Guidance for OTDR Assessment of Fusion Spliced Single-mode Fibers

Application Note

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Introduction

This Corning paper explains measurement behaviors of fusion spliced optical fibers and how glass properties and MFD (mode field diameter) differences across fiber splice junctions can lead to erroneous interpretations of splice loss when performing uni-directional OTDR (optical time domain reflectometer) tests. This paper explains how uni-directional OTDR test results yield misleading splice loss values in cases of heterogeneous splices (dissimilar fibers types) as well as homogeneous splices (fibers of the same type or specification). Examples of practical splice loss measurements using an OTDR are presented along with measurement and inspection techniques that can be used to assess splice loss performance relative to specification and industry requirements.

OTDR Inspection Techniques

OTDRs offer a convenient and powerful tool for rapidly assessing attenuation behavior in optical fibers. Due to the way an OTDR works, the attenuation characteristics along the length of a fiber or at particular regions of interest make them ideally suited for certification of installed optical fiber cable and assessment of fusion splice losses as well as attenuation testing. In very simple terms, an OTDR consists of a laser light source and optical detector to capture and record backscattered light as a means of assessing the optical characteristics of a fiber link. The optical receiver records the tiny proportion of light (typically <0.000001% or <-79 dB) that is backscattered by the molecular structure of the glass in response to an injected light pulse from the OTDR. The measurement trace generated by the OTDR is an integrated sum plot of the magnitude of light received from scattering locations along the length of the fiber. The time-dependent backscattered power $P_{bs}(t)$ received by the OTDR detector from an input light pulse power P_0 and pulse duration W is described by [1];

$$P_{bs}(t) = P_0 W \eta(z) e^{-2\alpha z} \tag{1}$$

where; α is the attenuation coefficient and η is the overall backscatter factor, which for a weakly guided single-mode fiber and using a Gaussian approximation is given by [2];

$$\eta = \frac{1}{2}\alpha_s B(z)\upsilon_g = \frac{12\, c\, \alpha_s}{(k_0 MFD)^2 n_{eff}^2\, n_g} \tag{2}$$

In (2) above it is apparent that the backscatter factor describes of a number of light and fiber interactions along the length governed by material properties and glass design; where α_s is the scattering-coefficient, which is the contribution of light attenuation due to localized inhomogeneity of the glass medium, n_{eff} is the effective refractive index, n_g is the group refractive index, υ_g is the group velocity, k_0 is the wave number in free space, and c is the velocity of light in a vacuum. The backscatter capture fraction $B(z)$ describes the proportion of light energy that is scattered by the structure of the glass at points (z) along fiber which is captured by the fiber in the return direction. Therefore, $B(z)$ describes factors related to fiber design, which include; core geometry, refractive properties of the core and cladding (i.e. index profile), material composition (glass and dopants) and coupling efficiency. Using a Gaussian approximation and assuming the modes to be weakly guided provides a simplified approximation of the backscatter capture fraction $B(z)$ with fiber properties which can be characterized for the purposes of interpretation of OTDR measurements.

Assessment of Fiber Attenuation and Splice Loss Using an OTDR

International Standards IEC 60793-1-40 and the Telecommunications Industry Association (TIA) optical fiber test procedure (TIA-FOTP-61) indicate that splice and attenuation measurements with an OTDR must be conducted from both directions and averaged for accuracy and to eliminate the effects of backscatter differences, also referred to as “gainers” and “exaggerated losses”. It is an industry misconception that uni-directional OTDR inspections can be used to accurately and reliably measure attenuation and or splice loss, particularly in deployed cables. When bi-directional OTDR measurements are not feasible (e.g. due to poor accessibility at one end of the spliced system), an installer may choose to rely upon uni-directional OTDR estimates. An assessment of fiber attenuation and or splice loss using only a uni-directional OTDR inspection, therefore, assumes all optical properties to be consistent along the length of fiber or any spliced sections under test. The problem with this assumption is that the level of backscatter light detected by the OTDR can increase or decrease at many points along individual or concatenated sections of fiber independently of fiber attenuation or actual splice loss [3]. Differences in the intensity of backscattered light can be the result of changes in the optical properties encountered by the forward propagating measurement pulse from the OTDR. The forward propagating light is unaffected by small intensity changes in backscatter and therefore has no functional impact on system performance. When two fibers (A and B) are spliced together the difference in the uni-directional backscatter apparent loss value is given by [2];

