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TECHNICAL REPORT

colour
inside

Guidance for the interpretation of OTDR backscattering traces for single-mode fibres

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GUIDANCE FOR THE INTERPRETATION OF OTDR BACKSCATTERING TRACES FOR SINGLE-MODE FIBRES

FOREWORD

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IEC TR 62316, which is a Technical Report, has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

This third edition cancels and replaces the second edition published in 2007. It constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) the scope has been extended to include single-mode fibres;

a) backscattered power effects are discussed in case of unidirectional trace, including so-called losers and gainers.

b) example of apparent splice loss evaluation for unidirectional OTDR measurements has been added:

c) description of launch and tail cords have been added;

d) figures have been improved.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
86A/1754/DTR	86A/1768A/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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GUIDANCE FOR THE INTERPRETATION OF OTDR BACKSCATTERING TRACES FOR SINGLE-MODE FIBRES

1 Scope

IEC 62316, which is a Technical Report, aims to provide guidelines for the interpretation of backscattering traces, as obtained by traditional optical time domain reflectometers (OTDRs) – not including polarization OTDRs – for single-mode fibres. Also, backscattered power effects are discussed in case of unidirectional trace.

Full description of the test measurement procedure can be found in Annex C of IEC 60793-1-40:2001.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Backscattering phenomenon

4.1 Rayleigh scattering

Rayleigh scattering or backscattering originates from fluctuations in the density, and hence in the index of refraction, of the material constituting the wave-guide; optical fibres are made of amorphous silica, and density fluctuations are a consequence of the manufacturing process.

4.2 Fresnel reflections and dead zone fibres

When a light ray reaches a surface at an angle of incidence from the normal to that surface and that surface separates two media of different index of refraction, part of this light ray is refracted in the second medium and part of it is reflected backward into the first medium. This is the Fresnel reflection, which can be very high, depending on the difference in the index of refraction of the two media, on the aspect of the surface, the surface roughness, the angle of incidence and the surface defects. In most situations, strong Fresnel reflections cause non-linearities at the receiver. These non-linearities can overload the receiver resulting in signal clipping, pulse widening, tailing, and ghosts. The corresponding section of the optical time domain reflectometer (OTDR) trace following the intense Fresnel reflection defines the deadzone. This particular deadzone should not be confused with the manufacturer's specification, always defined with a narrow pulse and small Fresnel reflection. The effect of the strong reflection on the deadzone is usually resolved by cleaning the connector responsible for the reflection. The so-called deadzone eliminator (adding a length of fibre after a strong reflection) does not reduce the deadzone nor the strong reflection. It artificially moves the virtual bulkhead connector to another location and assumes the following connector has a low reflection. Depending on the type of photodetector used in the receiver, the tailing due to a strong reflection can be greater than the fibre length inserted between the OTDR and the fibre under test.

5 Measurement of the backscattered power (OTDR)

5.1 General

The power backscattered by an optical fibre is measured by means of OTDRs. They are based on the principle of sending one pulse or typically a train of pulses from one fibre end, and measure the power back-reflected from the fibre at the same end. In OTDR traces, space and time are completely equivalent through the relation:

$$\frac{z}{t} = \frac{c}{n_\mathrm{g}(\lambda)} \tag{1}$$

where

z is the distance (in meters);

t is the time (in seconds);

c is the speed of light in vacuum (299 792 458 meters/second);

n_g is the group index of refraction (as a function of the wavelength).

The group index of refraction, to be supplied by the fibre manufacturer, takes into account the wave-guiding properties of the fibre and the different materials used for the cladding and the core. It also adjusts the speed of light in the studied material. The group index of refraction n_g is related to the phase index n or n_p (which is measured on a fibre and its fundamental attribute) by using the following expression:

$$n_\mathrm{g} = n_\mathrm{p} - \lambda \frac{dn_\mathrm{p}}{d\lambda} \tag{2}$$

5.2 Representation of the backscattered power

A possible schematic representation of the OTDR power $P(z)$ at wavelength λ backscattered by a point z along an optical fibre is:

$$P(z) = C \frac{\lambda^2}{(\omega(z))^2} P_\mathrm{i} \tau_\mathrm{w} 10^{-\frac{2}{10}\alpha z} \tag{3}$$

where

P_i is the input OTDR pulse power into the fibre;

τ_w is the input OTDR pulse width (in seconds);

z is the distance at which the backscattered power is generated;

α is the attenuation in m^{-1}. Multiply α_{dB} by 0,00023 to obtain α, and α_{dB} is the attenuation in dB/km (assumed constant to simplify the equation);

$\omega(z)$ is the fibre mode field diameter (MFD) at point z;

C is a proportionality factor, which depends on several parameters such as the fibre material or the refractive index value. For step-index single-mode fibre, this factor is expressed by:

$$C = \frac{3c\alpha_\mathrm{s}}{16\pi^2 {n_\mathrm{eff}}^2 n_\mathrm{g}} \tag{4}$$

where

c is the speed of light in vacuum;

α_s is the Rayleigh scattering coefficient in m^{-1};

n_{eff} is the effective refractive index of the fundamental mode, which is a number quantifying the phase delay per unit length in a wave guide, relative to the phase delay per unit length in vacuum;

n_{g} is the group index of refraction.

Equation (3) shows the relation between the backscattered power, the pulse width, the attenuation coefficient and the MFD. The optical reflected power, as given by Equation (3), is conventionally represented on a logarithmic graph: it therefore appears as a (theoretically) straight line, whose slope is the attenuation coefficient of the fibre, α, as better explained in Clause 6 below.

Note that Equation (3) is valid for short pulse width, i.e. $\tau_{\mathrm{w}}\alpha << 1$, which applies in most practical cases.

