Accurate Location of Fiber Cable Fault with OTDR

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Abstract—The paper reviews the factors limiting the accuracy of locating a fiber optic cable fault when using an optical time domain reflectometer (OTDR) and describes an error estimation method for typical use cases. The primary source of errors lies in the complex relationship between the length of the optical fiber (measured by OTDR), its routing, cable design depending on cable design and type of installation (i.e. duct, directly buried, aerial) as well as the spare lengths used for service purposes. The techniques which considerably improve the accuracy of the fault localization processes are presented, the importance of accurate documentation of the network and of referencing the fault location to the nearest splice instead of end of the line are discussed, as is the absence of cable helix factor in data sheets.

Keywords—fault location, fiber optic cable, helix factor, OTDR, single-mode fiber.

1. Introduction

OTDR is a measurement instrument used for diagnosing fiber optic networks [1], [2]. The main advantage of OTDR over a less expensive testing technique relying on a light source and a power meter is its ability to indicate the distance from the OTDR's optical port (or another reference location) to any discontinuity or "event" in the fiber being tested.

However, OTDR gives the length of the optical fiber between the OTDR's optical port and the fault. Due to the design and installation conditions, the measured length of the fiber is always longer than the length of the cable or the distance measured along its route. In order to be useful for fault location, such a value must be converted to cable route length to the fault or, much better, to the distance between the fault and the nearest component of the cable link that may be located without much difficulty – usually a cable splice.

Depending on the cable and installation technique used, the fiber length may exceed the route distance by up to 8%. With repeater sections in terrestrial fiber networks being up to 100 km long (or longer), even a reasonable difference of 1.5% may produce a location error of up to 1,500 m. This prevents the fault from being located and identified quickly by the service technicians arriving at the location that is equal (route distance) to the (fiber) distance shown by OTDR, as they may be unable to notice that a ditch that has caused the cable to be cut is located approximately 800 m away.

This paper focuses on diagnosing of long (10–130 km) fiber links used in telecom networks, where the accuracy of OTDR-based fault location is of key importance, and where installation techniques and record-keeping facilities used tend to be consistent.

The article is arranged as follows. Section 2 presents the relationships between cable route lengths, cable and fiber lengths, as well as gives the definitions. Section 3 presents a review of fiber optic cables and their helix factors. Section 4 highlights the effects of cable installation on extra lengths of cables and fibers. Section 5 presents OTDR operating principles and issues that are important for the accuracy of fault location, with Section 6 describing how the fiber distance should be converted to cable or route distance in order to facilitate the process of locating faults. Conclusions are presented in Section 7.

2. Optical Fiber Cables – Definitions

This section explains the definitions used: lengths (distances) of optical fiber, cable and cable route, understood as a line joining all facilities between specific terminations of the fiber optic cable link: buildings, manholes, poles, etc.

Several terms used in this paper, such as the "helix factor", "fiber overlength", or "index of refraction", are not fully standardized and are defined differently in the literature, in datasheets, and in OTDR user manuals. To accommodate this, alternative names are indicated throughout the paper.

There are three distinct lengths/distances between a line termination, typically at the optical distribution frame (ODF), where access to fibers for testing purposes is provided, and a cable failure (event) detected by OTDR:

- fiber length: physical length of optical fibers between ODF and the event,
- cable length (sheath length): sum of the length of all cables between ODF and the event,

- route length: cable route length projected onto the ground, as seen on a map, between ODF and the event.

The common rule is:

Fiber length $(L_F) >$ Cable length $(L_C) >$ Route length (L_R).

The difference between fiber and route lengths is usually the largest in aerial networks, where the $L_F : L_R$ ratio may reach 1.08. The other extreme is a cable link with a limited fiber count duct cable of a central loose tube design, and moderate spare segments of cable at each splicing location, say 2×25 m every 2 km, where the $L_F : L_R$ ratio is only 1.006–1.008. Even in this case, the difference between L_F and L_R reaches, after 50 km, 300–440 m.