$$\alpha_{splice} = |\Delta S| + \Delta BS \tag{3}$$

where ΔS is the difference in OTDR backscatter trace at the splice junction due to the actual loss and ΔBS is a measurement error artifact caused by changes in the backscatter efficiency between the two fibers, which can be described in terms of differences in fiber parameters [2];

$$\Delta BS = 5(\log \eta_A - \log \eta_B) \tag{4}$$

$$\Delta BS = 10 \log \left[\frac{MFD_B}{MFD_A}\right] + 5 \log \left[\frac{\alpha_{s_A}}{\alpha_{s_B}}\right] + 10 \log \left[\frac{n_{eff_B}}{n_{eff_A}}\right] + 5 \log \left[\frac{n_{g_B}}{n_{g_A}}\right] \tag{5}$$

By applying the approximations from (2) into (4), we obtain a more detailed estimation for the expected OTDR backscatter response at a splice location (5). In practical OTDR measurement terms, backscattering characteristics are mostly influenced by the refractive index profile and geometrical properties of the fiber. Figure 1 is an illustration of a pair of “unidirectional OTDR measurement” backscatter traces of two fibers spliced together as measured from each side of the splice. The A and B notations used in (4) and (5) refer to the fiber-measurement direction sequence A→B and B→A (→ indicates the OTDR launch direction). This example shows how the changes in MFD cause a measurable shift in both backscatter intensity traces as recorded by the OTDR at the splice junction, which can lead to misinterpretation of splice loss results.