5.3 Noise and perturbations

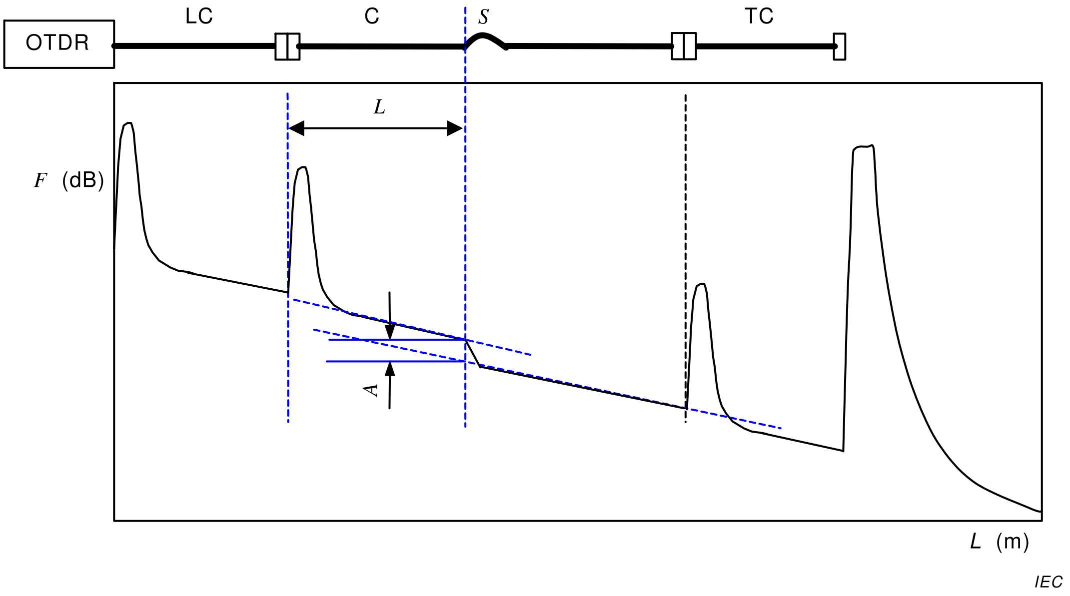
Normally, the fluctuations of fibre parameter and receiver linearity affect the backscatter traces; the trace can therefore appear as a perturbed line. The linear signal decreases exponentially – as from Equation (3); over long distance, the signal to noise ratio (SNR) decreases as a function of distance. As the backscatter signal approaches the noise floor, non-linearities can appear. A practical way to improve the SNR, also known as dynamic range, is to increase averaging time or increase the pulse width.

Any event, such as a splice, connector, macro-bend, micro-bend, can be detected by the OTDR and appear as a perturbation. Micro-bends are more evident at long wavelengths such as 1625 nm, far from the cut-off wavelength where the MFD is larger and the confinement of light in the fibre is reduced.

6 Interpretation of a backscattering trace

6.1 General

Figure 1 shows a typical unidirectional OTDR trace of an optical fibre showing a loss A dB, which can be a macrobend loss or splice loss. The reflection at the input face is exaggerated for clarity; normally it is reduced by means of a launch cord with clean connector meeting IEC 61300-3-35.



Key

OTDR	optical time domain reflectometer
LC	launch cord
C	cabling under test
F	reflected power level
L	distance from OTDR launch cord output port
A	macro bend or splice loss

TC	tail cord	S	macro bend or splice

Figure 1 – Unidirectional OTDR trace showing splice and/or macro bend loss

6.2 Launch cord

The optical fibre within the launch cord at the connection to the cabling under test should be of the same type, in terms of core diameter and numerical aperture, but not necessarily bandwidth, as the optical fibre within the cabling under test.

The length of the launch cord should be longer than the dead zone created by the pulse width selected for a particular length of fibre to be measured. Suppliers of OTDR equipment should recommend lengths. In addition, these lengths should be long enough for a reliable straight line fit of the backscatter trace that follows the attenuation dead zone with standard connector reflectance.

6.3 Tail cord

The optical fibre within the receive or tail cord should be of the same type, nominal core diameter and nominal numerical aperture as the optical fibre within the cabling under test.

The length of the tail cord should be longer than the dead zone created by the pulse width selected for a particular length of fibre to be measured.

6.4 Unidirectional trace

6.4.1 General

The accepted method of determining the attenuation of installed links by OTDR is performing bi-directional OTDR measurements[1] and average both these traces (see IEC 60793-1-40 and IEC 61280-4-2). However, in some situations, it is difficult in practice to perform such bi-directional OTDR measurements, in particular fibre-to-the-home (FTTH) applications. In those cases, OTDR traces obtained by the processing of the optical backscattered light collected from one end only of the fibre can be used, called unidirectional traces. Such unidirectional OTDR traces may be useful to quickly evaluate the optical continuity of a fibre and to estimate the link attenuation coefficient, which reliability, however, can be affected by several effects (such as perturbation changes in the fibre, backscatter coefficient changes, non-linearities, and ghosts).

For unidirectional measurement, the following should be understood and taken care of.

– The main requirement for total single mode unidirectional attenuation measurements using an OTDR is that the launch and tail cords used for the set-up have the same backscatter coefficient. In order to verify this hypothesis, the following test should be performed before using an OTDR for single direction measurement every time when it is not sure the launch and tail cords have the same backscatter coefficient.

– Launch cable test procedure: Connect the launch and tail cords together. Adjust the OTDR pulse width, so that a sufficiently large number of data points and an appropriate signal-to-noise ratio are obtained. Determine the backscatter traces from both fibre ends with averaging OTDR measurements from both directions.

– For each direction A and B, calculate the average loss between launch and receive cords LA and LB. The difference between the losses from both directions should be equal to zero, given the device and measurement uncertainties. This step ensures that the backscatter coefficient of the launch and receive cords are the same, allowing to proceed with total attenuation measurements for single mode links.

– For conformance testing of links and channels, an optical light source and power meter are required.