The relationship shown above is generally applicable due to the following factors:

- outdoor fiber optic cables contain excess lengths of each fiber to accommodate temperature variations and tensile forces without exerting excessive strain on the glass fibers. This is most often done by packing an extra segment into a protective tube a length of fiber slightly longer than this tube, with the fiber forming a helix. Cables with stranded loose tubes or slots include an additional ("dead") length of fibers which cannot be used to compensate for cable elongation;
- joint closures store additional lengths of fibers to allow re-splicing. They are usually 0.5–1 m long on each side of the splice;
- spare lengths of cables, typically 20–40 m, are placed at selected locations along the cable route, preferably near each joint closure to allow repair works;
- aerial lines include vertical runs of the cable at each splicing point;
- duct networks often include numerous road or railroad crossings and offset manhole locations. At each of them, an additional length of duct and cable is provided, e.g. 20 m, but this is not always recorded in network documentation and in the route length data;
- line terminations in big buildings include non-negligible lengths of cables between the entry to the building and ODF ports, typically they are 15–50 m long, while the cable route shown on a map seems to end at the entry to the building.

The above list is not exhaustive due to specific issues, such as wrapping a compact fiber optic cable around a support (messenger wire), which increases cable length.

2.1. Helix and Route Factors

The method used to install the fiber optic cable greatly affects the relationship between the lengths of cable route L_R, cable L_C, and optical fiber L_F. If the network connection follows a uniform set of rules, e.g. consistent lengths of cable sections and spare lengths are used, with one type of cable, the approximate relationship is:

$$L_F = HF \times L_C = HF \times RF \times L_R \;, \tag{1}$$

where HF or "helix factor" (sometimes also referred to as the "cabling factor") is the ratio between the length of fiber in the cable and cable sheath:

$$HF = \frac{L_F}{L_C} \;. \tag{2}$$

HF depends on the type of cable – see Section 3. RF or the route factor is the ratio between the length of cable and the length of route. This parameter accounts for all extra segments of cable in the line introduced by:

- spare lengths of cables,
- vertical sections in aerial installations,
- undulation of directly buried cables to compensate for soil movement,
- running the cable through manholes offset from a straight line, etc.

HF and RF vary within the 1.005–1.04 and 1.01–1.10 ranges, respectively. For example, if a cable section in a duct network is 2,000 m long, and spare lengths of 20 m are stored on each side of each joint closure, $RF = 2040 : 2000 = 1.02$, even with perfectly straight installation ducts. The highest HF and RF values are observed in aerial networks, in particular those with optical ground wire (OPGW) and all dielectric self-supporting (ADSS) cables suspended on high voltage overhead power lines. Such aerial cables are exposed to a wide range of temperatures and tensile loads. In order to accommodate the resulting cable length variations, the cable must have a high overlength of fiber with respect to cable length, with HF of up to 1.04 in cables with stranded loose tubes.

A consistent relationship between route, cable and fiber lengths may be expected in regional or long distance lines built as separate projects. In urban and suburban environments, a much greater variability of RF is observed due to non-straight cable routes resulting from limited rights of way, street layouts, re-use of existing ducts, and obstacles. Hence, only the helix factor is useful in such cases.

While the helix factor is rarely included in cable specifications, it may be calculated from internal dimensions of the cable or may be measured.

3. Fiber Optic Cables

In this section, a review of cable designs is presented to familiarize the reader with differences between the length of fiber in the fiber optic cable (natively indicated by the OTDR) and the cable itself (marked on the sheath), as well as with typical HF values.

