OTDR based Estimation of Optical Fiber Link Residual OFDM CFO

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Abstract: Optical time-domain reflectometer (OTDR) has long been and is still considered the main test tool for characterizing fiber optic links, i.e. identify and localize refractive and reflective events such as breaks, splices and connectors, and measure their insertion/return loss. Specifically, sufficient dynamic range and thus alike signal-to-noise-ratio (SNR) enable clear far-end visibility even of long fiber links. Moreover, under such conditions, the highest achievable optical bit-error-rate (BER) floor is to the large extent determined by major reflective events such as the specific trace distortion caused by connectors and splices, each with significant return loss. Realizing this has provided the opportunity window to extend the standard OTDR capabilities list by the appropriate trace postprocessing to predict the BER floor. Accordingly, considering the SNR high, and thereby the inter-symbol interference dominant error generating mechanism, we applied the time-dispersion channel model that determines the BER floor by the rms delay spread of the (fiber) channel power-delay profile. We verified the BER floor prediction in the exemplar practical test situation, by measuring the actual BER on the same fiber link, and found the obtained values well matching the OTDR - based predicted ones. Furthermore, when no dominant reflective events are identified on the OTDR trace, it implies very small time dispersion allowing the OFDM symbol cyclic prefix to always prevent inter-symbol interference. This retains the CFO to solely determine the residual BER floor and vice versa, enabling indirect estimation of CFO-induced phase distortion by simple BER testing. With this regard, we abstracted CFO with the AWGN being justified by the Central Limiting Theorem to enable efficient and quite accurate short-term BER (and so CFO phase error) predictions.

1 INTRODUCTION

Optical time-domain reflectometer (OTDR) has long been used as a test tool of choice during installation and maintenance of fiber optic communication systems. It has been useful for fault locating and troubleshooting - basically identifying various refractive and reflexive events such as e.g. breaks, as well as measuring attenuation, splice and connector insertion/return losses, and fiber length (Lipovac, 2020; Wenzer, 2018; Hui, 2009; Hui, 2020), Figure 1.

In short, OTDR transmits a pulse of laser light through the fiber, while detecting the reverse-direction travelling incoming signal, commonly referred to as Rayleigh backscatter that is being reflected back by irregularities in the optical fiber structure, with the reflections' delays expressed as in distance units, by appropriately scaling the time axis multiplying it with the speed of light in the fiber (Lu, 2017; Alekseev, 2016; Hartog, 2008; Lu, 2016).

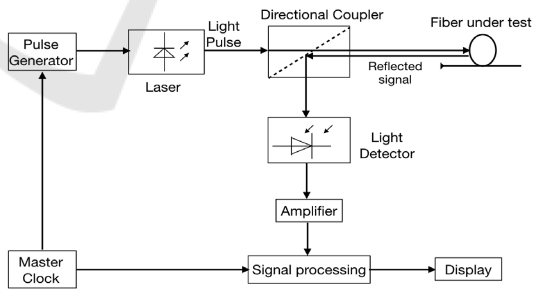

Figure 1: OTDR architecture.

Basically, an OTDR is made of a microprocessor, pulse trigger and generator, laser diode, optical coupler, detector, analog-to-digital converter and display, Figure 1.

So, initiated by the microprocessor accordingly commanding the trigger and generator, these make the laser transmitting a series of pulses unaffectedly passing through the optical directional coupler (ODC) to the near end of the actual fiber. However, in the

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reverse direction, the ODC re-routes the reflected backscatter signal to not come back (and potentially harm) the transmitting laser, but to the avalanche photodiode (APD) or positive-intrinsic-negative (PIN) diode detector. Then, following the detector, the signal passes through the analog-to-digital converter (ADC) to the microprocessor for analysis and forming the OTDR trace on the display, where the analysis includes signal averaging to increase SNR.