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[1] Further discussions on the same subject can be found in Annex C of IEC 60793-1-40:2001.

6.4.2 Slope as the attenuation coefficient of a fibre

Starting from Equation (3) for the backscattered power, taking logarithms on both sides, one obtains (with decimal logarithm written as “lg(x)”):

$$5\,\mathrm{lg}\left[P(z)\right] = const. + 10\,\mathrm{lg}\left(\frac{\lambda}{\omega(z)}\right) - \alpha_{\mathrm{dB}} z \tag{5}$$

The constant in Equation (5) includes some numerical factors and the logarithm of the parameter C:

$$const. = 5\left[\mathrm{lg}(C) + \mathrm{lg}(P_{\mathrm{i}}) + \mathrm{lg}(\tau_{\mathrm{W}})\right] \tag{6}$$

Equation (5), plotted on a logarithmic scale as a function of z, will appear as a straight line with slope α (taking properly into account the factor 2).

Due to the SNR characteristics described in 5.3, the evaluation of the attenuation coefficient is better undertaken with the best-fit straight line. Recall that a factor of 5 is used instead of 10 to report measurement traces on OTDR equipment, as the light travels through the fibres and events under test twice (round-trip).

6.4.3 Impurity and discontinuity

If an impurity, or any discontinuity, is present within the fibre (in the MFD region), the light can suffer a Fresnel reflection (see 4.2) and will appear on the OTDR trace as a peak, the amplitude of which depends on the size of the discontinuity (in some situations, the receiver can saturate). It is possible to locate the position of the discontinuity by Equation (1). A peak can be detrimental to link performance when its backscattered energy content is large enough to interfere with the source[2]. The reflectance, as defined and used for the characterization of the connectors, can be envisaged as the right parameter to evaluate the peak.

6.4.4 Pulse width

It is important to understand that the pulse width affects the returned energy and hence the dynamic range. The wider the pulse, the higher the dynamic range (assuming signal averaging is constant). However, the wider the pulse, the wider the deadzone[3].

6.4.5 Polarization effects

The OTDR includes a splitter that can act as a polarizer on the output pulses and an analyser on the receive side of the reflected pulses. Other elements can also polarize the light. As a result of polarization mode dispersion (PMD) in the fibre, the Stokes vector of polarized light rotates about the Poincaré’s sphere as it propagates through the fibre in both the forward and reflected directions. It also rotates with optical frequency or wavelength.

If the temporal OTDR pulse width and/or spectral width is sufficiently broad, the OTDR receiver yields the average of many Stokes vectors and the effect of varying polarization states is not seen. If these widths are reduced in comparison to the fibre PMD, or if the fibre PMD is low enough compared to these widths, fewer Stokes vectors are averaged and the apparent pulse magnitude can appear to vary with position along the fibre in a ripple pattern.

These apparent ripples can be reduced by rapidly varying the polarization of the source or by using a polarization scrambler or other appropriate devices.

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[2] Further discussions on the same subject can be found in Annex C of IEC 60793-1-40:2001.

[3] Further discussions on the same subject can be found in Annex C of IEC 60793-1-40:2001.

6.5 Bi-directional trace

6.5.1 General

Bi-directional traces are obtained by making measurements from each end of a fibre then combining both traces by averaging the results. The OTDR shall be physically moved to the either end of the fibre to make the measurement.

If using a launch and tail cord, commonly used when measuring a permanent link, only the OTDR is moved during the measurement. The launch and tail cord do not move.

Bi-directional measurements are mostly used when there are connectors and different sections of fibres in the link. The changes in backscatter coefficients between fibres are common and necessitate bi-directional testing.

Starting from the expression of the backscattered optical trace (Equation (3)), it is straightforward to calculate the bi-directional OTDR traces from unidirectional traces P_1 and P_2 obtained from the two ends of the fibre, applying the coordinate's transformation $z' = L - z$ on P_2 so that $P_3(z)=P_2(L - z')$, (where L is the total fibre length, and z and z' indicate the same point taken on the two traces), thus obtaining:

$$5\lg[P_1(z)] = const. + 10\lg\left(\frac{\lambda}{\omega(z)}\right) - \alpha_{\mathrm{dB}} z \tag{7}$$

$$5\lg[P_2(z')] = const. + 10\lg\left(\frac{\lambda}{\omega(L-z')}\right) - \alpha_{\mathrm{dB}} z' \tag{8}$$

$$5\lg[P_3(z)] = const. + 10\lg\left(\frac{\lambda}{\omega(z)}\right) - \alpha_{\mathrm{dB}} (L-z) \tag{9}$$

Equations (8) and (9) can be then summed or subtracted side-by-side, and the results, respectively S and D, are:

$$S(z) = 2 \times const. + 20\lg\left(\frac{\lambda}{\omega(z)}\right) - \alpha_{\mathrm{dB}} L \tag{10}$$

$$D(z) = -2\alpha_{\mathrm{dB}} z - \alpha_{\mathrm{dB}} L \tag{11}$$

Equations (10) and (11) show that the bi-directional approach allows, in principle, the separation of contributions due to variations of geometrical parameters of the single-mode fibre (the MFD ω) from contributions due to changes in the attenuation coefficients (α) of the fibre. Further details for the computation of S and D can be found in 6.5.2 and 6.5.3 below.

6.5.2 Attenuation uniformity[4]

6.5.2.1 General

Attenuation uniformity is based on the bi-directional backscattering technique. The bi-directional back-scattering trace can be represented as a function, $y(z)$, with y being the trace (in dB) and z being the position (in km). It is computed by reversing the position of each location of one of the uni-directional traces and computing the difference between the two uni-directional traces, divided by two, for each position. The bi-directional trace can be derived from multiple measurements or from appropriately filtered data having the same effect.

