1 and σ_0 are the standard deviation of the additive white noise of the Gaussian distribution of the signal.

The BER, in terms of the Q-factor, is given by Eqs. (7) and (8):

$$\text{BER} =0.5 \times (\text{erfc } (\text{Q}/\sqrt{2}\ )) \tag{7}$$

$$\text{erfc (x)} = (2/\sqrt{\pi}\ )\int_{x}^{\infty} e^{-t^2}\ dt \tag{8}$$

Where, erfc (x) is the complementary error function.

The objective of this research is to optimize the transmission of signals over long distances while minimizing power consumption and eliminating the need for signal amplification. To achieve this goal, we investigate the impact of various parameters on the performance of the optical network. In this context, we varied the transmitted power of the continuous wave (CW) laser within the range of -3 dBm to 3 dBm for DS transmission. Additionally, we changed the length of the bidirectional fibre from 10 to 20 km. By implementing these adjustments, we aimed to evaluate the resulting changes in the Q-factor and BER. In the subsequent subsections, we presented different configurations for the optical network, outlining the specific settings and parameters employed in each scenario. This comprehensive analysis allowed us to assess the performance of the network under varying conditions and identify optimal configurations for achieving maximum signal transmission distance with minimal power utilization.

The GPON comprises several key components, including a voice and data transmitter unit, a video transmitter unit, a circular bidirectional coupler, a bidirectional fibre, a splitter and an ONU. The voice and data transmitter unit in the GPON network consists of several components. One of the crucial components is a four-part Pseudo-Random Bit Sequence Generator (PRBSG), which is responsible for generating pseudorandom binary data consisting of zeros and ones. To convert the electrical pulses from zero to one, a non-return to zero (NRZ) pulse generator is utilized. An optical signal is generated using a CW laser. The final component in the transmitter unit is the Mach-Zehnder modulator (MZM), which plays a pivotal role in converting electrical pulses into optical pulses. This conversion allows for the transmission of data across the optical fibre. This is shown in Figure 2.

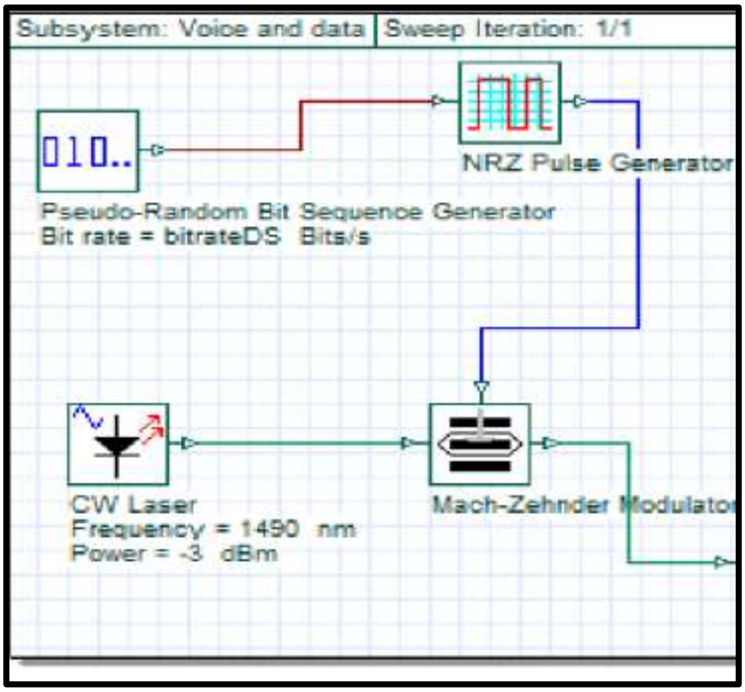

Subsystem: Voice and data
Sweep Iteration: 1/1
Bit rate = bitrateDS Bits/s
Frequency = 1490 nm
Power = -3 dBm

Fig. 2. Architecture of the voice/data transmitter using the Optisystem simulator

On the other hand, the video transmitter unit consists of five components. Two sine wave generators with different frequencies are combined using a combiner. The CW laser generates an optical signal and similar to the voice and data transmitter unit, the MZM converts the electrical pulses into optical pulses for transmission through the fibre. These components are collected form the construction of the investigated GPON network, enabling the efficient transmission of voice, data and video signals over the optical fibre infrastructure as shown in Figure 3.