Furthermore, in any phase of network lifetime cycle – no matter be it development, production, installation or maintenance of fiber transmission systems, the end-to-end bit-level transmission performance is most adequately described by the bit-error-rate (BER), which is measured out-of-service, using the pseudo-random binary sequence (PRBS) generator and receiver. (Most often, single BER test (BERT) unit comprises both the generator and the receiver, which presumes a loop-back at the far end of the fiber.)

Specifically, we focus here the residual (irreducible) BER, also commonly referred to as BER floor, which is achievable under high-SNR conditions, when practically it is just time dispersion that remains out of the bit error generating mechanisms.

Moreover, considering Orthogonal Frequency-Division Multiplexing (OFDM) signal transmission over optical fiber link, the BER floor is generally also determined by the two main OFDM shortcomings - the carrier frequency offset (CFO) and (large) peak-to-average power ratio (PAPR).

However, coming closer to our final test scenario of OFDM transmission over homogeneous optical fiber links, we consider no dominant discrete events (neither reflective, nor refractive ones detected by OTDR), as well as enough large optical receiver dynamic range (DR) or used any PAPR reduction method) to prevent the non-linear high-power transmitting amplifier from generating errors.

Finally, we consider time dispersion small enough to allow the OFDM symbol cyclic prefix (CP) prevent any inter-symbol interference (Lipovac, 2021).

This all imply that, under such conditions common in practice, the CFO remains the sole determining factor of the residual BER, which enables indirect estimation of CFO-induced phase distortion by much simpler BER testing (Lipovac, 2021).

This motivates our investigation of how accurate and reliable is to estimate the fiber BER floor and OFDM CFO from the related OTDR trace?

So, in Section 2, after reviewing the relevant OTDR basic concepts, we firstly present the BER floor model as a function of the crucial time dispersion parameter – rms delay spread of the reflective events dominant optical channel PDP that is considered determined by the OTDR trace.

Then, in case of uniform OTDR trace decay with a number of smaller discrete refractive events – attenuations, we modelled the residual BER and CFO by applying the link abstraction principle.

In Section 3, we present and discuss the obtained preliminary test results for the exemplar test situation, providing the according analysis to qualify matching between the OTDR - based and directly measured BER floor and CFO values. Conclusions are summarized in Section 4.

2 ANALYSIS

The backscatter signal returning to the OTDR consists of both Rayleigh scattering and Fresnel reflections, where the former enables calculating fiber attenuation as a function of distance, which is represented by the constantly falling part of an OTDR trace. However, Fresnel reflection occurs when the light pulse light hits an abrupt change in refraction index, which causes a strong reflection back, and so enables detection of physical events identifiable by spikes in OTDR trace due to connectors, mechanical splices, bulkheads, fiber breaks or opened connectors (the higher the spike with respect to the backscatter levels, the greater the reflectance), Figure 2.

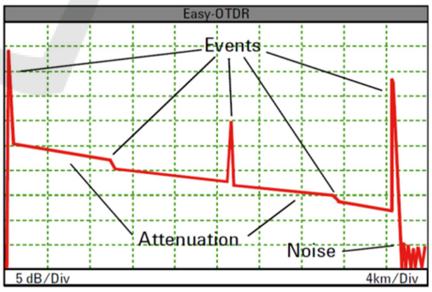


Figure 2: Typical OTDR trace for a longer fiber with various reflective and refractive events (5 dB/Div; 4 km/Div).

2.1 Basic OTDR Analytical OFDM BER Floor Model

More precisely, when the OTDR transmits the light pulse of power P_0 into the fiber, then the power $P_T(z)$ of the pulse propagating downstream the fiber, is the exponential function of distance z of the observation point from the fiber near-end (OTDR):

$$P_T\,(z) = P_0 \cdot 10^{-\alpha \cdot z/10} \tag{1}$$

where $\alpha = \alpha_s + \alpha_a$ is the sum of the scattering and absorption losses expressed in dB/km.