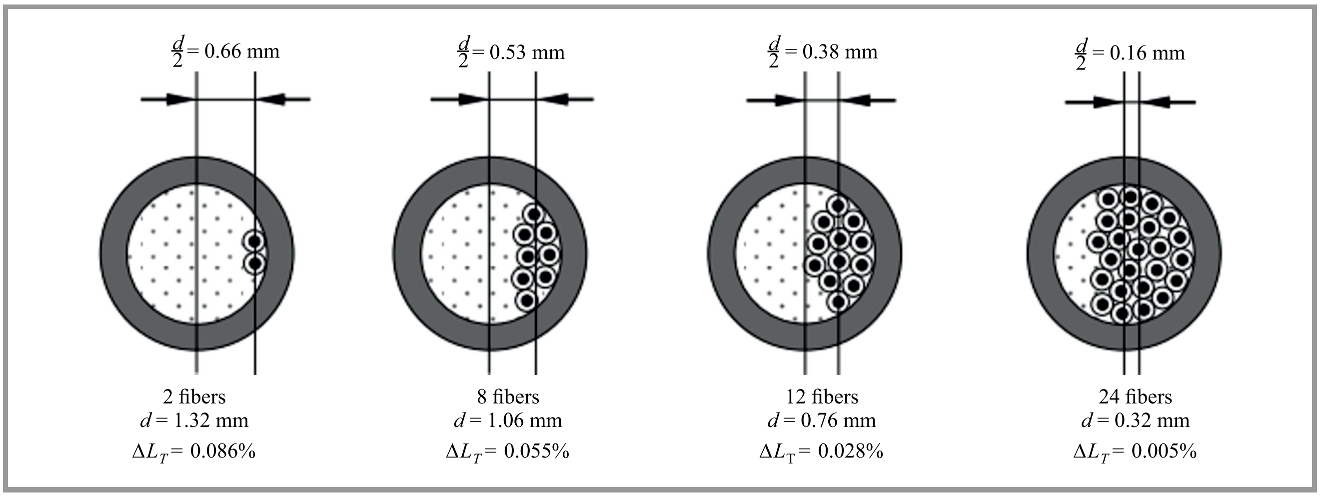

Fig. 1. Approximate helix diameter d and fiber overlength ΔL_T for different numbers of fibers in a 0.25 mm primary coating placed in a 1.6/2.2 mm loose tube. The bundle of fibers is assumed to form a helix with pitch p of 100 mm. All parts are to scale.

3.1. Loose Tube Cables

In outdoor cables, fibers shall be protected against strain, crush, or excessive bending that takes place when the cable length varies with temperature and tensile loads, or when deformation is experienced. A bundle of fibers (colored for identification purposes) [1], [2], is placed in a loosely fitting protective tube, called a loose tube, with a smooth inner surface. To prevent water penetration, the tube is filled with a gel or includes a water-swellable material. Alternatively, the fibers may be formed and glued into ribbons [3] which are placed in cables of either loose tube or slotted core design.

3.1.1. Loose Tube

The glass fibers are mechanically decoupled from the tube by placing an additional, uniformly distributed length of them with respect to the tube. This extra segment is known as fiber overlength or excess fiber length (EFL). It is a result of post-extrusion shrinkage of the polymer tube when it is cooled down from the extrusion temperature of 220–260°C to ambient temperature. Unlike thermoplastic polymers, the fused silica fibers are characterized by a low and almost temperature-independent thermal expansion coefficient within the range of temperatures typical for the manufacturing and use of fiber optic cables, i.e. approx. $0.55 \cdot 10^{-6}$ K for a bare glass fiber and $2.25 \cdot 10^{-6}$ K for a fiber with the standard primary coating with the diameter of 250 μm.

The fibers inside the tube are bent to form a helix, and may be partially or fully straightened when the tube and cable are elongated by tensile force or bent more sharply when the cable contracts in low temperature. As long as the fibers are not fully straightened, they are protected against excessive strain which may cause a failure. However, excessive overlength causes severe bending of fibers and increases attenuation.

