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A Discussion on the Development of Fault Detection in PON Systems

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A B S T R A C T

This study gives a broad review of the improvements achieved in the effectiveness of the currently used techniques for fibre optic monitoring in PON. As recent developments in improving the fault monitoring in PONs, speed of monitoring, measurement efficiency, signal-to-noise (SNR) ratio, dynamic range, and spatial resolution were all explored. In order to find the appropriate monitoring framework, a thorough evaluation of the fault monitoring in PONs was conducted. The final section of this paper discusses some of the challenges and possibilities that will be presented to attempts to create an effective optical link monitoring system for PON in the future.

Keywords: PON, Fault detection, fault monitoring, WDM, SNR

1. Introduction

The most economical way to set up fibre access networks is through passive optical networks (PONs) [1]. PON offers various advantages when utilised in a fiber-to-the-x (FTTx) infrastructure. In order to enable connection from the downstream (DS) direction to the upstream direction, it uses a point-to-multipoint (P2MP) architecture. Better triple-play services, pacy networks, and reasonably priced phone, TV, and internet services are further benefits [2]. The most energy-efficient technique to construct an access network is this [3]. Over the past few years, IEEE and ITU-T have developed and standardised PON designs. Numerous FTTx designs exist, including in-node (FTTN), home (FTTH), school (FTTS), and others. It appears to be the most popular choice for providing high-speed internet to residences, companies, and educational institutions [4]. The fundamental ideas for the creation of access networks are covered in detail in [5], while [6] examines the technological approach. Only thorough research can lead to the realisation of an economic system. To calculate the cost of establishing a FTTx access network, for instance, Phillipson updated geometric models [7].

The final mile of the network, which is thought to be more vulnerable, away from the fibre distribution point (FDP), is where FTTx is most vulnerable to network issues. It is frequently observed with certain fiber-optic connections that put the optical wires at peril in hostile environments [8]. Building a centralised, programmed fault detection system with prospective fault detection system that can recognise and locate issues in the CO's distribution fibre (DF) link is therefore crucial. Effective defect detection is required for the delivery of services to be at its best. For proper fault localization and repair, the network management system (NMS) has to automatically and centrally identify fibre link deterioration in optical access networks (OANs). The NMS offers helpful data that enables speedy network maintenance. This highlights the need of maintaining network resilience and reducing operational expenses (OpEx) for network operators.

The PON was developed to supply internet services to a significant number of ONU, and any malfunction in the distribution network may cause financial loss for service providers as well as dissatisfaction among subscribers. Any technique created to examine PON should provide a comprehensive strategy, manufacturing, and achievement in order to reduce OpEx. The monitoring apparatus must also support the maximum splitting ratio permitted by the current PON standard (e.g., 64, 128, and higher) [9].

The whole article's description is as follows: Section 1 discusses the description of PONs and monitoring, while Section 2 elaborates on a broad overview of fault monitoring in PONs. Section 3 describes the ideal defect detection monitoring system, and Section 4 provides a summary of the findings. Section 5 represents PON network monitoring issues, while Section 6 elaborates on defect detection in the future. Section 7 provides concluding observations.

2. Details of PON Fault Monitoring

Globally expanding PON access networks have brought attention to the need for a more advanced optical layer monitoring system. It is necessary to have a system with extensive monitoring capabilities that complies with IEEE and ITU-T standards, carrier requirements, and encourages interoperability. Since its introduction, PON technology has been the focus of a deluge of research, many of which have examined the system's resilience mechanisms. Some of these studies recommended network signal quality analysis using the signal-to-noise ratio (SNR) [11] as well as network physical layer fault monitoring in fibre optic distribution networks. The identification and localization of any network issue source is necessary for the access network maintenance function, which is a crucial duty. The maintenance standards (ITU-T L.310) recommend using optical time-domain reflectometer (OTDR) methods as the first line of defence for PON maintenance [12]. [13] describes the essential characteristics and criteria for both the operation and upkeep of optical fibre cable networks used for telecommunication services.