The total scattered power at distance z is:

$$P_s(z) = \alpha'_s \cdot \Delta z \cdot P_T(z) \tag{2}$$

where $\alpha'_s = 0.23 \cdot \alpha_s$ and Δz denote the fiber loss and the light pulse length, respectively.

The latter can be expressed as:

$$\Delta z = w \cdot v_{gr} = w \cdot c / n_{gr} \approx w \cdot c / n \tag{3}$$

where: w, v_{gr}, n_{gr}, and c denote the pulse duration, the group velocity in the fiber, the group refractive index (justifiably approximated by the ordinary index n), and the speed of light in vacuum, respectively.

Determined by the fiber numerical aperture, i.e. by limited efficiency of an optical fiber to confine the incident light, only a certain part $S<1$ of the scattered light travels back to the OTDR (and is being subjected to equal loss as during forward propagation), and reaches the arbitrary point that is z apart from the OTDR, with the total backscattered power:

$$P_{BS}\,(z) = S \cdot \alpha'_s \cdot \Delta z \cdot P_0 \cdot 10^{-2\alpha \cdot z/10} \tag{4}$$

implying that the backscattering power reflected from the end of the fiber ($z = L$) is:

$$P_{BS}\,(L) = S \cdot \alpha'_s \cdot \Delta z \cdot P_0 \cdot 10^{-2\alpha \cdot L/10} \tag{5}$$

So, for example, in order to estimate the backscattered power at 1550 and 1300 nm, we need to adopt some typical parameters' values in (5), such as the ones in Table 1.

Table 1: Typical parameters' values.

Wavelength	1550 nm
$\alpha=\alpha_s+\alpha_a$	0.2 dB/km = 1.046/km
α'_s	0.036/km
w	1 us
S	$9.8 \cdot 10^{-4}$
$P_{BS}(0)/P_0$	-51.5 dB

2.2 OFDM BER Floor Model for OTDR Trace with Significant Reflective Events

On the other hand, the orthogonal frequency-division multiplexing (OFDM) has become widely spread in optical communications as attractive modulation format for long-haul transmission (Hui, 2020).

As it is challenging to uniquely relate the OTDR trace events (primarily the reflective ones) to the parameter(s) determining the OFDM BER error floor under high-SNR conditions and therefore dominant time dispersion, which implies that we can apply the OFDM BER floor model (Lipovac, 2021), specifically when sampling time is just upon the arrival of the first impulse of the channel impulse response.

So, we consider the power-delay profile (PDP) as the sum of N impulses with powers A_i^2, and delays τ_i, $i = 1,2,...N$ (Lipovac, 2021).

Then, with no loss in (OFDM) generality, for simple NRZ transmission, the BER floor for the trace with significant reflections is:

$$BER \approx 0.28 \cdot \frac{\sqrt{E[\tau^2]}}{T_s} \tag{6}$$

where:

$$\frac{\sqrt{E[\tau^2]}}{T_s} = \frac{1}{2\sqrt{\pi}} \cdot \frac{\sqrt{\sum_{i=1}^{N} A_i^2 \tau_i^2}}{T_s} \tag{7}$$

is the standard rms delay spread (normalized to the symbol time T_S) of the channel PDP $P_{BS}(z)$, which we consider to conform to the OTDR backscatter trace (as describing time dispersion alike).

The BER floor condition of high SNR is fulfilled with large enough OTDR dynamic range, which is basically achieved with long enough transmitted pulse.

However, on the contrary, an OTDR trace being effectively an attenuated two-way squared response of the fiber channel to the transmitted laser pulse, can only be considered the PDP for short enough laser pulse considered an impulse.

Thus, with this regard, the crucial OTDR attribute is dynamic range, which is the difference between the backscatter level at the front end and the noise floor at the far end of the fiber, where the latter is mostly considered as where SNR equals unity, Figure 3.