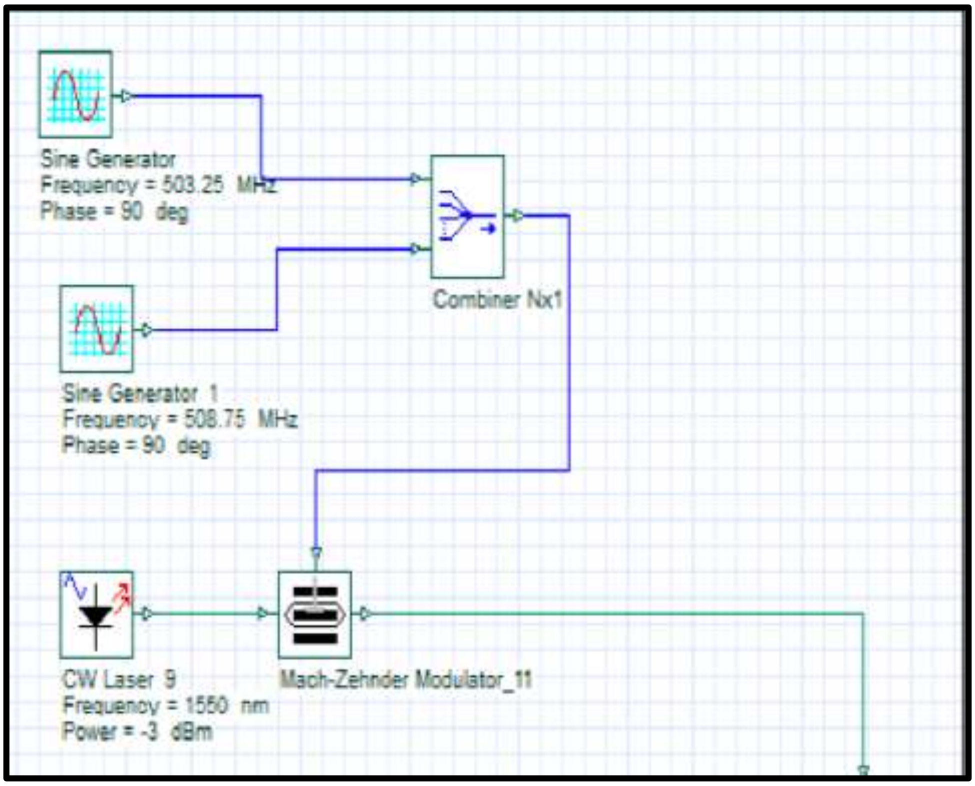


Fig. 3. Architecture of the video/data transmitter using the Optisystem simulator

In the investigated GPON network, the optical data is initially directed to a circulator, which acts as a device separating the DS and US signals. The circulator then directs the data to the bidirectional fibre, facilitating transmission over long distances. Subsequently, the data is routed to a splitter, which divides the input power into eight separate units. The construction of the ONU, as described in [27-30], involves the implementation of a Bessel optical filter to select the desired frequency from the received optical signal. Following this, a photodiode is utilized to convert the optical signal into an electrical signal. The electrical Bessel filter is then employed to further refine the received signal by selecting the specific frequency. By incorporating these components and techniques, the GPON network ensures efficient transmission, separation and filtering of optical data, allowing for enhanced signal quality and reliable communication within the network. The evaluation parameters of the GPON used in the Optisystem simulation, such as wavelength, bit rate and fibre distance, are outlined in Table 1.

Table 1
Evaluation parameters

Parameter	GPON
Voice and data wavelength (nm)	1490
Video wavelength (nm)	1550
Transmitted power (dBm)	−3 to 3
Maximum reach (km)	20
Power splitting ratio	1:8
Intrinsic attenuation (dB ⁄km)	0.216
Bit Rate (Gb ⁄s)	1.244
Dispersion (ps ⁄km.nm)	16.75
Coding mode	NRZ

This approach allows for a more robust and meaningful analysis of the simulation results, facilitating accurate conclusions and informed decision-making in the context of optical network design and optimization.

