A Practical Demonstration of the Cumulative Effect of Noise in Submarine Systems.

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Abstract

Erbium doped Fibre Amplifiers (EDFA) has found applications in many communication systems. The performance depends on the components of the electronic devices found in the system (like Pump power, fibre length and the ratio of the optical and electrical filter bandwidth).

The data is acquired from an existing link connecting Yzerfontein in South Africa to Lekki in Nigeria across 89 repeaters by connecting an RS232 cable at the F interface of the 1660 SM NE (PFE) to the 1320 CT, Craft Terminal proposed for the Q3 Network Elements which is a standardized network management interface, according to ITU-T recommendations. The acquired data was analyzed with Excel.

It is observed that the excess noise in the link accumulates as the signal propagates from the transmitting station to the receiving station. This work has been able to show that the network under consideration has a noise value higher than the 1.5 dB threshold at some points using descriptive analysis.

Key words: Repeater (Erbium Doped Fibre Amplifier), APDs, Excess noise, cumulative noise, communication system.

I Introduction

Over the years the need to enhance or optimize the quality of communication signal has grown tremendously, hence the transition from cable, radio, satellite, optical fibre (terrestrial and most importantly submarine) communication media. The aforementioned media in their various capacities served or are still serving their purpose.

The later, optical fibre submarine communication system evolved in the quest for high carriage capacity for both voice and data. This medium was established to satisfy the customers’ desire for more effective, low cost and accessibility of the system [1]. The subsequent paragraphs explain the parameters that were considered systematically to design this medium.

System capacity defines the total information rate transmitted between the different points of the link while, Transmission quality defines the allowable number of errors for the system (one error represents receiving a 1 for a 0 or vice versa). The quality of transmission of the link is expressed as bit error rate (BER) or as a transmission quality Q-factor (where Q-factor is expressed in dB). Those characteristics depend on the type of signals to be transmitted (voice, data). Current systems are defined for data transmission. A bit error rate of less than 1E-13 is required by the G.826 recommendation. It affects the provisioning of the optical interfaces and the fibre used. The cost of the system is obviously linked to the line bit rate and other system parameters.
The lifetime of a link is generally more than 25 years. Often equipment becomes obsolete long before reaching this limit.

The most interesting thing about submarine communication is the networking of the parameters which constitute the system [2]. The repeaters play a very crucial role in the submarine optical fibre network systems as they are placed at specific and constant distances to amplify the weak received signal. It is well known that attenuation increases with increasing distance. So, as the optical signal travel down the fibre cable, it reduces in strength but is amplified by the repeaters.

This research is centered on the quality of the signal transmitted (Q-Factor), though, to effectively discuss and investigate this, the system network has been elaborately emphasized in the subsequent chapters and some parameters like signal-noise-ratio (SNR) has also been discussed in order to gain precision.

Figure 1 shows the point-to-point Repeatered system that links two base stations across the ocean.

![Figure 1. Submarine network layout. [1.]](image1)

In long-haul point-to-point optical fiber communication the signal traveling inside the fiber suffers from various losses like fiber attenuation losses, fiber tap losses, fiber splice losses, etc., due to these losses it is difficult to detect the original signal at the receiver side. So in order to transmit signal over a long distance in a fiber it is necessary to compensate all losses in the fiber. The introduction of optical amplifiers allowed the signal amplification in optical domain. There was no need to convert the optical signal to electrical signal. There are mainly three types of optical amplifiers: erbium doped fiber amplifier (EDFA), Raman amplifier and Semiconductor Optical Amplifier (SOA).

In this paper, EDFA is considered because of its low noise figure and high gain. Figure 2 shows the various components of an EDFA.

![Figure 2: Schematic of EDFA [3.]](image2)

The amplification of the signal is done at the highlighted region of the EDFA. Before the signal is amplification of the signal, the propagating signal is first coupled into the device, the photodetector then receives the input signal and
forward it to the microcontroller based monitor. This monitor gives a supervisory feed-back of the received and transmitted signal via the amplifier. The photodetector is made of avalanche photodiode. The following describes the processes of detection.

**Avalanche Photodetectors**

Photodetectors are made of semiconductor materials. Photons incident on a semiconductor are absorbed by electrons in the valence band. As a result, these electrons acquire higher energy and are excited into the conduction band, leaving behind a hole in the valence band. When an external voltage is applied to the semiconductor, these electron-hole pairs give rise to an electrical current, termed the photocurrent [4].

It is a principle of quantum mechanics that each electron can absorb only one photon to transit between energy levels. Thus the energy of the incident photon must be at least equal to the bandgap energy in order for a photocurrent to be generated.

This is also illustrated in Figure 3. This gives us the following constraint on the frequency $f_c$ or the wavelength $\lambda$ at which a semiconductor material with band-gap $E_g$ can be used as a photodetector [4]

$$hf_c = \frac{hc}{\lambda} \geq eE_g$$

Here, $c$ is the velocity of light, and $e$ is the electronic charge.