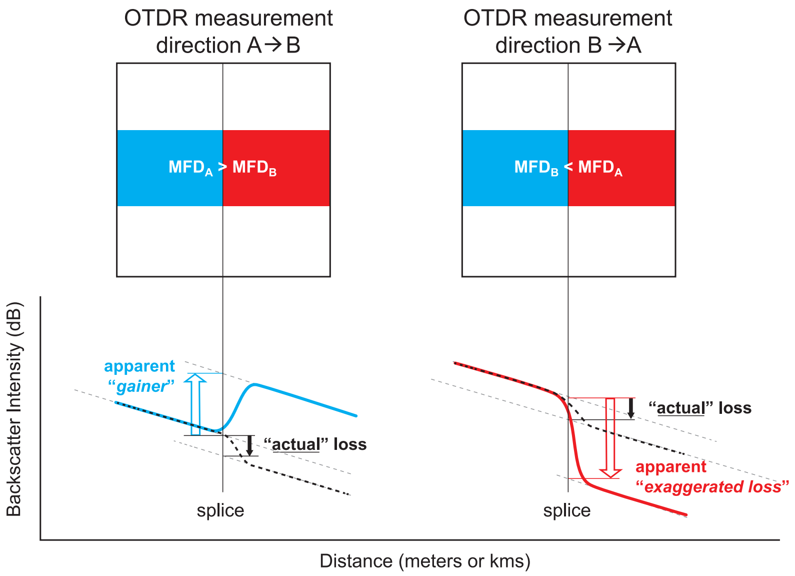
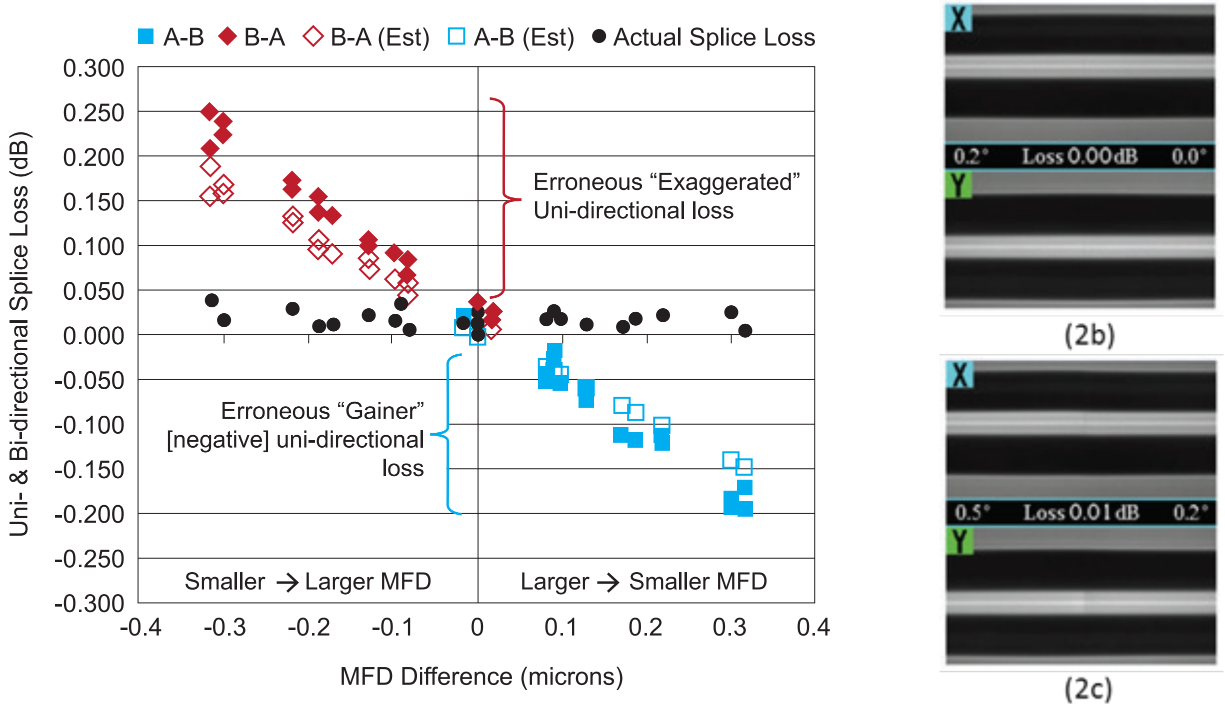


Figure 1. Illustration of OTDR backscatter trace behavior at splice location between fibers of different MFD; a) larger MFD → smaller MFD, b) smaller MFD → Larger MFD.

The backscatter capture fraction of an optical fiber is inversely proportional to the MFD. Thus, when two fibers of dissimilar MFD are spliced together, measurable differences in the OTDR backscattered signal will occur. A uni-directional OTDR trace will show the MFD transition as either a "gainer"; an apparent increase in optical power, or as an "exaggerated loss", depending on the direction of the measurement. When measuring from a fiber with a larger MFD to one with a smaller MFD, the OTDR measurement will result in a "gainer". Conversely, when measuring from a smaller MFD to a larger MFD, the measurement will result in an exaggerated loss. Figure 1 illustrates both "gainer" and "exaggerated loss" events as depicted on an OTDR measurement trace. The "true" or actual attenuation or splice loss is calculated from the bi-directional average of the two uni-directional OTDR inspection measurements, which eliminates any spurious backscatter differences from the two uni-directional measurements. The blue [gainer] and red [exaggerated loss] colored traces show the results collected from A→B and B→A measurement directions respectively, whereby MFD$_A$ is larger than MFD$_B$. The actual splice loss depicted by the black-dotted trace is the mathematical bi-directional average of the two measurement traces.