In order to intercept the DS and US signals without being detected by the user, eavesdroppers may employ an optical coupler in the following scenario. By strategically placing themselves at distances of 5, 7 and 10 km from the OLT, the eavesdroppers utilize couplers with different splitting ratios (10:90, 5:95, 2:98, 1:99) to perform signal interception. This simulation is conducted using the Optisystem. The optical coupler serves as a passive device that allows eaves droppers to tap into the optical fibre network without disrupting signal transmission or raising suspicion. By utilizing the appropriate splitting ratio, the eavesdroppers can extract a fraction of the transmitted signal while allowing the majority of the signal to continue towards its intended destination.

This scenario sheds light on the potential vulnerabilities of optical fibre networks and highlights the importance of implementing robust security measures to protect against unauthorized interception. As technology advances, it is crucial for network operators and researchers to continuously develop innovative solutions to enhance the security and privacy of optical communication systems.

4. Results and Discussion

In the proposed simulation structure of the GPON network, several experiments are performed to evaluate the performance of the system. The power transmitted from the CW laser is adjusted within the range of -3 dBm to 3 dBm. Simultaneously, the length of the optical fibre is modified, spanning from 10 km to 50 km. The key metrics analysed in this study are the Q-factor and the BER, which provide insights into the signal quality and reliability of the transmission. At an input power of -3 dBm and a fibre length of 10 km, the simulation yielded a Q-factor of 3.973 and a BER of 5.54×10-5, as shown in Table 2. These results indicate a reasonable level of signal quality and a low error rate, suggesting robust transmission performance. However, when the fibre length is increased to 20 km, the Q-factor decreases to 2.658 and the BER increases to 3.93×10^{-3}. This decrease in signal quality and increase in bit error rate can be attributed to the higher attenuation experienced over the longer distance and thus, the maximum range of -3 dBm transmitted power is 20 km. To further investigate the impact of power and distance, the simulation is iterated with increased power levels of -2, 1 and 3 dBm at the same fibre length. As shown in Table 2, these power increments led to improved Q-factor value and lower BERs. This trend indicates that higher input power levels can compensate for signal degradation and improve the overall performance of the system. However, when the fibre length was extended to 30 km and transmitted powers of -3 dBm and −2 dBm are used, the Q-factor dropped to zero and the BER increased to one, indicating a complete loss of signal quality. This outcome suggests that the system capabilities are exceeded at these parameter settings. Interestingly, when the power levels are increased to 1 and 3 dBm, the Q-factor increases to 5.89 and the BER decrease to 1.9×10−9, indicating a significant improvement in performance.

Upon further increasing the fibre distance to 50 km, the Q-factor reached zero again. This finding suggests that the maximum achievable fibre length at the minimum power level of -3 dBm is limited to 20 km, as per the simulation results in Table 2. These observations indicate that the simulation aligns with the expectations and behaviour of real-world GPON systems. In summary, the simulation results provide valuable insights into the performance of the GPON system under various power levels and fibre distances. By analysing the Q-factor and BER, it is possible to identify the system's limitations and determine optimal operating conditions to achieve reliable and high-quality signal transmission.

Table 2
Q-factor and BER at different applied powers for the GPON network

Distance (km)		Transmitted Power (dBm)			
		-3	-2	1	3
10	Q-factor	3.973	5.003	9.948	15.667
	BER	5.54×10^{-5}	2.81×10^{-7}	1.28×10^{-23}	1.27×10^{-55}
20	Q-factor	2.658	3.341	6.639	10.485
	BER	3.39×10^{-3}	4.17×10^{-4}	1.59×10^{-11}	5.09×10^{-26}
30	Q-factor	0	0	3.72	5.89
	BER	1	1	9.95×10^{-5}	1.9×10^{-9}
40	Q-factor	0	0	0	3.963
	BER	1	1	1	3.7
50	Q-factor	0	0	0	0
	BER	1	1	1	1