6.5.2.2 Sliding window

The uniformity parameter, X_A, is defined in terms of the sliding window (SW) algorithm, in which the attenuation coefficient is evaluated across a fixed sub-length, SL (sliding window

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[4] The text of this paragraph is an extract from the more detailed IEC TS 62033.

width) of the fibre, ideally sliding along the fibre starting from each of a set of positions: z_1, z_2, etc. The attenuation coefficient values at those positions can be represented as:

$$A(z_\mathrm{i};SL) = \frac{y(z_\mathrm{i}) - y(z_\mathrm{i} + SL)}{SL} \tag{12}$$

Alternatively, the fitted slope of the trace at the defined positions can be substituted for the values of $A(z_\mathrm{i};\ SL)$. The uniformity parameter is the difference between the maximum of the $A(z_\mathrm{i},\ SL)$ values and the average attenuation coefficient of the whole fibre, given by its end-to-end attenuation coefficient, α, as determined by any method in the IEC 60793-1-40:

$$X_\mathrm{A} = \max[A(z_\mathrm{i};SL)] - \alpha \tag{13}$$

6.5.2.3 Generalised sliding window

The generalised sliding window (GSW) algorithm will provide coefficients, α_r, and ε_r such that for a defined range of SL:

$$Max\{A(z_\mathrm{i},SL)\} = \alpha_\mathrm{r} + \frac{\varepsilon_\mathrm{r}}{SL} \tag{14}$$

α_r is a baseline attenuation coefficient and ε_r is a loss penalty parameter that allows scaling non-uniformity with variable SW lengths. The GSW parameters may be used to compute the sliding window maximum in Equation (14) for a variety of sub-lengths, SL.

6.5.3 MFD uniformity

Combining the two traces P_1 and P_3 in the half-sum $S(z)$

$$S(z) = \frac{10\lg[P_1(z)] + 10\lg[P_3(z)]}{2} \tag{15}$$

the MFD as a function of the position, $\omega(z)$, can be easily calculated, inserting a reference fibre before the fibre under test with a known MFD, $\omega(z_0)$, at the position z_0, and neglecting longitudinal variations of α:

$$S'(z) = S(z) - S(z_0) = 20\lg\left[\frac{\omega(z_0)}{\omega(z)}\right] \Rightarrow \omega(z,\lambda) = \omega(z_0,\lambda)10^{-\frac{S'(z,\lambda)}{20}} \tag{16}$$

6.6 Splice loss evaluation

6.6.1 General

It is difficult to evaluate a system loss budget by measuring splice losses, since there exist several different approaches and some of them can sometimes lead to misunderstandings.

One traditional method for measuring link loss is by an end-to-end light source power meter (LSPM) measurement, but note that this method does not provide fault location. For that type of problem or troubleshooting, the OTDR plays an important role in evaluation of systems.

The basic backscattering principle makes the OTDR very sensitive to many parameters of optical fibre which can influence the light coupling properties (see Equation (3)). Different fibres will intrinsically capture more or less backscattered light resulting in varying signal levels back to the OTDR.

"Different" here means different geometrical and/or transmission properties and not the manufacturing method. This means that the same fibre type can be manufactured by different technologies and are easy to splice to each other, provided the geometry is well controlled.

6.6.2 Event measurement methods

The unidirectional splice loss is usually provided by the OTDR equipment itself thanks to some signal processing and events detection algorithms. In Figure 2, an idealized OTDR trace is illustrated at the vicinity of a splice joint made between two fibres A and B. The splice location is at point O.

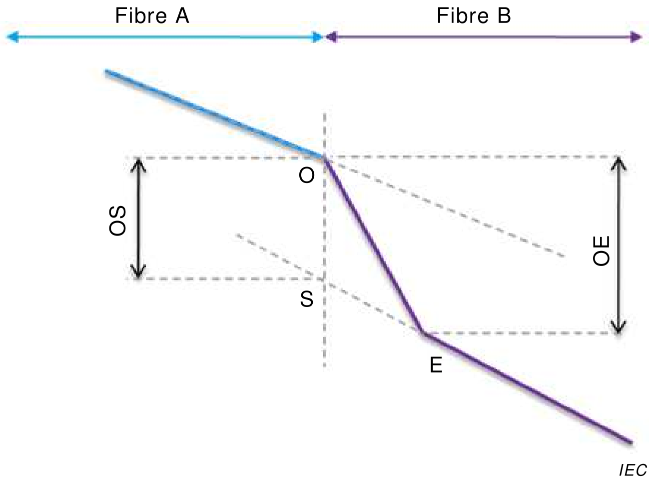


Figure 2 – Idealized unidirectional OTDR traces corresponding to a non-reflective splice between two fibres

Two methods can be employed to analyse the traces and estimate the event loss: least-square method or two point methods.

- When using the least-square approximation (LSA) method, the apparent splice loss α_{LSA} which is reported on the OTDR equipment correspond to the vertical separation between the linear attenuation curve fittings for Fibre A and Fibre B at the splice location. On the figure, this correspond to height OS.
- The two-point method consists in measuring the vertical height of the event between two points located just before and just after the event. Doing so, the two-point method is usually known to be less accurate and more dependent on the accuracy of the positioning of the points and the OTDR settings (as the OTDR curve could exhibits more or less noise and therefore influencing the result). In Figure 2 above, the splice loss α_{2Pt} as per the two-point method will report a splice loss corresponding to the height of the segment OE.

In that case, it is obvious that OS ≤ OE so that:

$$\alpha_{LSA} \leq \alpha_{2Pt}$$

While the least-square method is almost independent on the OTDR pulse width, so that α_{LSA} would be of the same magnitude whatever the OTDR settings, the two-point method is on the contrary highly dependent on the OTDR settings (and position of the markers) and the attenuations of the second fibre. The longer the OTDR pulse width, the higher α_{2pt}.