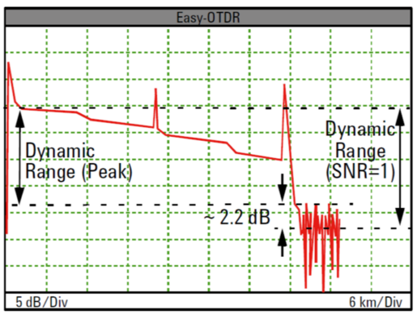
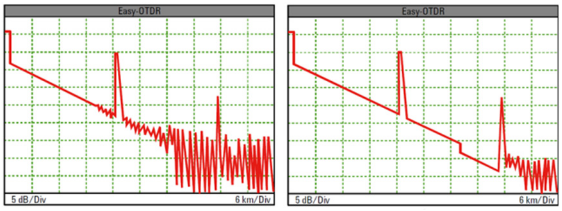


Figure 3: Dynamic range definitions with two definitions of the noise floor.

Measured in decibels, DR is the difference between the backscatter level at the front end of the fiber and the noise floor at the far end of the fiber, where most often the latter corresponds to the signal level (i.e. where SNR=1).

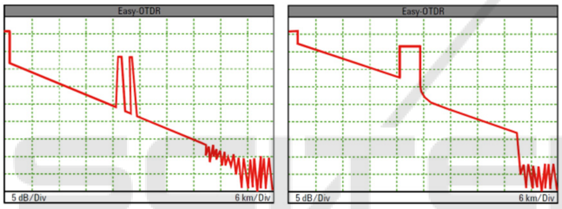
Thus, small dynamic range disables proper OTDR measurements at the fiber end, Figure 4.



a) b)

Figure 4: OTDR trace; a) small dynamic range, b) large dynamic range.

Longer pulses provide larger dynamic range, as well as worse event resolution and longer attenuation dead zone, Figure 5.



a) b)

Figure 5: OTDR trace; a) small dynamic range, b) large dynamic range.

Furthermore, in addition to pulse width, receiver bandwidth is another crucial performance criterion, which determines the actual OTDR resolution (Charlamov, 2013).

So, for each OTDR laser pulse width and desirable attenuation dead zone, we can calculate the impulse response and bandwidth of an optical receiver.

With this regard, in Table 2 some exemplar OTDR receiver bandwidth (BW) values for given pulse width (PW) values, are presented.

Table 2: OTDR pulse width and bandwidth.

PW	BW [MHz]
3 ns	110
5 ns	71
10 ns	39
30 ns	16
100 ns	5,6
300 ns	2,2
1 µs	0,8
3 µs	0,3
10 µs	0,1
20 µs	0,06

Considering that:

$$P_{BS}(z) = P_{BS}(c/2\cdot n\cdot\tau) = C_0\cdot 10^{-\alpha\cdot c\cdot n\cdot\tau/10}\ ; \quad C_0 = S\cdot\alpha'_s\cdot\Delta z\cdot P_0 \tag{9}$$

the response of the fiber-made link onto the OTDR-transmitted pulse $P_T^{1/2}(z)$, is the convolution of the latter with the fiber impulse response $h(\tau)$.

$$P_{BS}^{1/2}(\tau) = P_T^{1/2}(\tau) * h(\tau)\ ;\ \ \tau = (2z\cdot n)/c \tag{10}$$

So, to obtain $h(\tau)$, we need to de-convolve it from $P_T^{1/2}(\tau)$, which means to solve (9) per $h(\tau)$, leading to:

$$h(\tau) = c/2n\cdot E_i\cdot S\cdot\eta_i\cdot\exp(-2\alpha z) \tag{11}$$

where c, n, E_i and η_i stand for speed of light, laser energy, average refractive index of the actual fiber, and APD quantum efficiency, respectively.