The fiber length to tube length ratio is defined by:

$$HF_T = \frac{L_F}{L_T} \ , \tag{3}$$

where: HF_T – helix factor of straight loose tube (≥ 1), L_F – physical length of optical fiber, L_T – physical length of tube.

In some publications and OTDR user manuals, an alternative definition of the helix factor (for tubes and cables) is used, defined as an extra fiber length divided by tube length and expressed as a percentage figure:

$$\Delta L_T = \frac{L_F - L_T}{L_T} \cdot 100\% \ . \tag{4}$$

This parameter is also known as fiber overlength, and this concept will be used here.

If the fiber has a regular helical (spiral) shape with pitch p and diameter d, HF_T may be calculated as:

$$HF_T = \frac{L_F}{L_T} = \sqrt{1 + \left(\frac{\pi d}{p}\right)^2} \ , \tag{5}$$

while fiber overlength in the tube, expressed as percentage rate, is calculated as follows:

$$\Delta L_T = \left[\sqrt{1 + \left(\frac{\pi d}{p}\right)^2} - 1\right] \cdot 100\% \ . \tag{6}$$

For overlengths of up to 1%, encountered in all typical cable designs, a simplified formula is used, retrieved after error correction from [4]:

$$\Delta L_T \approx 493 \cdot \left(\frac{d}{p}\right)^2 \ [\%] \ . \tag{7}$$

Medium and high fiber overlengths, such as 0.1–0.6% ($HF_T = 1.001$–1.006) are desirable in outdoor cables that are exposed to tensile forces and variable temperatures. The helix diameter d is lower than the inner diameter of the tube, roughly by the width of the bundle of fibers, as shown in Fig. 1. When the tube is filled with fibers, the fibers are positioned straight and overlength is close to zero. This is typical in "tight-fitting" tubes for micro cables or duct cables with very high fiber count.

There is a trade-off between mechanical protection of fibers and their density in the cable. According to the applicable standard [5], a long-term strain of 0.20% is permitted for silica fibers proof-tested at 1% strain. Overlength typical of small diameter loose tubes is not satisfactory for many applications, particularly in aerial networks. Therefore, small tubes are suitable for cables in which stranding results in additional overlength or for cables which are blown into ducts by dedicated pneumatic devices using well-controlled tensile force.

3.1.2. Cable with Central Loose Tube (Unitube)

This type of a loose tube cable incorporates a single, straight tube located in the center and surrounded by sheath, strength members, ripcords, etc. An example is shown in Fig. 2.

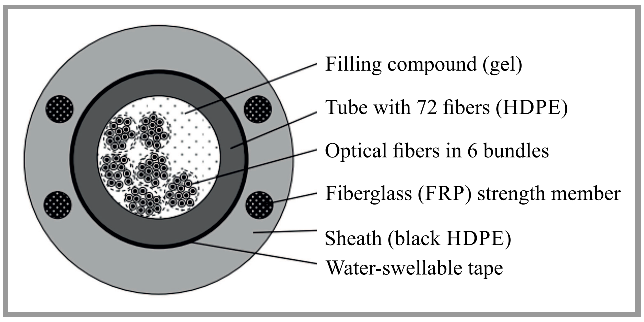

Fig. 2. Cross-section of a duct cable with central a loose tube.

In this case, the overlength of fibers is caused only by forming a helix inside the tube, and:

$$HF = \frac{L_F}{L_C} = HF_T = \frac{L_F}{L_T} \ , \tag{8}$$

where: HF – helix factor of cable, L_C – length of cable, marked on its sheath.

3.1.3. Cable with Stranded Loose Tubes

In this design, the cable core incorporates multiple and identical loose tubes stranded around a central rigid strength member in one or more layers. The number of tubes is 4–12 in a single layer (Fig. 3). Stranding is either helical or reversible, also known as SZ or reverse oscillating lay (ROL). Reversible stranding makes it easier to manufacture cables with the use of more compact machinery and allows to extract selected tubes during cable splicing. The mechanical conditions for fibers are similar. The cable frequently gets a second external strength member made of aramide, glass or basalt fibers to withstand significant tensile forces, especially in aerial applications.