The (ITU-T L.40) suggests providing optical fibre support and maintenance for external devices. Based on this assumption, the essential specifications, notions, and architecture for fibre optics have been defined, including facilitation, surveillance, and assessment. In-service fibre lines were creating a very precise and practical optical fibre link that sends WDM signals over a wider frequency range, as determined by the servicing and monitoring criteria in [14]. It addresses the needs and expectations for service spectrum as well as in-service fibre cable test light filtering that doesn't interfere with the transmission. Testing is necessary during the first PON installation to make sure that all optical components and fibre optic connections are set up correctly and are functional. To guarantee that data signal transmission does not suffer, in-service monitoring of optical link bottlenecks and different ODN health phases is crucial. The pros and cons of several of these techniques in terms of cost, complexity, reliability, sensitivity, and performance are discussed in this section. While some techniques are available commercially, others are still being investigated.

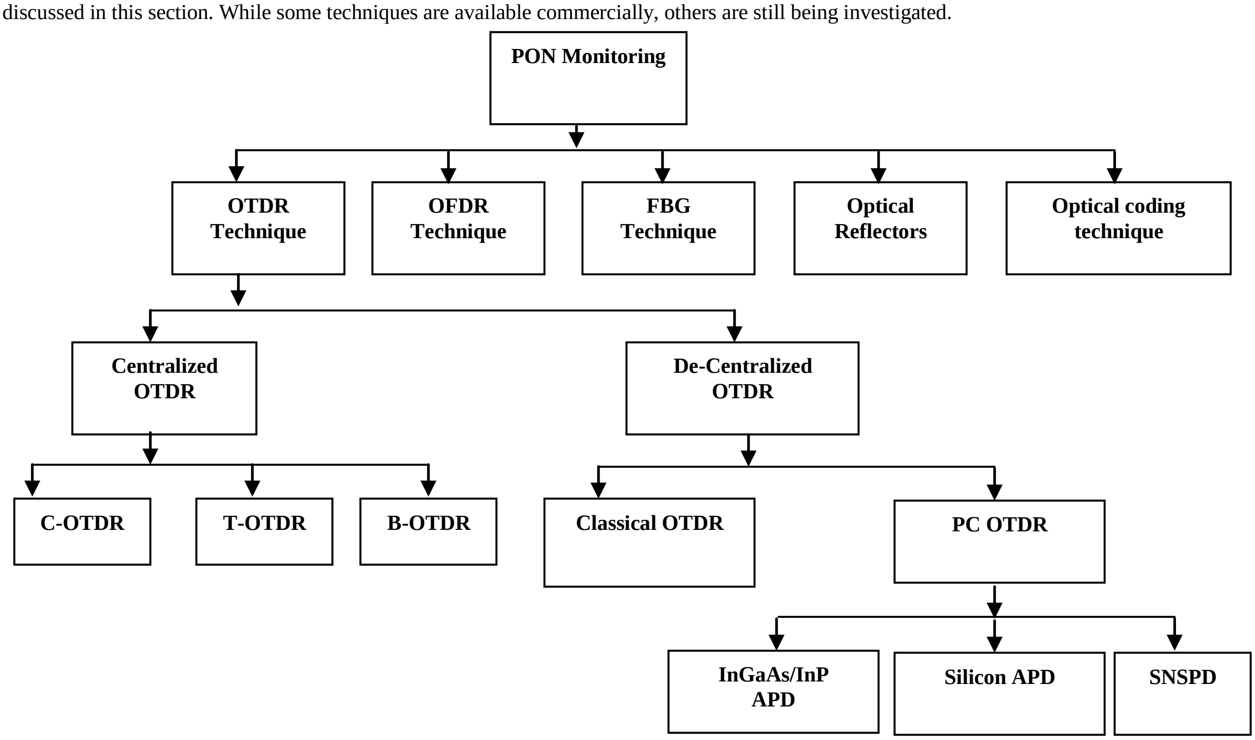

Figure 1 PON Monitoring Classifications

Figure 1 illustrates several PON monitoring classes. Decentralised and centralised are two of the categories. The latter requires either dispatching a technician to check the connection using OTDR [15] or integrating additional monitoring capabilities within the ONU [16]. The former, however, permits remote problem detection and localisation from the CO, obviating the need for labour or input from the ONU, as well as client issue tickets. The centralised PON monitoring system provides an interface with NMS and the capacity to automatically locate and identify problems [17].