The largest value of $\lambda$ for which (1) is satisfied is called the cutoff wavelength and is denoted by $\lambda_{\text{cutoff}}$. Table 1 lists the bandgap energies and the corresponding cutoff wavelengths for a number of semiconductor materials. We see from this table that the well-known semiconductors silicon (Si) and gallium arsenide (GaAs) cannot be used as photodetectors in the 1.3 and 1.55 μm bands. Although germanium (Ge) can be used to make photodetectors in both these bands, it has some disadvantages that reduce its effectiveness for this purpose.

![Figure 3. Principle of photo detection [5].](image)

The efficiency of photo detector is the fraction of the optical signal that is absorbed to give rise to photocurrent.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (eV)</th>
<th>$\lambda_{\text{cutoff}}$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.17</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Table 1. Bandgap energies and cutoff wavelengths for a number of semiconductor materials [4].
For transmission at high bit rates over long distances, optical energy is scarce, and thus it is important to design the photodetector to achieve an efficiency $\eta$ as close to 1 as possible [4]. This can be achieved by using a semiconductor slab of sufficient thickness. The power absorbed by a semiconductor slab of thickness $L$ μm can be written as

$$P_{\text{abs}} = (1 - e^{-\alpha L})P_{\text{in}}$$  \hspace{1cm} (2)

where $P_{\text{in}}$ is the incident optical signal power, and $\alpha$ is the absorption coefficient of the material; therefore,

$$\eta = \frac{P_{\text{abs}}}{P_{\text{in}}} = 1 - e^{-\alpha L}$$  \hspace{1cm} (3)

The absorption coefficient depends on the wavelength and is zero for wavelengths $\lambda > \lambda_{\text{cutoff}}$. Thus a semiconductor is transparent to wavelengths greater than its cutoff wavelength. A photodetector is usually characterized by their responsivity, $\mathcal{R}$.

If a photodetector produces an average current of $I_p$ amperes when the incident optical power is $P_{\text{in}}$ watts, the responsivity

$$\mathcal{R} = \frac{I_p}{P_{\text{in}}} \frac{A}{W}$$  \hspace{1cm} (4)

Since an incident optical power $P_{\text{in}}$ corresponds to an incidence of $P_{\text{in}}/hf$ photons/s on the average, and a fraction, $\eta$, of these incident photons are absorbed and generate an electron in the external circuit, we can write

$$\mathcal{R} = \frac{\eta h f}{\lambda c} \frac{A}{W}$$  \hspace{1cm} (5)

The responsivity is commonly expressed in terms of $\lambda$; thus

$$\mathcal{R} = \frac{\eta \lambda}{1240} \frac{A}{W}$$  \hspace{1cm} (6)

where $\lambda_{\text{in}}$ the last expression is expressed in μm.

In practice, the use of a slab of semiconductor as a photodetector does not realize high efficiencies. This is because many of the generated conduction band electrons recombine with holes in the valence band before they reach the external circuit.

These secondary electron-hole pairs can generate even further electron-hole pairs when they are accelerated to sufficient levels. This process is called \textit{avalanche multiplication}. This Multiplicative gain makes avalanche photodiode a better choice in the design of the network [6].

II \hspace{0.5cm} Data Acquisition Method

The internal parameter is centered on repeaters mostly. The network architecture is designed in such a way that the signal does not escape from the channel either from the transmitter or the receiver. The measured data consists of the optical power sent from the transmitter’s output to the input of the repeater. The signal attenuates as it propagates down the fibre but is amplified at the repeater. The repeater is also known as optical amplifier with the recent
technology focused on erbium doped fibre amplifiers (EDFA). This technology records minimal dispersion and hence low attenuation. The PFE has computer interface and thus compatible with PCs. Figure 4 shows how the serial cable can be used to connected the submarine network element.

Figure 4: Data acquisition method [1].

The TMN is structured in layers, which includes: Element Management Layer (EML) and Network Management Layer (NML) to manage the network element configuration, alarms and performance. The stages explained below explains the data acquisition procedures

Stage 1: The RS232 cable was connected at the F interface of the 1660 SM NE (PFE) to the 1320 CT, Craft Terminal proposed for the Q3 Network Elements. Q3 is a standardized network management interface, according to ITU-T recommendations. It provides the necessary local operation and maintenance functionality.

The IOO (Internet Order Online) is an open interface that exports Alarm Data, Performance Monitoring Data, NE Directory Data and NE Remote Inventory Data. It also exports the remote inventory data of the NEs managed through ASCII (American Standard Code for Information Interchange) interface via TCP/IP (Transmission Control Protocol/Internet Protocol).

1350 OMS - SN displays Network measurements and performances management. From this display, Acquisition of repeater measurements (input and output optical power) and alarm generation on threshold crossings are made possible.

Stage 2: From the OMS1350, proceeded to GUI (Graphics User Interface) Desktop display. This window contains a menu, a tool bar, a status bar, 3 panels (the tree explorer, the thumbnail view and a console) and a desktop displaying the different views of the application (Network, Fibre Pair, Line, Optical, Power). This is shown in Figure 5.
Stage 3: Go to Fibre Pair Optical Path view, the data is displayed as shown Figure 6.