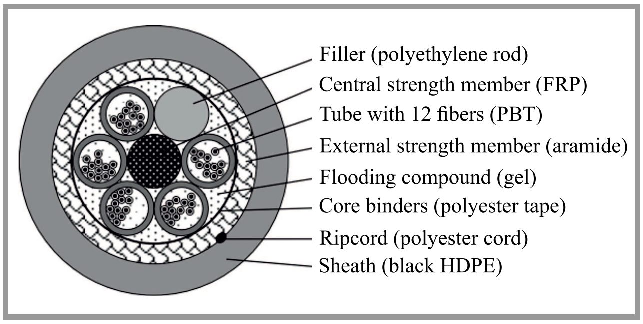

Fig. 3. 60-fiber dielectric, gel-filled duct cable with 5 stranded tubes and filler. All parts are to scale. Fillers enable to strand the core with a reduced fiber and tube count.

Stranding results in overlength of tubes and fibers inside with respect to cable sheath, adding to the overlength of fibers existing in (straight) tubes. For helical stranding, the formulas for the tube helix factor HF_S and overlength are the same as for fibers in the tube:

$$HF_S = \frac{L_T}{L_C} = \sqrt{1 + \left(\frac{\pi d_S}{p_S}\right)^2} \ , \tag{9}$$

$$\Delta L_S \approx 493 \cdot \left(\frac{d_S}{p_S}\right)^2 [\%] \ . \tag{10}$$

Here, p_S and d_S are the pitch and diameter of the helix formed by each tube in the cable. Equations (9) and (10) apply also to helically twisted slots in a slotted core cable. The cable helix factor may be obtained by adding 0.03–0.05% to account for the typical fiber overlength inside a loose tube.

There are several differences with respect to straight loose tube:

- helix diameter d_S is large, typically 4–8 mm in a single layer cable (Fig. 3), and ΔL_S in the range of 0.5-4% may be obtained,
- helix pitch p_S is set during stranding, and ΔL_S is adjusted as desired,
- fibers cannot move all the way to the axis of the cable. Most of the fiber's overlength is "dead", not useful for accommodating cable elongation, but the remaining "net" overlength of 0.15–0.8%, is sufficient.

The resulting helix factor in a cable with stranded tubes is a product of both components:

$$HF = \frac{L_F}{L_C} = HF_T \cdot HF_S \ . \tag{11}$$

For relative fiber overlength, the approximate formula is:

$$\Delta L = \Delta L_T + \Delta L_S \ . \tag{12}$$

The second component is most important, because the tubes have usually a small diameter of 1.5–3 mm.

If the cable contains more than 12 tubes, they are stranded in 2 or 3 layers, e.g. with 6 tubes in the inner layer and 12 tubes in the outer one (Fig. 4), each with a different helix diameter and pitch. The resulting helix factor for fibers in each layer may be different, because the cable is manufactured to achieve an identical "net" overlength and a strain-free window for all fibers. Additionally, manufacturers tend to minimize the length of fibers to reduce costs. A detailed description of the manner in which helix factors are calculated and other related parameters may be found in patents filed by the Corning company [6], [7]. For example, the said description includes the calculation of a complete strain window i.e. cable extension and contraction range with zero fiber strain.

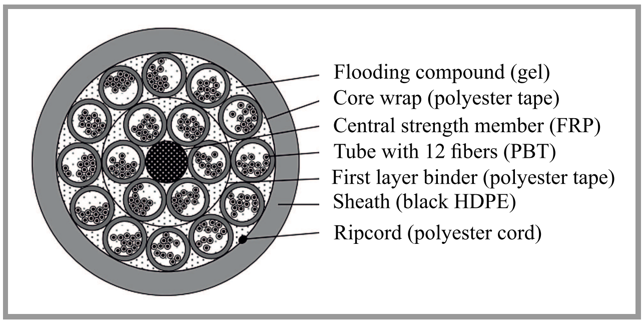

Fig. 4. The cross section of 216-fiber duct cable with 18 (6+12) loose tubes stranded in two layers.