2.1. OTDR Decentralised Monitoring System

The importance of optical fiber link monitoring in ensuring constant network accessibility cannot be overstated. Reflectometry is a well-known technique for locating a defect location in an optical layer. The OTDR [18] is a widely used device to characterize optical links. Just one side of the fiber optics is needed for the OTDR apparatus to retrieve details concerning its reliability. The OTDR is a valuable method for examining the properties of a photonic transmission in a point to point network. It typically comprises of laser and a photon detection, which are both incorporates to detect various defects in a fiber optical link. OTDR uses Rayleigh backscattered as well as Fresnel reflected light for high speed monitoring. The amplitude of Rayleigh backscattering-induced reflected signals is measured but also summed as a time - dependent, subsequently displayed against the correlating fiber [19]. For creating the trace, OTDR processing unit gets signals and calculates the backscattered power as shown in Figure 2.

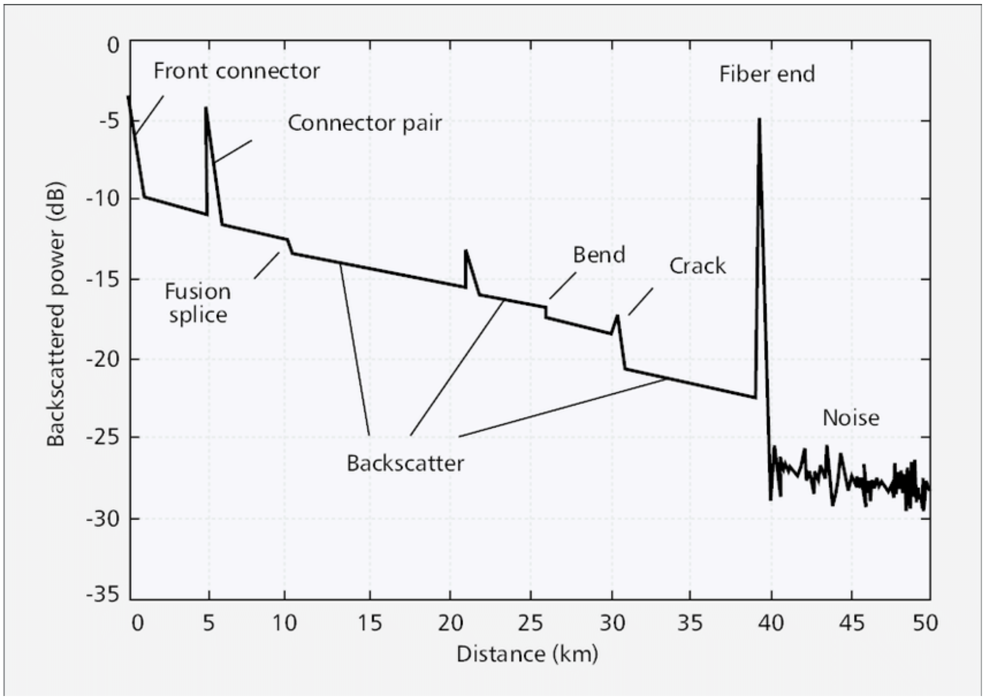

Figure 2 Backscattered power versus distance for traces of OTDR in PON system

Splice losses, optical connector losses, and fibre break/bend in a fibre connection may all be determined using OTDR traces. The two most important characteristics of an OTDR (SR) are dynamic range (DR) and spatial resolution (SR). The DR (expressed in dB) (provided in dB) is the maximum loss of spending that can be assessed in a transmission fibre. However, SR also considers the length of the laser pulse that reaches the fibre in order to determine how sensitive it is to discriminate between two neighbouring events. A distinguishing technical aspect of OTDR is the combination of SR and DR. The produced OTDR pulses can be made shorter to increase SR, but increasing the length reduces the gathered power and decreases DR. When using PC-OTDR and a single photodetector, higher DR and SR are seen [20]. The PC-OTDR based on InGaAs/InP APD showed a DR that was 10 dB higher than the traditional OTDR, superior SR with a 20-fold improvement factor. Author in [21] shows the benefits and drawbacks of a PC-OTDR using InGaAs/InP APD-based. Because of its high sensitivity over an extensive wavelength array, and low dark count rate, the superconducting nanowire single-photon detector (SNSPD) becomes crucial for monitoring systems [22].