The correlation between fibre length and the minimum logarithmic BER is presented in Figure 4. The acceptable BER value, typically set to approximately 10−12 or lower, is a crucial metric in determining the quality and reliability of the transmission. At a transmitted power of -3 dBm, the graph shows that the highest received signal value at the ONU is observed when the fibre length is 10 km. This indicates that, within the tested range, a shorter fibre length results in a stronger received signal at the ONU, which translates to better performance and lower error rates. However, when the transmitted power is increased to 1 dBm, the graph reveals a shift in the optimal distance for the maximum received signal value. In this case, the highest received signal value at the ONU is observed at a maximum fibre distance of 18 km. The increase in transmitted power allows for longer fibre lengths while maintaining a strong signal at the ONU.

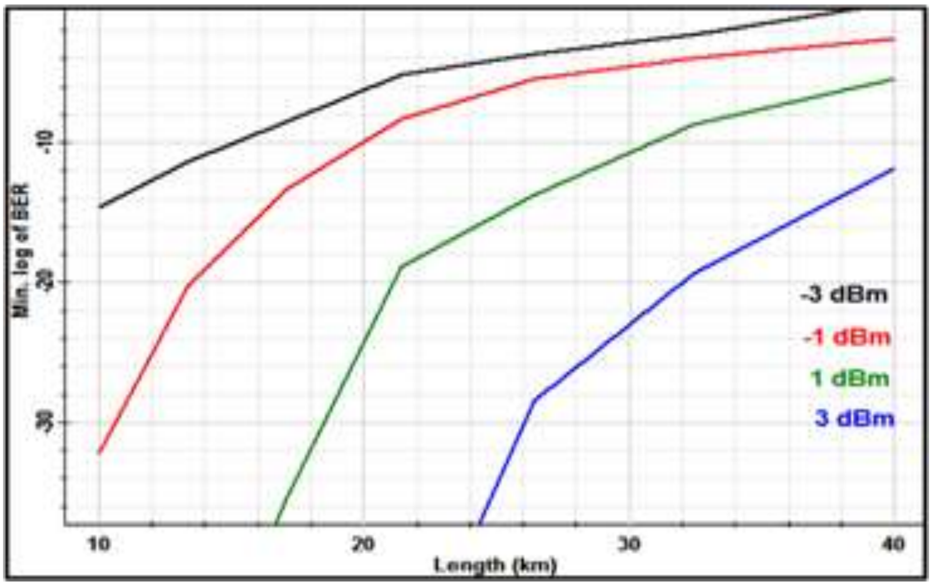


Fig. 4. Optical fibre length impact on the BER across different transmitted power levels

This information can guide network designers and operators in optimizing their GPON systems to achieve reliable and high-performance communication while considering the constraints and requirements of the specific application.

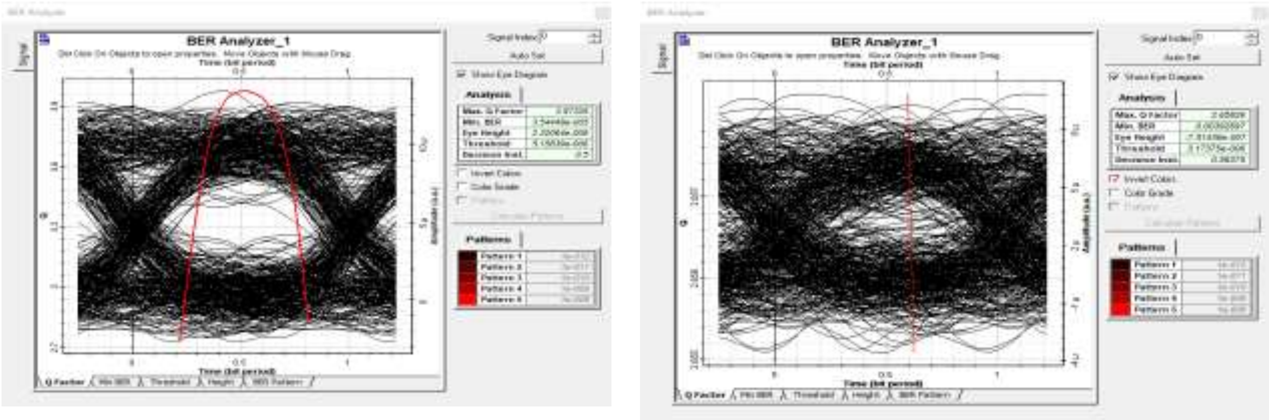
Table 3 provides a summary of the simulation results for the proposed GPON structure. When a transmitted power of -3 dBm, the simulation yields a Q-factor of 3.973 and a BER of 5.54×10^{-5} at a fibre length of 10 km. These values indicate a good signal quality and a low error rate, suggesting reliable transmission performance. In addition, the results show that with an increase in the fibre length to 20 km, there is a corresponding decrease in the Q-factor to 2.658, while simultaneously observing an increase in the BER to 3.93×10^{-3}. This drop in the Q-factor and the increase in the BER indicate a degradation in signal quality and an increase in the error rate due to the higher attenuation over the longer distance.