However, pragmatically looking, large OTDR dynamic range still makes its transmitted pulse (of about 1 µs duration) short enough (with respect to the reciprocal of the OTDR receiver bandwidth) – almost as of an impulse described by delta-function:

$$P_T(z) = \delta(-2\alpha z) \tag{12}$$

so that (10) modifies to:

$$P_{BS}^{1/2}(z) = \delta(-2\alpha z) * h(z) = h(z)\ ;\ z = c\cdot\tau/2 \tag{13}$$

Consequently, the normalized power – delay profile of the fiber can be approximated by the normalized (to unity area) relative OTDR trace as:

$$|h(\tau)|^2 = P_{BS}(z = c\cdot\tau/2) \tag{14}$$

Thereby, we can consider the OTDR trace to be the first approximation of the average fiber PDP.

2.3 AWGN Abstraction of CFO from Uniform-Decay OTDR Trace

Regardless of whether any kind of CFO compensation used or not, the task here is to quantify the residual CFO-caused phase error for given conditions (Lipovac, 2016).

Furthermore, back to basics, the well-known BER expression for the M-QAM signal transmission over the additive white Gaussian noise (AWGN) channel, as a function of the ratio of the energy E_b of a bit to noise spectral density N_0, is (Lipovac, 2021):

$$BER = \frac{4\cdot Q\left(\sqrt{\frac{3\frac{E_b}{N_0}\cdot\log_2 M}{M-1}}\right)}{\log_2 M} \tag{15}$$

where Q denotes the Gaussian tail function.

Now, as it is already elaborated in Introduction, the scenario of interest here is OFDM transmission over homogeneous fiber link, where we consider no dominant discrete events of any kind detected in the OTDR trace, and qualified as either reflective or refractive. This practically implies that we can then justifiably consider CFO as the main error generating mechanism, and thus determining BER.

Moreover, from the OTDR trace, we can read out the SNR (i.e. E_b/N_0) value at the far end, and substitute it into (12), considering that it abstracts the actual BER with the AWGN one (as if a number of mutually independent small distortions in summary enable the application of Central Limit Theorem) of the according mean and variance (Lipovac, 2021).

Then, having calculated this AWGN-modelled BER due to CFO, we can calculate the maximal squared CFO-caused phase deviation as (Lipovac, 2016):

$$\Delta\Phi_{k\max}^2(BER) \approx 30 \cdot \frac{(\Delta f_{CFO} M T_s)^2}{s_k^2} \cdot \frac{\sqrt{\frac{3}{M-1}} \cdot \frac{1}{\left[Q^{-1}\left(\frac{BER \cdot \log_2 M}{4}\right)\right]}}{10}; \quad 1 \le k \le M \tag{16}$$

where Δf_{CFO} denotes the CFO.

3 TEST RESULTS

3.1 Test System

The HP 8147A optical time domain reflectometer was used for preliminary BER floor prediction model. It was designed long ago and aimed for lightwave network operators during installation and field maintenance of their networks.

The OTDR with the plug-in optical interface module supporting both 1310 nm and 1550 nm windows, was connected in the test configuration alternately with the BER tester (BERT) according to Figure 6.

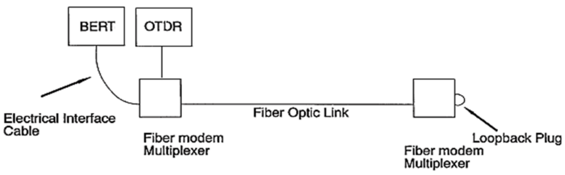


Figure 6: OTDR and two-way BERT configuration.

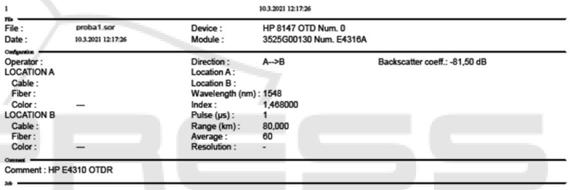
OTDR aided fiber testing is naturally out-of-service, which is certainly not what network operators favour with neither OTDR, nor BER testing (BERT). That is why, to make our tests, we connected both the OTDR and then the BERT to unused Gbit/s "dark" fiber, and so not interrupt active fibers carrying live traffic by neither OTDR nor BER tests.