2.2. OTDR Centralised Monitoring System

As was already said, optical connections need to be tested at the time of first installation to make sure that all of the network hardware is configured properly. In order to prevent interruptions in the transmission of data signals, it is essential to monitor degradations and breakdowns in fibre line service in real time. As a result, many techniques for monitoring optical links in service have been utilised with the OTDR approach [23–24]. For in-service OTDR, a research using Raman backscattered light was conducted in article [25]. The study used a supervisory channel to watch the OTDR pulses in order to prevent obstruction in the multichannel network. Figure 3 shows that an OTDR pulse is blocked at the distant note, but that the multichannel wavelengths are unaffected. Although situated at RN, arrays waveguide grating (AWG) simplifies the WDM system, its implementation is challenging. Due to the transmission of DS signals in the same fibre or line as OTDR signals due to the installation of multiplexers and demultiplexers, OTDR pulse detection becomes challenging.

In one research [26], the probe signal was particularly designed for a particular DF connection to be studied by the accompanying WDM transmitter, but in another investigation [27], the AWG at the RN was bypassed utilising extra interconnects. However, several of the aforementioned methods call for stopping WDM channel operation while keeping the DF link active. approach that made use of an in-service OTDR in the DS signal, as suggested in [25]. Background noise was reduced and Rayleigh backscattered signal was acquired at RN in service OTDR for 1:64 users.

In contrast to the OTDR technique, which covers the whole probing band at once, the detection signal gradually overshadows a specific frequency of the pump signal in the sweep of frequencies approach. In order to increase SR using the conventional OTDR approach, a high bandwidth detection is required, together with a foundational frequency sweep and a Fourier transform that converts frequency into distance based on frequency sweep rate [28]. According to the lock-in amplifier's computations of the whole aggregate of infinite reflections using the sweeping of frequency tone sweep technique described in [29], a characteristic back-scattered pulse and power indicate this complete aggregate. It is challenging to find non-reflective faults due to the minor integration loss and lack of a peak of reflected signal.

However, using the recommended approach, such instances were located and detected across the fibre link, with the network analyzer being a high-frequency tone subcarrier with a 205 MHz centre frequency and a 10 MHz rate of sweeping. To produce a trace that approximated the OTDR profile, the recovered transfer function was subjected to an inverse Fourier transform processing step. The technique's reduced DR—which can only be employed in networks with a lower splitting ratio—is a serious flaw [29]. It is not practical to use this approach to discover several fault occurrences because of the lengthy measuring interval. The subcarrier frequency tone technique was suggested by the author in [30] as a way for identifying a variety of flaws, but it was only appropriate for P2P networks with a constrained measurement range. It's important to note that both high and low frequency tones can be employed with the frequency sweep tone methods discussed here to find non-reflective fault occurrences in an optical communication link. However, if a fibre link reflection failure occurs and the fault size grows significantly, the performance of both systems may be negatively impacted. Figure 4 shows a PON monitoring method for the low frequency band.