Table 3
Q-factor and BER analysis at a power level of -3 dBm for the GPON network

	Max. distance (km)		
	10	20	30
Q-factor	3.973	2.6583	0
BER	5.54×10−5	3.93×10−3	1

Further increasing the fibre length to 30 km resulted in a Q-factor of 0 and a BER of this outcome indicates a complete loss of signal quality, rendering the transmission unreliable and the system non-functional at this particular length. From these results, it can be concluded that when using a transmitted power of -3 dBm, the maximum achievable distance without significant signal degradation is 20 km. Beyond this distance, an increase in power is necessary to maintain an acceptable level of signal quality and error rate. These findings emphasize the importance of carefully considering the power levels and fibre lengths in GPON systems. Balancing these parameters is crucial to ensure reliable and efficient communication over longer distances while minimizing signal degradation and maintaining an acceptable BER.

In Figure 5(a), the effects of increasing the fibre distance on the signal quality and error rate in a GPON system are visually represented. At a transmitted power of -3 dBm and a fibre distance of 10 km, the eye diagram illustrates a well-defined and opened eye pattern, indicating a high-quality signal. The corresponding Q-factor is measured at 3.973 and the BER is 5.54×10^{-5}, confirming the simulation results. However, when the fibre length is increased to 20 km while maintaining the same transmitted power of -3 dBm, the eye diagram shown in Figure 5(b) demonstrates a narrower and less open eye pattern. This reduction in eye-opening signifies a decrease in signal quality due to increased attenuation over a longer distance. As a result, the Q-factor decreases to 2.6583 and the BER increases to 3.93×10^{-3}.



(a) (b)

Fig. 5. Eye diagrams of Q-factor and BER at transmitted power -3 dBm and a distance of (a) 10 km and (b) 20 km, for the GPON network

Additionally, when the fibre length is further extended to 30 km, the eye diagram indicates a complete closure of the eye pattern, implying an inability to accurately detect and decode the transmitted signals. In this case, the Q-factor becomes zero and the BER is not quantifiable, rendering the transmission ineffective.

Based on these visual representations and simulation outcomes, it can be concluded that the maximum achievable fibre length, while maintaining acceptable signal quality and error rates at a transmitted power of -3 dBm, is 20 km. This observation aligns with the realities of GPON systems and highlights the importance of considering power levels and fibre distances when designing and optimizing such networks. In the absence of any threats, the DS signal in our study exhibits a Q-factor of 10.224 and an impressively low BER of 7.73×10^{-25}. Similarly, the US signal displays a Q-factor of 5.57 and a BER of 1.3×10^{-8}. These values serve as baseline references for comparison.

To investigate the impact of a tapping structure on signal integrity, we conducted simulations using an optical coupler with different splitting ratios, namely 10:90, 5:95, 2:98 and 1:99. These ratios correspond to insertion losses of 0.75, 0.4, 0.3 and 0.25 dB, respectively. Notably, the optical coupler is strategically placed to intercept both the DS and US signals without being detected by users. The distances between the coupler and the OLT are varied at 10, 15 and 20 km.