Figure 2 shows the results of uni-directional and bi-directional averaged OTDR measurement values used to assess splice loss in fusion spliced Corning® SMF-28e+® fibers. The results are presented using the same conventions as the illustration in Figure 1 to indicate the results obtained in forward and reverse measurement directions. The test specimens were specially selected to span a range of MFD values and OTDR traces were taken in both measurement directions, A→B and B→A, for each spliced fiber pair tested. The splices were conducted using a commercially available fusion splicer operating in a default automatic core-alignment G.652 single-mode splicing program. In all instances the splicer reported a predicted splice loss of 0.01 dB or lower and all splicing images indicated good visual splice quality and passed a 25 kpsi mechanical proof test (applied by the splicing machine). The results show uni-directional splice loss dependency on MFD difference as measured on each of the A and B samples. The increase in the OTDR backscatter intensity is inversely proportional to the square of the MFD difference at the splice junction. Many uni-directional results falsely predict high splice loss values that would likely raise a concern during network cabling installation. In reality, all actual splice loss values comfortably met typical industry requirements of ≤0.10 dB/splice average and all splices were below 0.05 dB.

Predicted uni-directional splice loss values show no correlation to the bi-directional averaged (actual) splice loss values over the MFD range tested. In fact, some of the lowest measured splice loss values were recorded with moderate MFD mismatches. Corning estimates that MFD mismatch in the same type fiber contributes less than 0.04 dB to the actual splice loss. Examination of the results also indicated that other extrinsic effects, such as fiber cleave angle (typically 0.3°), had no impact on the actual splice loss results. However, from (5) it is possible that small localized variations in other optical parameters could alter the backscatter factor $\eta(z)$ which would increase measurement uncertainty in uni-directional OTDR traces.



(2a)

(2b)

(2c)

Figure 2a. Comparison of uni-directional and bi-directional OTDR inspection results of spliced SMF-28e+® G.652.D fiber samples with known MFD mismatch. **2b** and **2c** are representative fusion splicer machine images of spliced SMF-28e+ fiber with MFD mismatches.

The results in Figure 2 show the accuracy of uni-directional OTDR backscatter traces in predicting actual splice loss is limited to near zero values or in cases where there is little or no fiber parameter mismatch. For field splicing and taking into account the existence of variability in MFD, uni-directional testing typically requires splice loss acceptance criteria of 0.3 dB or higher although proportionately such elevated uni-directional losses typically occur less frequently. Table 1 below shows the MFD variability that may be permitted according to ITU-T recommendations for single-mode fibers alongside Corning specified values for various widely deployed G652 and G657 category fibers. Industry specifications for MFD typically employ tighter limits than permitted by ITU-T range limits. For example, a nominal MFD of 9.2 ± 0.5 microns is more typical at 1310 nm.

Table 1. Estimated uni-directional OTDR splice loss based upon MFD mismatch.

MFD / Wavelength	**ITU-T G.652.D & IEC 60793-2-50 type B1.3 fibers**	**ITU-T G.657 A1 & A2 & IEC 60793-2-50 type B6_a fibers**	**SMF-28® Ultra, SMF-28e+® LL & SMF-28e+® fibers (G.652)**		**ClearCurve® single-mode fibers (G.657)**	
Wavelength (nm)	1310	1310	1310	1550	1310	1550
MFD (microns)	8.6 to 9.5±0.6	8.6 to 9.5±0.4	9.2±0.4	10.4±0.5	8.6±0.4	9.5±0.5
Max. Diff. (microns)	2.1	1.7	0.8	1.0	0.8	1.0
Estimated Uni-directional OTDR Loss (2)[1] $10 \log \left[\frac{MFD_{B/A}}{MFD_{A/B}} \right]$	Max: 1.0 dB Typ: 0.47 dB (9.2 ± 0.5 microns)	Max: 0.82 dB Typ: < 0.4 dB	Max: ±.38 dB Typ: ±< 0.2 dB	Max: ±0.42 dB Typ: ±< 0.2 dB	Max: ±0.4 dB Typ: ±< 0.2 dB	Max: ±0.45 dB Typ: ±< 0.2 dB

[1] These estimates are based exclusively MFD mismatch for fibers of same classification or specifications that may be encountered during field installation testing (excludes other optical or fiber design property differences).