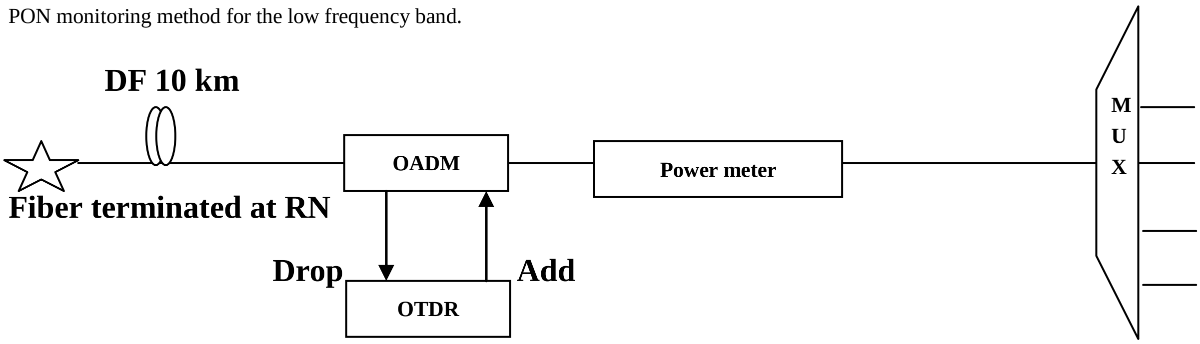

Figure 3 PON monitoring scheme for higher frequency systems

2.3. Optical Frequency Domain Reflectometer (OFDR) Monitoring System

Optical frequency domain reflectometers (OFDR) are gaining popularity as a high resolution defect monitoring tool these days [33–34]. Given that OTDR cannot produce both a high SR and a big DR, it appears to be a good replacement for long fibre optic properties. The OFDR monitoring method in PON is made up of interferometer (IF) units at the ONT/ONU terminals and an OFDR module at the OLT (see Figure 4). The following elements, such as a coupler, FBG, and a mirror, were employed to produce a peak of signal on the OFDR trace [35]. After the splitter, an OFDR trace shows the condition of the fibre link to check the signal's continuity. The intermediate frequency unit is positioned to produce a clock signal for the OTDR and nonlinear laser correction for the OFDR. The resulting clock signals, however, are not always accurate due to the substantial optical length variation in the IF arms, which results in sampling error in the clock signals that may reduce the SR of the OFDR system [36].

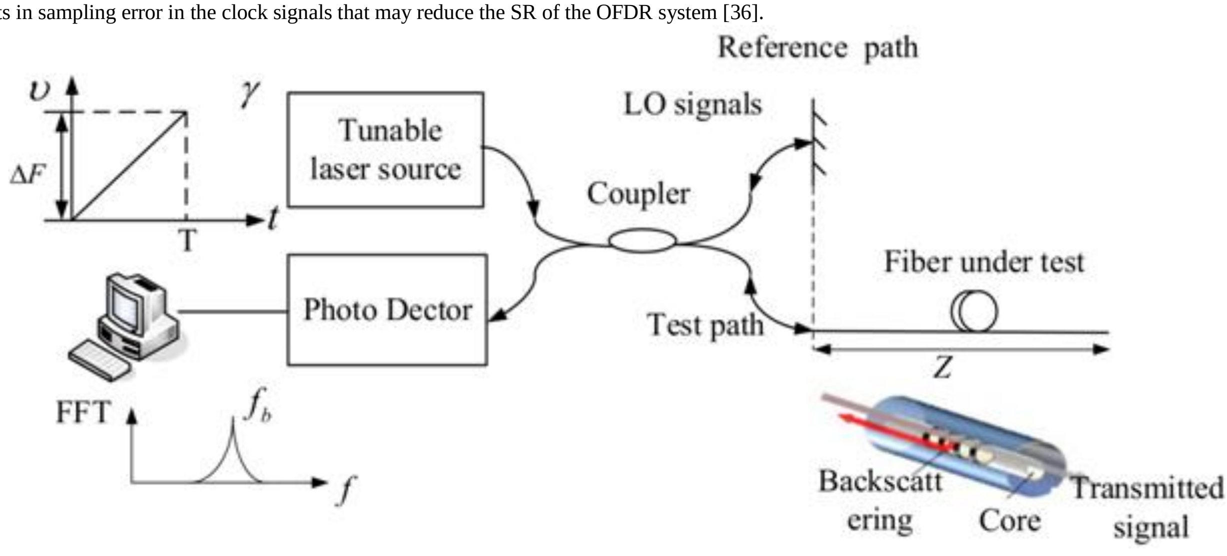

Figure 4 OFDR Monitoring

2.4. Reflection based Monitoring System

Reflection monitoring uses the reflective semiconductor optical amplifier (SL-RSOA) mode of cavity of a self-injection locking optical amplifier. Each ONU is equipped with RSOA, FBG, and a coupler to create US data and monitoring signal. The flaw, which pointed to a damaged optical link in the network, was found when the corresponding ONU identifying peak's amplitude was lowered. The simultaneous detection methodology is problematic for a setup with large power splitting ports due to the simultaneous detection method, which might lead to a significant loss of power in upstream data signals

[42]. Due to the interaction of the probe signal and the upstream signal, which makes the system complicated and increases CapEx, a protocol adjustment was necessary to eliminate noise.