Throughout the simulations, we measured essential performance metrics including the Q-factor, BER and eye height derived from the eye-diagram. The results obtained from these simulations are presented in Figure 6 and Figure 7.

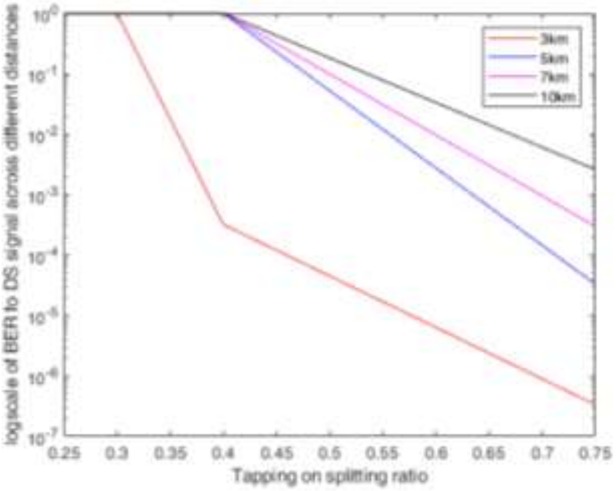


Fig. 6. Splitting ratio *vs.* the eavesdropper BER for the US signal across different fibre lengths

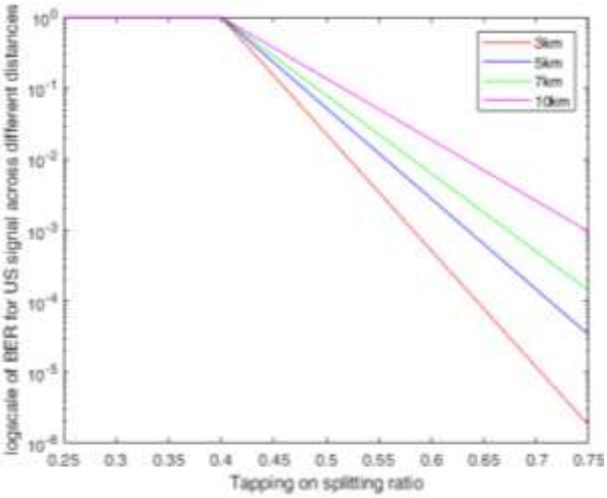


Fig. 7. Splitting ratio *vs*. the eavesdropper BER for the DS signal across different fibre lengths

To provide a comprehensive overview and facilitate comparisons, we summarize the simulation outcomes for each tapping scenario in Tables 4 to 7. These tables consolidate the measured values of the Q-factor, BER and eye height before and after the signal interception, offering valuable insights into the potential impact on signal quality and integrity.

Table 4(a)
Q-factor and BER for the GPON network at a 2 km distance between the eavesdropper and the OLT for US

SR	US			
	Eavesdropper		OLT	
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	18.224/1.64×10^{-74}	3.5×10^{-5}
2:98	0/1	0	17.945/2.57×10^{-72}	3.41×10^{-5}
5:95	2.72/0.00032	-4.63×10^{-7}	17.26/5×10^{-7}	3.21×10^{-5}
10:90	4.967/3.37×10^{-7}	3.39×10^{-6}	15.588/4.345×10^{-55}	2.74×10^{-5}

Table 4(b)
Q-factor and BER at different SRs for the GPON network at a 2 km distance between the eavesdropper and the OLT for DS

SR	US			
	Eavesdropper		OLT	
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	5.191/1.049×10^{-7}	5.04×10^{-6}
2:98	0/1	0	5.08/1.89×10^{-7}	4.79×10^{-6}
5:95	0/1	0	4.813/7.436×10^{-7}	4.167×10^{-6}
10:90	4.64/1.75×10^{-6}	3.91×10^{-6}	4.21/1.292×10^{-5}	2.77×10^{-6}

Table 5(a)
Q-factor and BER at different SRs for the GPON network at a 5 km distance between the eavesdropper and the OLT for US