A typical network operation support system (OSS), where data for all cable routes is stored in the network database, usually cannot handle separate HF values for specified ranges of fiber numbers in a single cable, e.g. 1–72 and 73–216 for the cable shown in Fig. 4. Instead, a single HF value for all fibers in a given cable is stored, which causes errors in locating faults for specific parts of the fibers. To overcome this problem, a comment on what range of fiber numbers the HF applies to, e.g. 1–72, and using only OTDR traces of these fibers for locating faults, may be the solution.

Another OSS issue is the need to assign different HF values to each cable section, as future maintenance of the link may be performed with the use of a different cable type.

Duct and directly buried cables need only a moderate net fiber overlength (0.05–0.20%), because they are exposed to large tensile forces only temporarily during installation, and are protected against temperature extremes by thermal inertia of the soil. A compact central tube may be a good approach here.

A different situation is experienced in aerial cables, such as ADSS and OPGW, exposed to variable tensile loads, extreme temperatures and sun heat, where a "net" overlength of 0.4–0.8% is expected. This is realized by adopting a short tube stranding pitch, typically equaling 100–150 mm, as opposed to 300–600 mm in duct cables. Another solution is to use a large diameter central tube, but such a design suffers from other issues, like tube stiffness and migration of fibers inside the tube in aerial installations.

3.1.4. Microcables

A microcable is a compact type duct cable with an outer diameter of 1.2–9.5 mm. While the optical unit is of the loose tube type, major differences may be identified:

- it has only a minimal strength member and a thin sheath,
- it requires blowing with pneumatic machinery and strict control of tensile forces,
- it is installed in plastic microducts of a small diameter (5–14 mm).

Fiber counts reach up to 576 - this is possible due to the use of compact fibers in 200 μm or 180 μm primary coating. The loose tubes in micro cables have small diameters (1.2–2 mm), thin walls and are almost completely filled with fibers. Designs with stranded tubes and a low stranding pitch dominate, but due to the compact optical unit, the HF of a micro cable is usually below 1.015.

3.2. Ribbon Cables

A fiber ribbon is a group of 4–24 fibers in colored primary coatings, laid in parallel and bonded together with a thin, soft matrix (Fig. 5) that may be easily removed mechanically [8]. The ribbon does not include any overlength of fibers.

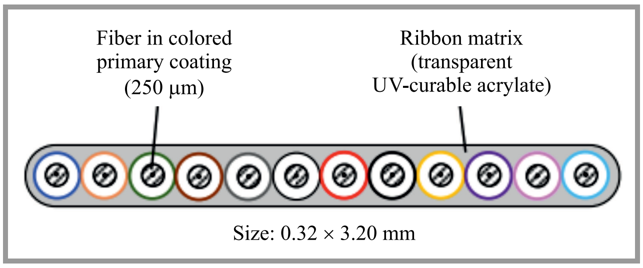

Fig. 5. Cross-section of a fiber ribbon with 12 single-mode fibers.

Back in the day, ribbons were fully coated with a binder material and therefore relatively stiff and difficult to bend or twist. Multiple ribbons of this type may be densely stacked in a large diameter loose tube, or in a rectangular groove in a slotted core cable, with fiber counts of up to 1000 (Fig. 6).

While stacked ribbons fill well rectangular slots, their stiffness restricts undulation that is necessary to obtain overlength of fibers in a tube or slot. A larger net fiber overlength may be obtained in a cable with stranded tubes or a slotted core, where the slots in the central element form a helix. The helix factor of such cables is comparable to that of conventional loose cables with stranded tubes.