The high-SNR condition that was earlier considered by the proposed BER floor model as equivalent to the requirement for large dynamic range, which is mostly achieved by using long enough transmitted pulses.

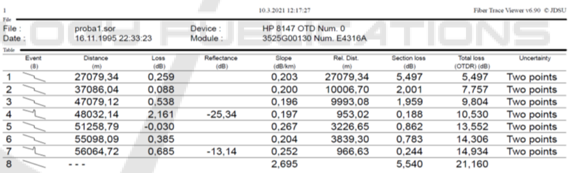
However, as on the contrary, longer pulses are less credibly considerable as impulses, thus our choice of about 1 µs long pulse seems to be a good compromise for the fibers under test.

3.2 Preliminary Test Results

The exemplar OTDR setup, discovered and qualified events, and screen shots of detailed test traces are presented in Figures 7 a) – c):

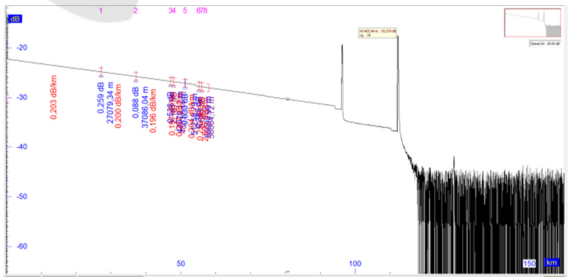

1 10.3.2021 12:17:26
File
File : proba1.sor Device : HP 8147 OTD Num. 0
Date : 10.3.2021 12:17:26 Module : 3525G00130 Num. E4316A
Configuration
Operator : Direction : A-->B Backscatter coeff.: -81,50 dB
LOCATION A Location A :
Cable : Location B :
Fiber : Wavelength (nm) : 1548
Color : --- Index : 1,468000
LOCATION B Pulse (µs) : 1
Cable : Range (km) : 80,000
Fiber : Average : 60
Color : --- Resolution : -
Comment
Comment : HP E4310 OTDR
Job

a)


1 10.3.2021 12:17:27 Fiber Trace Viewer v6.90 © JDSU
File
File : proba1.sor Device : HP 8147 OTD Num. 0
Date : 16.11.1995 22:33:23 Module : 3525G00130 Num. E4316A
Table

Event (8)	Distance (m)	Loss (dB)	Reflectance (dB)	Slope (dB/km)	Rel. Dist. (m)	Section loss (dB)	Total loss (OTDR) (dB)	Uncertainty
1	27079,34	0,259		0,203	27079,34	5,497	5,497	Two points
2	37086,04	0,088		0,200	10006,70	2,001	7,757	Two points
3	47079,12	0,538		0,196	9993,08	1,959	9,804	Two points
4	48032,14	2,161	-25,34	0,197	953,02	0,188	10,530	Two points
5	51258,79	-0,030		0,267	3226,65	0,862	13,552	Two points
6	55098,09	0,385		0,204	3839,30	0,783	14,306	Two points
7	56064,72	0,685	-13,14	0,252	966,63	0,244	14,934	Two points
8	- - -			2,695		5,540	21,160	

b)



c)

Figure 7: OTDR screen shots: a) setup; b) discovered and qualified events; c) detailed trace printout.

As it is summarized in Table 3, good matching is evident between the estimated and the actually measured residual BER values, both in case of considering the same test traces as having or not having dominant reflective events. In the latter case, abstracting the CFO by the AWGN model provided the CFO phase error prediction.

Table 3: OTDR trace based estimate vs. measured BER floor; 50 and 80 km fiber link, 1 Gbit/s.

Link length	50 km	80 km
$BER\_OTDR_{SNR>>}$	$4.13 \cdot 10^{-12}$	$6.31 \cdot 10^{-12}$
BER_OTDR_{CFO}	$4.24 \cdot 10^{-12}$	$6.41 \cdot 10^{-12}$
BER_BERT	$4.49 \cdot 10^{-12}$	$6.89 \cdot 10^{-12}$
$\Delta\Phi^2_{k\,\max}$ [rad]	$4.7 \cdot 10^{-8}$	$6.1 \cdot 10^{-8}$

This validates the proposed model.