Assuming short pulses (< 1 µs), it is possible to relate α_{2Pt} with α_{LSA} and τ_w

$$\alpha_{2Pt} - \alpha_{LSA} \sim \alpha_{fibreB} \times \tau_w$$

Decreasing the OTDR pulse width will reduce the difference between the bias for the two methods. Nevertheless, to avoid possible misinterpretation in the results, it is highly recommended to use the LSA method when evaluating unidirectional splice loss.

In the rest of this document, the apparent loss will be referred to as being the splice loss reported as per the LSA method at the splice position.

6.6.3 Apparent losers and gainers

When two fibres with different backscatter properties, such as with different MFD values, are joined and measured with an OTDR, either an "apparent loss" or "apparent gain" appears at the interface as shown from Figure 3. This is a result of the backscatter coupled power detected by the OTDR. In the case of similar fibres types being spliced together, this change in coupled power can be a function of the mode field diameters of the fibres joined. The apparent splice loss for a gainer is negative and positive for a loser.

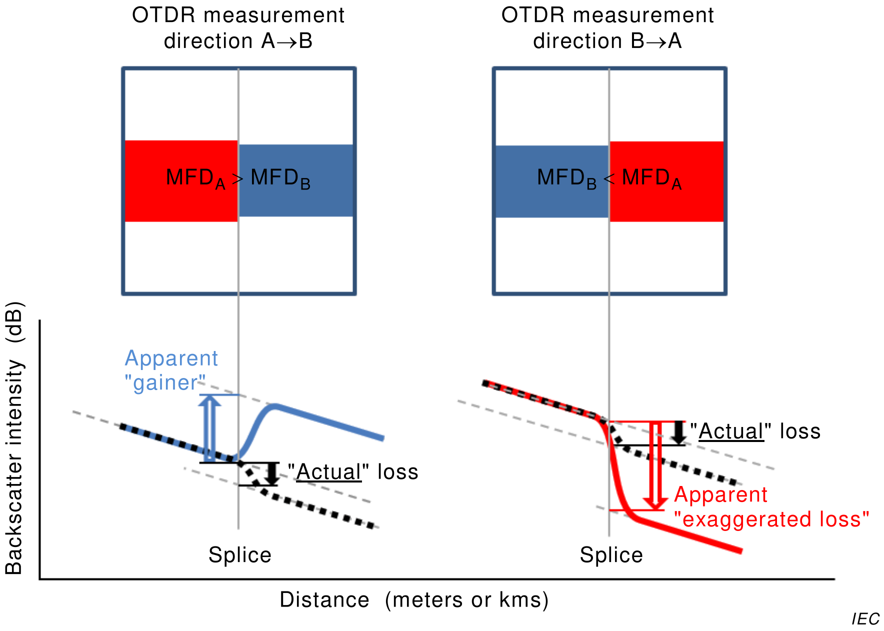


Figure 3 – OTDR traces for similar or different fibre types with different MFD and/or different backscatter properties

Figure 3 shows the OTDR traces for similar or different fibre types with different MFD and/or different backscatter properties, causing an equal "loser" and "gainer", which – due to the presence of real loss – are unequally shown in the OTDR trace.

This commonly known phenomenon is an artefact of the unidirectional OTDR measurement and is caused by the fact that the OTDR is not directly measuring loss but is measuring backscatter power, which is different if both spliced fibres have different MFDs and/or different backscatter properties. The error component of measured unidirectional loss is governed by the following Equations (17) and (18):

$$\alpha_{\mathrm{OTDR}} = |\Delta S| + \Delta RBS \tag{17}$$

where

ΔS is the difference in OTDR backscatter trace at the splice point due to the actual splice loss;

ΔRBS is the relative backscatter light;

and

$$\Delta RBS = 10\lg(\frac{\omega_2}{\omega_1}) + 5\lg(\frac{\alpha_{\mathrm{s1}}}{\alpha_{\mathrm{s2}}}) + 5\lg(\frac{n_{\mathrm{eff2}}}{n_{\mathrm{eff1}}}) + 5\lg(\frac{n_{\mathrm{g2}}}{n_{\mathrm{g1}}}) \tag{18}$$

where

ω is the mode field diameter;

α_{s} is the scattering coefficient;

n_{eff} is the effective refractive index of the fundamental mode, see 5.2;

n_g is the group refractive index.

Figure 4 shows this unidirectional apparent loss/apparent gain (negative loss) as function of the MFD difference between the two (perfectly aligned) spliced fibres considering ω_1 = 9 µm.

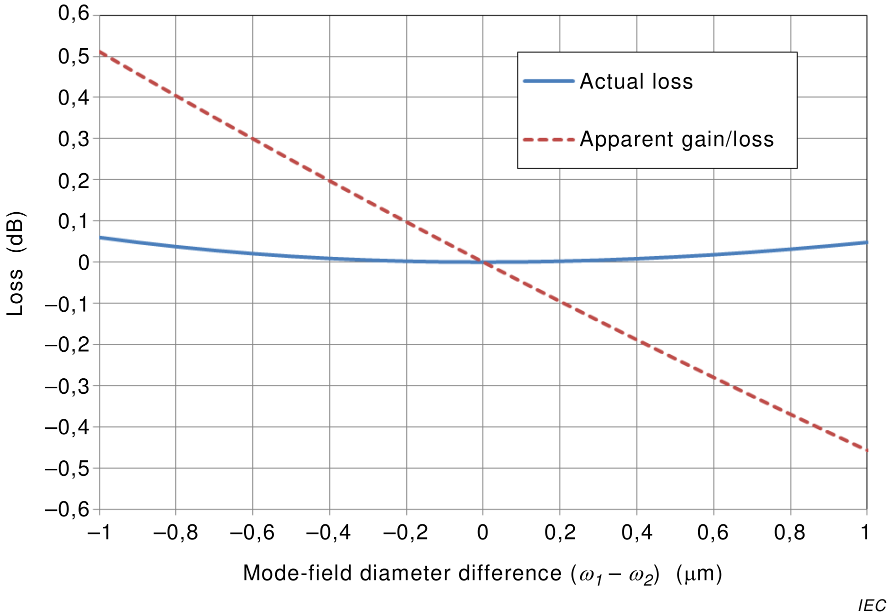


Figure 4 – Loss in unidirectional OTDR measurements as function of the MFD difference between two spliced fibres

For example, when the MFDs of the spliced fibres are 9,0 µm and 9,2 µm, an apparent unidirectional loss/gain of 0,1 dB is present. This apparent loss, however, does not have an effect on the system loss budget and should not be considered as real splice loss.