When splicing dissimilar fiber types, larger changes in uni-directional OTDR backscatter are to be expected as a result of differences that may exist in the intrinsic glass properties of the fibers being spliced together [2][5]. These can be due to differences in fiber manufacturing processes, glass composition, or differences in the fiber refractive index profile design. For example, larger "gainers" or "exaggerated losses" may be observed when splicing G.652 and G.657, owning to the typically smaller MFD range of G.657 bend-insensitive fibers. Similarly, splicing conventional G.652 to "*ultra low loss*" technologies such as SMF-28® ULL fiber, results in larger "gainers" and "exaggerated losses" due to glass composition and fiber design differences although they share the same MFD specifications. OTDR traces that may result from these splicing arrangements are illustrated in Figure 3.

Figure 3 shows the splice loss measurements of SMF-28e+ fiber [*A*] spliced to SMF-28 ULL [*B*] fiber using an OTDR. Uni-directional estimates taken in the measurement direction (A→B) show exaggerated splice loss values due to a combination of optical property differences due to fiber design as well as MFD mismatch. The spliced fibers had a MFD range of 9.1 ~ 9.5 microns at 1310 nm and were chosen to compare measurement results of closely matching MFD versus splices with typical ranges of MFD mismatch.

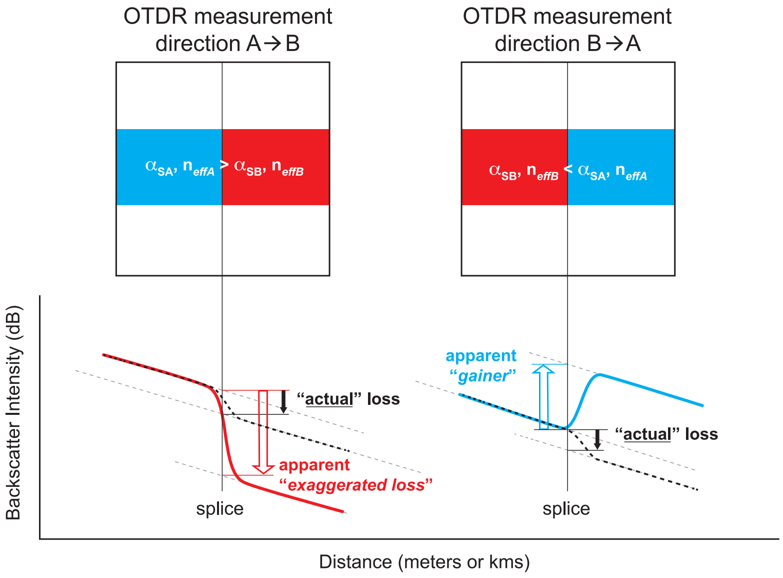
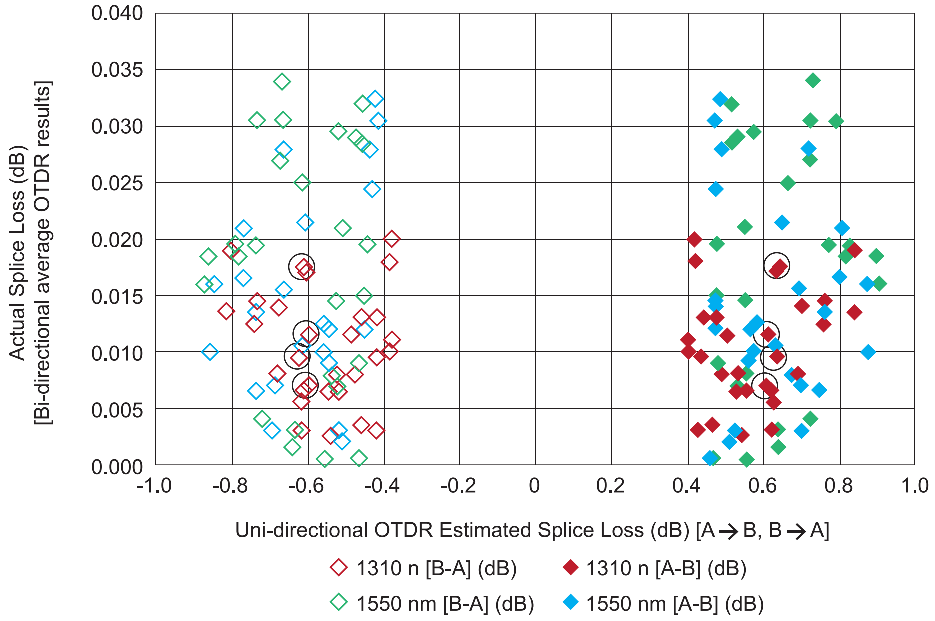