SR	US			
	Eavesdropper		OLT	
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	12.4/1.266×10^{-35}	1.896×10^{-5}
2:98	0/1	0	12.17/2.22×10^{-34}	1.84×10^{-5}
5:95	0/1	0	11.61/1.934×10^{-31}	1.72×10^{-5}
10:90	3.947/3.946×10^{-5}	1.6×10^{-6}	$10.2834.152\times10^{-25}$	1.432×10^{-5}

Table 5(b)
Q-factor and BER at different SRs for the GPON network at a 5 km distance between the eavesdropper and the OLT for DS

SR	US			
	Eavesdropper		OLT	
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	3.184/6.836×10^{-5}	1.84×10^{-6}
2:98	0/1	0	3.73/9.51×10^{-5}	1.65×10^{-6}
5:95	0/1	0	3.53/0.00021	1.2×10^{-6}
10:90	3.988/3.33×10^{-5}	2.39×10^{-6}	3.12/0.00091	2.76×10^{-7}

Table 6(a)
Q-factor and BER at different SRs for the GPON network at a 7 km distance between the eavesdropper and the OLT for US

SR	US			
	Eavesdropper			OLT
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	9.262×10^{-20}	1.217×10^{-5}
2:98	0/1	0	$9.04/7.607\times10^{-20}$	1.18×10^{-5}
5:95	0/1	0	$8.597/4.083\times10^{-18}$	1.088×10^{-5}
10:90	3.43/0.0003	7.139×10^{-7}	$7.569/1.859\times10^{-14}$	8.808×10^{-6}

Table 6(b)
Q-factor and BER for the GPON network at a 7 km distance between the eavesdropper and the OLT for DS

SR	US			
	Eavesdropper			OLT
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	3.258/0.000561	5.7136×10^{-7}
2:98	0/1	0	3.188/0.000715	4.17×10^{-7}
5:95	0/1	0	3.021/0.00126	4.564×10^{-8}
10:90	3.637/0.00014	1.525×10^{-6}	0/1	0

Table 7(a)
Q-factor and BER at different SRs for the GPON network at a 10 km distance between the eavesdropper and the OLT for US

SR	US			
	Eavesdropper			OLT
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	$5.85/2.458\times10^{-9}$	5.38×10^{-6}
2:98	0/1	0	$5.729/5.05\times10^{-9}$	5.15×10^{-6}
5:95	0/1	0	$5.436/2.713\times10^{-8}$	4.6×10^{-6}
10:90	2.79/0.0026	-3.47×10^{-7}	$4.77/9.22\times10^{-7}$	3.3×10^{-6}

Table 7(b)
Q-factor and BER at different SRs for the GPON network at a 10 km distance between the eavesdropper and the OLT for DS

SR	US			
	Eavesdropper			OLT
	Q/BER	Eye height	Q/BER	Eye height
1:99	0/1	0	0/1	0
2:98	0/1	0	0/1	0
5:95	0/1	0	0/1	0
10:90	3.11/0.00095	2.51×10^{-7}	0/1	0

By analysing and contrasting the results presented in these tables, one can gain a deeper understanding of the consequences of implementing different tapping scenarios on both DS and US signals in terms of the BER, Q-factor and eye height.

These findings contribute to our understanding of the vulnerabilities and potential risks associated with signal interception in optical communication networks. In the case of GPON, the maximum distance achieved is 20 km when utilizing a transmitted power of -3 dBm. However, at this distance, the receivers at each ONU attain a Q-factor of 2.6583 and a BER of 3.93×10^{-3}. This implies a significant degradation in signal quality and an increase in the error rate, making it less desirable for long-distance communication. In the context of the signal interception, our investigation of the tapping method revealed that an eavesdropper employs a directional coupler with a splitting ratio of 10:90 for US signal with inserting an optical amplifier with gain 3.8 dB tailored for US or DS signals as shown in Table 8.