4 CONCLUSIONS

A simple prediction of fiber optic link residual BER coming out directly from the OTDR trace, is proposed to extend the standard OTDR functionalities beyond bare identifying and characterizing various bit-error generating events, and so enable troubleshooting of fiber optic links, but also predict the residual BER, as the ultimate end-to-end transmission performance.

This came out of the idea to consider the reflective events in the OTDR trace as determining the time dispersion standard describing parameter – mean delay spread, so modelling the residual BER of the fiber link.

The obtained preliminary test results that we conducted on a dark fiber (to avoid the network operator dissatisfaction with out-of-service testing), validated the analytical model, showing good matching between the OTDR-predicted and actually measured residual BER, for short transmitted pulses and large enough OTDR receiver (photodetector) bandwidth, at least 40 % wider than the reciprocal pulse width.

Furthermore, when no dominant reflective events are identified on the OTDR trace, it implies very small time dispersion allowing the OFDM symbol cyclic prefix to always prevent inter-symbol interference, retaining the CFO to solely determine the residual BER floor. Thus, we abstracted CFO with the AWGN to enable efficient and quite accurate short-term BER (and so CFO phase error) predictions.

REFERENCES

Lipovac, A. Practical Enhancement of Fiber Installation and Maintenance Test Tools - Example of Extending OTDR Distance Range by Optical Preamplifier, Proceedings of the European Lasers, Photonics and Optics Technologies Summit, Paris, France, September 2020.

Winzer, P. J.; Neilson, D. T.; Chraplyvy, A. R. Fiber-optic transmission and networking: the previous 20 and the next 20 years. *Optics Express* 2018, 26, pp. 24190-24239.

Hui, R. Passive optical components. *Introduction to Fiber-Optic Communications,* 1st ed.; Academic Press: USA, 2020; pp. 209-297.

Hui, R.; O'Sullivan, M. Characterization of Optical Devices. *Fiber Optic Measurement Techniques*, 1st ed.; Academic Press: USA, 2009; pp. 259-363.

Lu, X.; Soto, M. A.; Thévenaz, L. Temperature-strain discrimination in distributed optical fiber sensing using phase-sensitive optical time-domain reflectometry. *Optics Express* 2017, 25, pp. 16059-16071.

Alekseev, A. E.; et al. Fading reduction in a phase optical time-domain reflectometer with multimode sensitive fiber. *Laser Physics* 2016, 26, pp. 95-101.

Hartog, A. H. Frequency-scanned optical time domain reflectometry. US Patent 7859654B2, 2008.

Lu, X.; Soto, M. A.; Thévenaz, L. Optimal detection bandwidth for phase-sensitive optical time-domain reflectometry, Proceedings of the Sixth European Workshop on Optical Fibre Sensors EWOFS'2016, Limerick, Ireland, 2016, pp. 374-377.

Lipovac, A.; Lipovac, V.; Modlic, B. PHY, MAC, and RLC Layer Based Estimation of Optimal Cyclic Prefix Length. Sensors 2021, 21, 4796. https://doi.org/10.3390/s21144796

Lipovac, A., V. Lipovac and B. Modlic, Modeling OFDM Irreducible BER with Impact of CP Length and CFO in Multipath Channel with Small Delay Dispersion, *Wireless Communications and Mobile Computing*, vol. 16(9), pp. 1065-1077, 2016.

Charlamov, J., R. Navickas, A. Baskys, V. Barzdenas, L. Nickelson, Optical Receiver for Optical Time Domain Reflectometer, Computer Engineering Department, Vilnius Gediminas Technical University, Naugarduko St. 41, LT–03227 Vilnius, Lithuania, 2013.