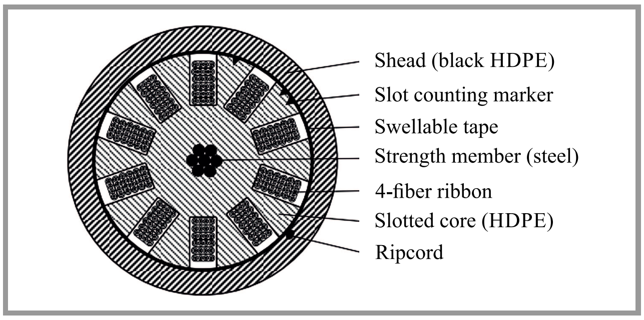

Fig. 6. Schematic of a 200-fiber slotted-core cable with 4-fiber ribbons in rectangular slots.

3.3. High Fiber Count Cables

The recent trend is to develop duct cables with extremely high fiber counts. Such cables have either one or 4–6 large tubes filled with 12-fiber ribbons. The ribbons are of the partially (periodically) bonded type, a solution that allows for easy twisting or bending and ensures that almost 100% of space in the tube is used, also because the "bending tolerant" or "bending insensitive" single mode fibers comply with the ITU-T G.657.A1/A2 standard [9] and, hence, tolerate some mechanical pressure without an increase in attenuation. A good example is a duct cable developed by Fujikura, with the outside diameter of 35 mm and 6,912 fibers in 200 μm primary coating formed into 12-fiber partially bonded ribbons, all in a single central tube.

Similarly to micro cables, this solution is characterized by a low overlength of fibers in tubes (fibers are almost straight). The helix factor may be higher in large diameter cables having stranded tubes.

3.4. Cables with Tight Buffered Fibers

The tight buffer is a layer of a rigid polymer, such as PBT, polycarbonate, polyamide or (moderately) plasticized PVC extruded over a single primary coated fiber – directly or with intermediate layer of a soft polymer, e.g. silicone. The outer diameter of a tight buffered fiber is 0.9 mm (0.036"), and is sometimes reduced to 0.6 mm in compact type cables.

The fiber overlength of 0.05–0.15% (HF = 1.0005–1.0015) is provided by the post-extrusion shrinkage of the outer layer of the polymer, as in a loose tube. The ability to form the fiber into a helix to accommodate overlength is limited by the lack of empty space, and the glass fiber is subjected to compressive strain that decreases with temperature.

The helix factor of an indoor cable with 1–12 straight fibers is higher, e.g. 1.005, because the tight-buffered fibers are surrounded by soft aramid fibers (the strength member) and form a helix or assume a similar shape after the cable jacket has been extruded and cooled. Large capacity indoor cables typically include stranded fiber units, and their HF may be calculated using Eq. (9).

4. Issues with Cable Installation

In this section, we explain how the type of the fiber optic cable and the method of its installation affect the relationship between fiber distance (determined by OTDR) and route distance.

4.1. Duct Installation

This type of outdoor network design is characterized by low requirements in terms of the cables used. The cables are pulled into ducts having the inner diameter of approx. 100 or 37 mm (or even lower in the case of micro cables) and are subjected to moderate tensile loads after installation. Duct cables are protected from temperature extremes by significant thermal inertia of the 80–120 cm thick layer of soil above the ducts, and against crushing forces transferred from the soil. The joint closures and spare segments are stored in underground manholes or handholes. However, the underground environment is frequently humid and cables may be surrounded by water or mud entering the manholes and/or ducts.

Duct cables are designed to withstand moderate tensile loads and temperature ranges. Cables with a single central tube and with multiple stranded tubes, as well as slotted core cables with fiber ribbons (in some countries only) are used here. Their HF ranges from approx. 1.005 for thin unitube cables to 1.015 for large fiber count cables with stranded tubes.