Table 8
Q-factor and BER at 10:90 splitting ratios and 3.8 dB amplification gain for the GPON network for US

SR	US			
	Eavesdropper		OLT	
	Q/BER	Eye height	Q/BER	Eye height
10:90	$6.271/1.8{\times}10^{-10}$	$5.77{\times}10^{-6}$	0/1	0

The Performance of GPON network analysis is illustrated in the previous tables that contain data on the efficiency of a GPON under some conditions. Here is a breakdown of the key elements and observations: Data Points: SR (Splitter Ratio), which measures the number of ONUs/Optical Network Units that can be supported in a given splitter. Conversely, a higher value of SR suggests that the power is divided in portions and as such, which may result in a low signal strength. US/DS (Upstream/Downstream) which is data that moves from one ONU to one OLT or from one OLT to one ONU. Eavesdropper/OLT: Q-factor and BER units with respect to the signal as isolated by the eavesdropper or the targeted ONU, OLT. Eye Height: A measure of the quality of the signal in the eye diagram, which is generally relative to the noise levels. Observations: In most instances, a high Q-factor represents an enhanced quality of the signal of the receiver. This is always above 10 and high value expected while values below 7 will indicate a problem. BER: Smaller values for BER signify that the number of errors in the received data is relatively small. In a normal situation, when data is being transmitted, it is usually desirable that the BER should be very small that is close to zero.

Impact of Distance: As shown in the Tables 4 to 7, the results of Q-factor for the eavesdropper sub-channel signal reduce as the distance between the eavesdropper and the OLT increases with regard to US data. This means that at larger distances, the signal strength is comparatively low. Therefore, eavesdropping shall be somewhat difficult. Impact of Splitter Ratio: Higher splitter ratio (a greater number of ONUs) could also have slightly impacted Q-factor and increased BER for eavesdropper as well as for the ONU (Tables 4(a), 5(a), 6(a) and 7(a)). This highlights the problem of the trade-off between the number of OLT-ONU pairs and signal quality of the received signal. Downstream vs. Upstream: In most of the downstream signals (OLT to ONU), it is found that the Q-factor and BER are slightly higher than the upstream signals (ONU to OLT) at different distance splitter ratios (Tables 4 to 7). This could perhaps be blamed on the higher power levels that are utilized in downstream transmission. Critical Points in Tables: It is observed that at 10 km distance, the US signal is very weak for higher splitter ratios as observed for 5:95 and 10:90 splitter ratios and the BER is also observed to be very high. Hence, both the Q-factors are omitted in this figure to show the worst-case scenario for the eavesdropper side.

This means that it becomes increasingly difficult for eavesdroppers to eavesdrop US data depending on the distance. Table 7(b): The DS signals at a distance of 10 km shows that BER at splitter ratios of 5:95 and 10:90 for all is 0; meaning no errors are detected. However, for these samples, OLT does not have data for these cases and thus these values may not be indicative of the true performance of the system.

Overall: From these tables, it is possible to realize the influence of parameters, for example, distance and splitter ratio on the key GPON security. Also, while it is possibly to spy on the equipment closer to them, the quality of the data transmitted is extremely low at longer distances making it impossible to intercept from a distance. However, one disadvantage is that increased splitter ratios can also decrease the strength of the signals a little bit as well to make the task of eavesdropping all the more challenging.

5. Conclusion

This study explores the possibility of optimizing the data transmission system using optical fibre cables, with a focus on achieving a long-distance coverage while minimizing power consumption and ensuring high signal quality. Through extensive simulations and measurements in GPON, we evaluated the Q-factor and BER under varying power levels from a CW laser. The simulation results demonstrate that the maximum achievable link length in GPON is 20 km, achieved at a power level of -3 dBm, with a corresponding Q-factor of 2.6583. However, when attempting to extend the link length beyond 30 km, the system performance became impractical, indicating the limitations of GPON in achieving long-distance communication with low power. Considering the objectives of maintaining system performance with low power, GPON can be hacked by undetectable tapping when we inserted optical amplifier with 3.8 dB gain in the US signals with approving BER=10^{-10}.

A future work could focus on the implementation of Forward Error Correction (FEC) techniques to detect and correct transmission errors, thereby improving both Q-factor and BER.

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