MFD differences do add a minimal additional loss to the total splice loss; this additional loss is given by Equation (19) and can only be measured by using a power through technique or determined from a bi-directional OTDR measurements.

$$\alpha_{\mathrm{MFD}} = -20\,\lg\left[\frac{2\omega_1\omega_2}{\left(\omega_1^2+\omega_2^2\right)}\right] \qquad (19)$$

For small differences between two spliced fibres' MFD, this actual MFD splice loss can be ignored (see Figure 5).

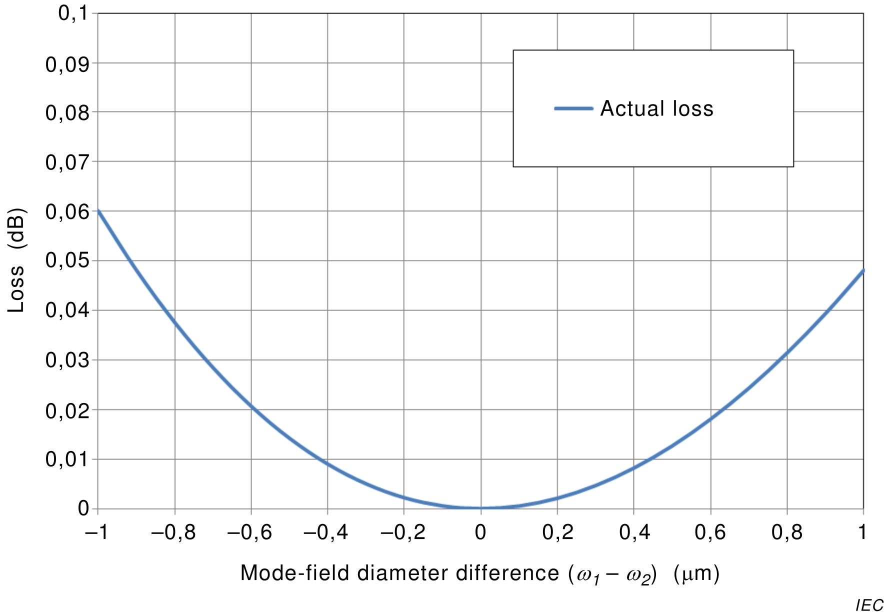


Figure 5 – Theoretical power through splice loss due to MFD difference (with ω_1 = 9µm)

For example, for the same fibre type, when the MFD values of the spliced fibres are 9,0 µm and 9,2 µm, the theoretical power through splice loss due to this MFD mismatch is only 0,002 dB.

Equation (20) shows each loss contributor to the unidirectional OTDR measured loss, where α_{others} includes attenuation due to core to core offset, tilt, and other loss mechanisms:

$$\alpha_{\text{measured}} = [\alpha_{\text{others}} + \alpha_{\text{MFD}}]\text{splice loss} + \alpha_{\text{otdr}} \tag{20}$$

To a first approximation and for MFD mismatch up to about 1 µm, α_{MFD} can be considered negligible, so the equation reduces to

$$\alpha_{\text{measured}} = [\alpha_{\text{others}}]\text{splice loss} + \alpha_{\text{otdr}} \tag{21}$$

The most effective way of overcoming this measurement error is by taking bidirectional OTDR measurements. Therefore, the evaluation of a splice loss is carried out according to the following steps:

- obtain the backscattering trace from the two opposite sides of the spliced fibres;
- evaluate the step/gain G_1 and G_2 in the point z_0 where the splice is located; G_1 and G_2 are composed by a term ($\Delta w = \alpha_{\text{otdr}}$) depending on the MFD mismatch of the two fibres, and a term which is the proper splice loss ($\delta = [\alpha_{\text{others}}]_{\text{splice loss}}$);
- to extract the significant value, δ, compute

$$Splice\ loss = \frac{G_1 + G_2}{2} = \frac{(\Delta w + \delta) + (-\Delta w + \delta)}{2} = \delta \tag{22}$$

Accurate splice loss measurements can only be determined by using light source power metre (LSPM) or a bidirectional OTDR measurement method. Unidirectional loss is convenient but it is not an accurate predictor to the final splice loss. In the event that a power through or a bidirectional loss measurement is not possible, the installer should rely on the procedure followed to make the splice, the visual inspection of the splice and the estimated splice loss from the fusion splicer. A point-to-point power through loss validation should be made at a later date when access is possible.