Figure 3. Illustration of OTDR backscatter trace behavior at splice location between heterogeneous splice junctions with fibers of different optical properties such as scattering coefficient, α_s, and group refractive index, n_{eff}.



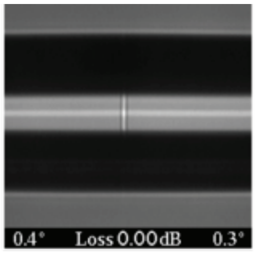


Figure 4b – SMF-28® ULL fiber spliced to SMF-28® ULL fiber

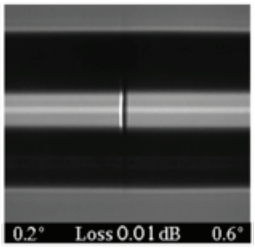


Figure 4c – SMF-28e+® fiber spliced to SMF-28® ULL fiber

Figure 4 - 4a. Comparison of unidirectional estimates and actual splice loss (bi-directional averaged results) for Corning SMF-28e+® fiber spliced to Corning SMF-28® ULL fiber. 4b and 4c show fusion splicer images of b) SMF-28® ULL spliced to itself and c) spliced to SMF-28e+ fiber.

The results in Figure 4 show larger errors in the estimated uni-directional OTDR results as compared to the actual bi-directional averaged results. The splice values circled are of the fiber pairs with closely matching MFDs (difference <0.04 microns) and show that the uni-directional estimates include a backscatter change of ~0.6 dB when measured in the A→B direction. This apparent loss is due to the change in scattering characteristics of the fiber when transitioning from a 'good' attenuation fiber to the superior, lower attenuation characteristics of SMF-28 ULL fiber. The images collected from the fusion splicer show an apparent refractive index artifact at the splice junction between SMF-28e+ and SMF-28 ULL fiber, which is not functional. The maximum actual splice loss was less than 0.035 dB, and the average splice loss was less than 0.02 dB for all wavelengths measured.

Uni-directional OTDR Inspection – Splice Loss Estimate Uncertainty

Statistical analysis can be used to evaluate the validity of a rule of thumb that may be applied to uni-directional OTDR inspections of splices losses where the accuracy of the results are in question [5]. For homogenous fiber types, Table 2 provides guidance on the typical probability of uni-directional splice accuracy based upon normal distributions of MFD.

Table 2. Statistical assessment of uni-directional OTDR splice loss accuracy

Splice Loss (actual)	Estimated Splice Loss [uni-directional OTDR] (Homogenous splices)
±0.05 dB	54%
±0.10 dB	78%
±0.20 dB	97%
±0.30 dB	<100%

NOTE: These estimates are based upon homogenous splices. Inclusion of fiber types with differing MFD specifications or different fiber design may lead to increased uncertainty of uni-directional OTDR-based estimated values.