At the right side an optical channel table of the selected group displays optical path information at either end of the optical path (channel frequency, protection status, tributary identifier, cable fault indication and Q-Factors).
Stagen4: Proceed to Line view to get the display in Figure 7.

Figure 7. Optical line view

The Line View shows the submerged Line Equipment. It allows performing measurements on Repeaters and Bus. From this display, the data is downloaded and recorded.

Once this is successfully achieved, we go to output signal folder, thereafter the output power and repeater. The details of the transmitted power from the PFE to the repeaters are displayed on the computer with time stamps on them as we will see in the data table. This process was repeated once every year for two years due to limited access to the PFE base station. The various repeaters are placed at specific distances apart and the activities there in are recorded through this process.

From Yzerfontein South Africa to Nigeria is an optical fibre of length 5608km buried under water to transmit and share data between the two locations. The link has several branching unit branching units which branches off the signal to the landing stations of the neighboring countries with the sole interest of connecting their national grid. The signal is branched off at Angola, Namibia, Congo, Cameroon, Ivory Coast, Congo DR, Nigeria and so on but the link is between Yzerfontein in South Africa to Sexial in Portugal with a total length of 11378km. But the section under consideration (Yzerfontein to Lekki) has a length of 5608km (see Fig. 8).
Though the signals entire link is acquired, the area of interest remains the Yzerfontein to Lekki Nigeria where the network operator have their landing station. Alternatively, the data can be acquired by mere looking at the PFE and documenting the readings manually. This approach is strenuous and has limitations in recording real time events.

III Results and Discussion

The standard value for the link under consideration is 1.5dB according to Alcatel Lucent as seen in Figure 9. From the data, exactly 44 amplifiers, which is 50% of the amplifiers have their input more than the threshold value, with an average of 0.21dB more which is regarded as excess noise because the input power is recorded after photo detection. This value constitutes 12% of the input power of the various amplifiers. Using the minimum noise figure, $F_n = 3$dB, about 20% of the output power is actually noise (3dB noise on the approximate 15 dB).

Cumulative noise ($N_c$) = Average Excess Noise ($E_{Nav}$) × Number of Repeater.

\[
N_c = 0.21 \times 44 \text{ (number of repeaters with noise above the threshold)}
\]

\[
= 9.24 \text{dB}
\]  

(7)

Recall that the gain is flat at 10dB, therefore, at the output of the preamplifier, we will have

\[
P = G + N_c = 19.24 \text{dB}.
\]  

(8)

This implies that 48% of the signal received is noise power (Gain + cumulative noise $N_c$)
A plot of input power and output power shown in figure 9 and 10 for the signal propagated from Yzerfontein to Lekki and from Lekki to Yzerfontein.

Figure 9. Pout and Pin against Number of Repeaters
Figure 10 shows that a reasonable number of repeaters have their input power above the specified threshold for the link as acquired. Additional noise is added into the signal at the amplifiers and the cumulative noise from the various amplifiers becomes additive. Hence, the received signal becomes a combination of both the noise and the transmitted signal. It is observed that clusters of amplifiers whose input signal exceeds the operators’ limit as the signal propagates from Yzerfontein to Lekki are found towards the shores of Lekki. Conversely, as the signal returns from Lekki to Yzerfontein, the cluster is seen towards Yzerfontein. This observation is a clear indication that the effect of cumulative noise becomes obvious as the signal approaches the receiving station.

From [4], the time rate of photon emission and absorption are 1 μs and 10 ms for electron transition from energy levels $E_3$ to $E_2$ and $E_2$ to $E_1$ respectively during amplification in the EDFA module as the signal is transmitted through it. This implies that 10% of the laser power is lost to spontaneous emission which becomes the significant noise power (Noise figure).

This is a clear indication that noise is added to the received signal. The signal is received by an APD, which, during the avalanche process, introduces its own noise. This is recorded through the aid of the microcontroller based monitor.
imbedded in the EDFA device to monitor real time activities of the link. This observation explains the cumulative effect of noise as the signal travels across the repeaters.

Another thing to also consider is the fact that, since inception of this optical fibre link, the recorded values has remained the same. The implication is that, during manufacturing and installation, the APDs of the repeaters cannot be easily replaced once the network is commissioned, hence the Avalanche multiplicative Gain has to be controlled before during manufacturing.

IV Conclusion and Recommendation

The optical fibre communication system is a better system to transmit optical signal over a long-haul. For a very long distance, the propagating signal becomes attenuated and hence requires amplification. The EDFA being the amplifier in use in this link, contributes some noise to the signal. This noise is traced to arise from the APDs. Avalanche Photodiodes as a photo-detector contributes a significant noise during the avalanche process causing the input signal to over-shoot the allowable limit before it is recorded and displayed by the microcontroller based monitor, which gives a supervisory feedback to the SLTE.

It has been seen from Figures 9 and 10 that the noise in the system becomes cumulative as the signal travels across amplifiers.

This research therefore recommend that further studies on the effect of the cumulative noise on the Quality of transmission (Q-Factor) is investigated.

V References