6.6.4 Example of apparent splice loss evaluation for uni-directional OTDR measurements

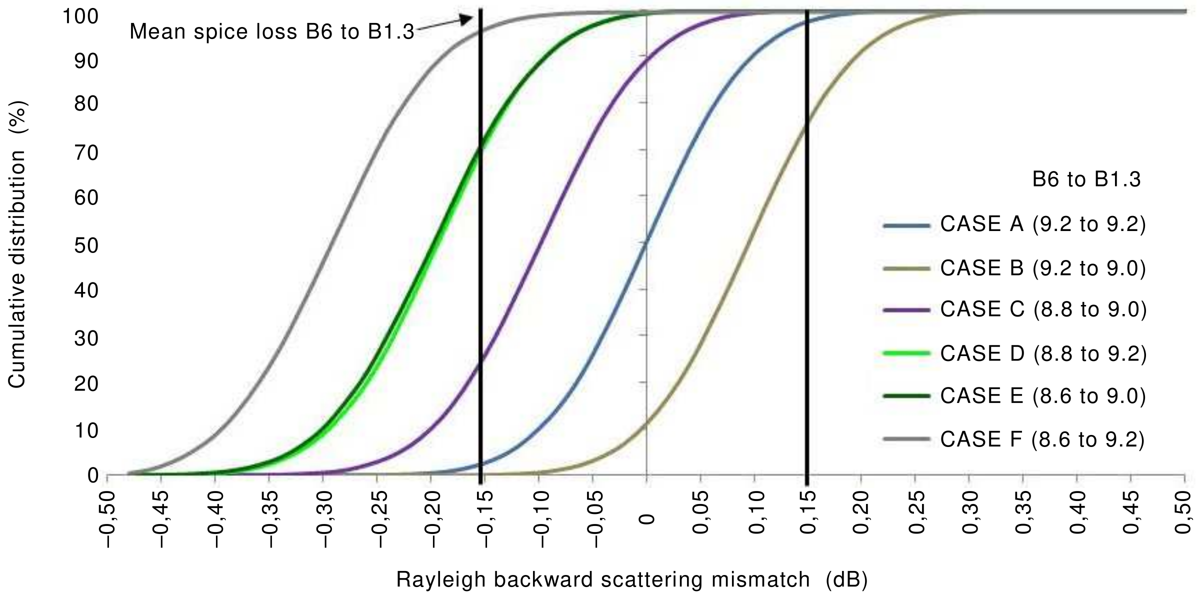
Although bi-directional OTDR measurements are favoured, in some cases only unidirectional OTDR measurements are possible, for example in FTTH installations, combining B6 bend-insensitive fibres with B1.3 access fibres. The impact of apparent gain or apparent loss can be minimized by combining single-mode fibres with small MFD differences.

This is exemplified by means of six different and popular 1 310 nm MFD distributions, as shown in Table 1, with two commonly used distributions for B1.3 fibres (nominal 9,0 µm and 9,2 µm), and three B6 fibres with nominal MFD at 8,6 µm 8,8 µm and at 9,2 µm, ranked by increasing MFD difference.

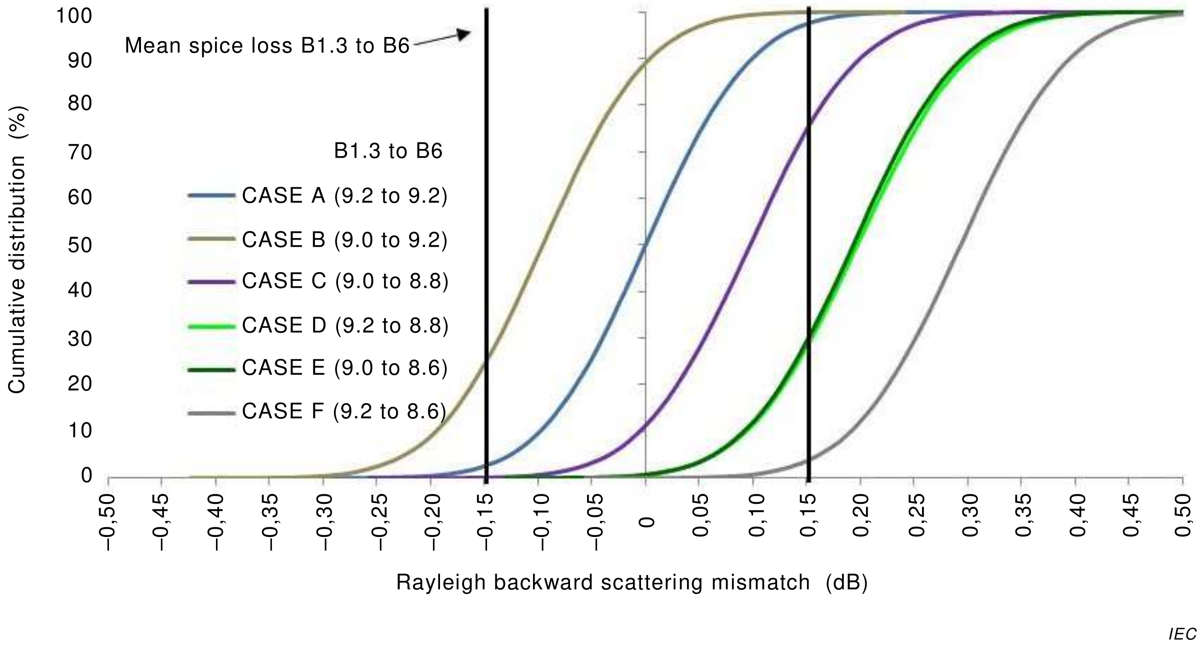
Table 1 – Summary for six fibre splice combinations of B1.3 and B6 based on popular 1 310 nm MFD fibre distributions

Nominal MFD 1 310 nm and tolerance	B1.3	B6	Delta nom. MFD
Case A	9,2 ± 0,4 µm	9,2 ± 0,4 µm	± 0,0 µm
Case B	9,0 ± 0,4 µm	9,2 ± 0,4 µm	± 0,2 µm
Case C	9,0 ± 0,4 µm	8,8 ± 0,4 µm	± 0,2 µm
Case D	9,2 ± 0,4 µm	8,8 ± 0,4 µm	± 0,4 µm
Case E	9,0 ± 0,4 µm	8,6 ± 0,4 µm	± 0,4 µm
Case F	9,2 ± 0,4 µm	8,6 ± 0,4 µm	± 0,6 µm