In cases where uni-directional OTDR inspection measurements indicate “gainer” or suspected “exaggerated loss events”, the following steps can be used to reduce the uncertainty in uni-directional OTDR measurement results:
NOTE: None of the following options should be regarded as preferable substitutes for proper OTDR splice loss measurements that can only be obtained with bi-directional averaging. Reliance upon uni-directional OTDR measurements may not be a viable option as evidenced by the Splice Loss Estimate Accuracy shown in Table 1 and may mask poor splices or invalidate acceptable splices. For optimal splicing results, good working practices and suitable equipment and procedures should be followed [6].

- System links should be engineered with specification acceptance criteria for average splice loss and overall attenuation of the end-to-end link. The use of average splice specification targets can be used to accommodate outlier values provided the attenuation and insertion loss targets of the overall link are satisfactory. e.g. average link splice loss of 0.1 dB/splice and a threshold of 0.3 dB for uni-directional loss estimates (above which further steps are taken to assess the measurement uncertainty, described below).
- In cases where dissimilar fiber types are being spliced e.g. FTTx installations using bend insensitive fibers with typically smaller MFD or in long distance networks using optimized low attenuation fibers, any use of uni-directional estimates should make allowances for potentially larger “gainer” or “exaggerated loss” estimates of 0.3 dB or higher. For FTTx networks, it may be possible to combine OTDR inspection results with measured 1490 nm down-link signal power in such services as GPON.
- A gainer event is most likely the indication of a glass refractive index property change, either by dissimilar fiber types, differing MFD values, or a change in bulk scattering level. Comparing the loss characteristics of adjacent splices in the link can enable a pseudo averaging based on a uni-directional trace. Breaking and re-making splices is unlikely to change the result, but could be used to confirm measurement data accuracy.
- Suspected inaccurate “exaggerated loss” estimate: Compare results of adjacent splices, a corresponding “gainer” may confirm MFD mismatch or index of refraction mismatch between fibers. Breaking and re-making of a splice and yielding the same loss characteristics in combination of the above may reduce uncertainty in results.
- For heterogeneous splices, information should be obtained about the fiber types prior splicing to ensure the optimal fusion splicing program or setting are selected. Knowledge about the fiber types being spliced allows the use rules of thumb to address uncertainty when interpreting uni-directional OTDR traces. Heterogeneous splices tend to be location specific, e.g. at a demarcation point in a network and are usually less commonplace. If there is uncertainty about the accuracy of uni-directional traces, then bi-directional measurements should be used to accurately determine splice loss.
- Fusion splicers with PAS (profile-alignment system) and/or LID (local injection/detection) can help reduce uncertainty in uni-directional measurements, either through estimated splice loss based upon visual and geometrical alignment characteristics or, in the case of LID, an insertion-loss based splice loss estimate. A visual inspection of X-Y axis splicing imagery captured by the splice machine can be used to assess uncertainty in uni-directional estimates.
- It is also suggested that a test splice using a reference fiber sample with a known MFD be used to separately test and compare uni-directional values to the objective fibers being spliced in the field.

Summary

Uni-directional OTDR inspection testing of fiber attenuation and splice loss can lead to inaccuracies due to the manner in which OTDR backscatter data is recorded and reported. Discrepancies usually arise when backscatter results suggest "exaggerated loss" or "gainer" values that are cause by optical refractive index changes at splice locations. These may be caused by MFD mismatch between same type fibers or other refractive index property differences between fibers. Bi-directional OTDR inspection measurements are recommended by international standards bodies as a reference method for accurate fiber attenuation and splice loss assessment. However, in cases where uni-directional inspection tests are the basis of field installation testing or certification, there are several additional steps that can be taken to reduce the level of uncertainty in the results. These include capture of other records and data to help certify field installations.

References

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