3. Comparison of different fault monitoring schemes

Different monitoring techniques are contrasted in Table 1 based on their complexity, impact on digital signals, tracking frequency, continuous monitoring components, event dead zone, multipoint malfunction functioning, and low-cost module.

Table 1 PON monitoring schemes comparison

Monitoring/Approach	Cost	Fault detection in P2P/P2M	Fault localization (FL)/Multiple LF (MFL)	Single monitoring wavelength	Complexity	Impact on signal
Conventional OTDR/ Decentralised ((DC) [15, 18]	Avg	P2P	FL	Yes	Low	No
PC-OTDR/DC [20, 21]	Avg	P2P	FL	Yes	Low	No
E-OTDR/DC [45]	Avg	P2P	FL	Yes	High	Yes
E-OTDR/Centralized (C) [46]	Avg	P2P/P2M	FL	Yes	High	Yes
T-OTDR/C [47]	High	P2P/P2M	FL/MFL	No	High	No
FBG-OTDR/C [10, 11]	low	P2P/P2M	FL/MFL	Yes	low	No
OPWM/C [48]	low	P2P	FL	Yes	Avg	Low

4. Future scope

More accurate and comprehensive methods for optical fibre physical connection characterisation are needed as the PON FTTx network grows in size and capacity. It takes an OTDR with improved SR and DR to characterise an optical link. The three primary steps to improve the DR and SR to be successful in fibre monitoring are (1) improved signal [186], (2) greater receiver sensitivity [29], and (3) no requirement for numerous photo detectors (PD) [187]. The first technique makes use of a high-power laser source to increase the injected power into the FUT. Backscattered light detection may be challenging and expensive due to SBS and modulation non-linearity [188]. The second and third techniques, meanwhile, employ coherent detection and photon counters, respectively. With the addition of PC-OTDR, a single PD is employed for high SR [189]. Short laser pulses can be employed to boost performance, but their wide bandwidth, which is increased by fibre pulse spreading, inevitably leads to SR degradation. Implementing the suitable DC method might resolve this. The monitoring system should include a portal/application and gated mechanism that alert the support team to do maintenance when an issue is found. In order to close the ticket and prevent the client from receiving a repeat trouble ticket, it should also have a feature to demonstrate that the maintenance work complies with the standard or threshold.

5. Conclusion

This study examined how far we've progressed in the past several decades in terms of monitoring an OAN's physical layer, with a focus on the PON network. The performance, accuracy, reliability, SR, DR, and scalability of optical monitoring devices were examined and discussed in this paper. Among the topics covered are PON test, maintenance, and monitoring utilising various methodologies. The difficulties encountered in characterising optical network connections and monitoring in-service optical link breakdown are also discussed. The ideal PON fault monitoring design must meet a number of criteria. Despite the significant contributions made to the PON optical link monitoring system's development, numerous obstacles still need to be investigated further. This research looked at how far we've come in terms of monitoring an OAN's physical layer, with an emphasis on the PON network, over the last few decades. This article examines and discusses various topics, such as PON test, maintenance, and monitoring using different techniques, that were aimed at improving the performance, accuracy, reliability, SR, DR, and scalability of optical monitoring devices. Furthermore, the challenges faced in optical network connection characterisation and in-service optical link failure monitoring are addressed. There is a set of requirements for an optimal PON fault monitoring design. Despite the substantial contributions to the development of the PON optical link monitoring system, many barriers need to be explored further. The development of a monitoring system that can simultaneously identify and find numerous fibre impairments for multiple DF connections in a high-capacity P2MP PON network may be the subject of future study. The suggested device should take into account the criteria listed in the performance framework. To combine the monitoring system with monitoring and fault detection, additional passive optical components, such as filters and FBG sensors, may be added.

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