Figure 6 a) and Figure 6 b) show the cumulative distribution of the backscattering mismatch for the six given B1.3 and B6 fibre splice combinations, shown in Table 1. The measurement direction of Figure 6 a) is from B6 towards B1.3 fibre, and for Figure 6 b) the measurement direction is from B1.3 towards B6 fibre. Obviously, the ***apparent*** unidirectional backscatter mismatch as shown by the OTDR is the smallest when the median MFD offset between two fibre categories is the smallest (as in case A).



a) Mean spice loss measured from B6 to B1.3 fibre



b) Mean spice loss measured from B1.3 to B6 fibre

Figure 6 – Apparent cumulative unidirectional backscattering mismatch distribution for six splice combinations of B1.3 and B6 reported in Table 1

Assuming perfect splices, the percentage of splices with apparent gain/loss is indicated. The smallest risk is present when combining fibres with median MFD as close as possible to each other (here case A). Choosing B1.3 and B6 fibres with relative small median MFD differences is another pragmatic approach in reducing the risks for unidirectional splice control.

The backscattering difference arisen from MFD mismatch accounts for most part of the apparent splice loss.

7 Uncertainties, deviation and resolution

7.1 General

Attenuation coefficient measurements and fault location with an OTDR can be characterised in terms of uncertainties, deviation and resolution, generally defined as follows.

- One part of uncertainties is the spread of values, resulting from repeated measurements, around a target value; for a large number of measurements following a Gaussian distribution, it is the standard deviation around the average.
- Deviation indicates the difference between the measured output (or the average for multiple measurements) and the actual, or accepted, or reference, value. Deviation can be corrected with calibration (see IEC 61746-1).
- Resolution is the ability to separate fine details in the measurement.

7.2 Attenuation coefficient measurements

Uncertainties associated to the attenuation coefficient measurements with an OTDR can be affected by the duration of the measurement (i.e. the number of averaged backscattered signals) and in general by the amount of backscattered power, in turn depending on the fibre length and the coupling loss (see also 5.3). Under appropriate conditions, the uncertainties of a measured attenuation coefficient can be as low as few thousandths of dB/km.

Accuracy of attenuation measurements depends on the calibration status of the equipment. It should also be noted that different OTDR can have different source wavelengths, and their measurements will therefore be different.

Resolution of attenuation coefficient measurements can be associated with the minimum significant decimal place of the measurement, i.e. 1 thousandth of dB/km.

7.3 Fault locations

A break or impurity in a fibre, or a coupling between two fibres, can appear in the OTDR trace either as a feature with higher reflectivity, or a higher loss, or both. By means of the relation between the back-and-forth propagation time ($\tau/2$) and the distance (x) through the speed of light in the fibre (v):

$$\frac{\tau}{2} = \frac{x}{v} \tag{23}$$

it is possible to identify the location (x) of the defect. It must be noted also that $v = c/n_g$ where n_g is the effective group index of the fibre.

Deviation and uncertainties of a measured fault location can be affected by the quantity of backscattered power and by the uncertainties related to the fibre group index which is only approximately known: however, for typical applications, an approximate evaluation of the defect position is acceptable.

Resolution can be considered as a combination of the capacity to detect a “small” fault and the minimum possible distance between two detectable consecutive defects. Generally speaking, a defect so small as to be negligible to the OTDR will also be negligible to system operation. For two detectable consecutive defects, more consideration is necessary.

We consider in Figure 7 the schematic drawing of a fibre with two consecutive defects 1 and 2:

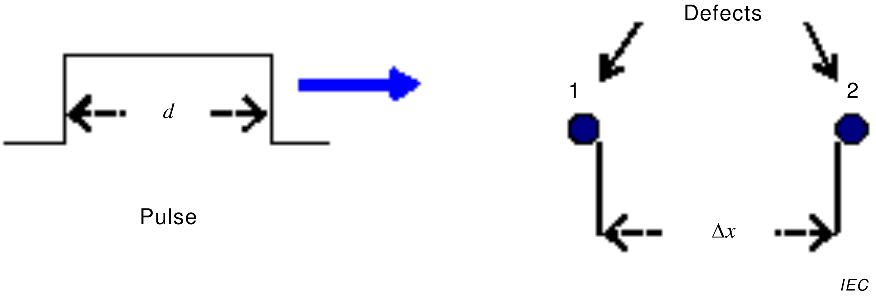


Figure 7 – Schematic drawing of a fibre with two consecutive defects 1 and 2

The pulse duration d can be expressed, in the time co-ordinate, as

$$\Delta t = \frac{d}{v} \tag{24}$$

where

v is the light velocity in the fibre.

The time which the light takes to go from 1 to 2 is

$$\tau = \frac{\Delta x}{v} \tag{25}$$

In order to make the two defects detectable, the pulse back-reflected by the defect 2 should reach the OTDR when the pulse back-reflected by the defect 1, which persists for a time Δt, has been totally received by the OTDR; this condition can be expressed as

$$2\tau > \Delta t \tag{26}$$

The factor 2 in this expression appears because the incoming pulse should arrive to the second defect before being reflected back: therefore it has to cover the distance Δx two times. Remembering that $v = x/t$, Equation (26) can be easily translated in the following space-domain relation:

$$2\Delta x > d \tag{27}$$

which is interpreted as "two consecutive defects are detected separately by an OTDR if, and only if, their distance is larger than half the OTDR pulse width"; for instance, in a measurement using a 10 μs pulse, which covers a length $d \sim 2$ km5), two consecutive defects are separated on the OTDR trace (outside the deadzone) if their distance is greater than (or equal to) 1 km.

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5) This value comes from $d = \Delta t \cdot v = \Delta t \cdot (c/n_g)$ where c is the vacuum light speed, approx. 3 x 10^8 m/s, and n_g is the group index of refraction of the fibre, approximately 1,5; therefore $d \sim 10 \times 10^{-6} \cdot 3 \times 10^8 / 1{,}5 = 2 \times 10^3$ m = 2 km.

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