The route factor is the lowest in newly built cable networks located outside of towns, e.g. with cables pulled into plastic ducts laid directly in soft soil. For example, with the length of a cable section of 1500–2500 m, the spare lengths of 20–30 m on each side of the joint closure, with 0.25% of the total length added to account for failing to lay the ducts in an ideally straight line and to take into consideration other factors, the resulting RF equals 1.018–1.042.

In a complex urban environment with multiple obstacles, with existing manholes being used, RF may exceed 1.10. Similar conditions prevail when large spare cable segments, i.e. 200 m and more, are stored in underground containers to allow for splicing work to be performed away from inconvenient terrain. Under such conditions, it makes no sense to apply a uniform route factor. Large spare sections or deviations from a straight route shall be documented as separate objects with precisely recorded lengths and cable length markings.

4.2. Direct Burial

In this type of network design, cables of the strengthened variety, preferably armored, are laid directly in the soil, and therefore are exposed to considerable crush forces and potential soil movements. However, the range of operating temperatures and tensile forces are similar to those experienced in the duct networks, and the design of an optical unit of the cable and its HF are similar.

The route factor is usually low and equals 1.01–1.02, because the spare segments cannot facilitate servicing operations, as moving the cable would require troublesome and costly excavation work. However, the cable is frequently laid in a somewhat undulated form if soil movement, particularly in areas with underground mines, is a known risk.

4.3. Aerial Type of Installation

In the aerial network, each segment of the cable is suspended between two pylons. At both ends of each 2–3.5 km section, the cable enters an enclosure where a spare length L_{SP} = 20–30 m is stored, allowing for splicing work at ground level and for future repairs – see Figs. 7 and 8. In addition, there are vertical runs of the cable at the end of each section, down to the joint closure. For the OPGW cable suspended over the power conductors of a high voltage overhead power line 30–40 m above ground level, a 25 m vertical run is a typical solution. For ADSS cables placed below phase conductors, the vertical runs are shorter. In a high voltage network using OPGW or ADSS cables, the joint closure is usually attached to the pylon 5–15 m above ground to prevent acts of vandalism. When the cables are installed on a medium or low voltage power network or on telecom infrastructure, the vertical runs are short, so we will focus on an OPGW installation on a high voltage overhead power line, considering it to be the worst case scenario.

A section of an aerial cable is presented in Fig. 7.

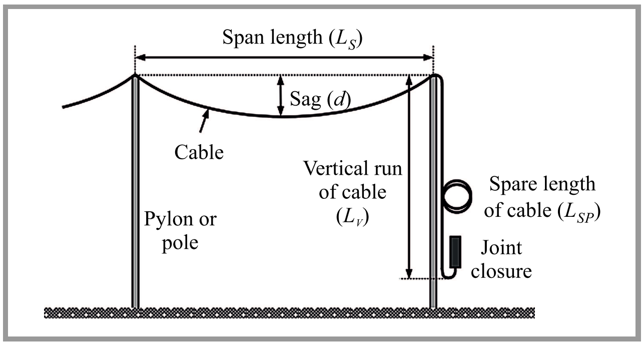

Fig. 7. Schematic of an aerial cable line with key parameters.

The aerial cable forms a catenary line whose length L_A in a section having the span length of L_S and sag (drop) d may be calculated using [10]:

$$L_A = L_S + \frac{8d^2}{3L_S} \,. \tag{13}$$

In this scenario, the cable is subjected to tension. The tensile strain in reference conditions (20°C, no wind, no ice) is approx. 0.15–0.20% for OPGW [11], [12]. To find the true (strain-free) length of the suspended cable in the span, a corrected formula for a reference strain value of 0.2% is suitable:

$$L_A = 0.998\ L_S + \frac{8d^2}{3L_S} \,. \tag{14}$$

Because the fibers in an aerial cable are protected from strain at moderate tensile forces applied to the cable (see subsection 3.1), the sag and its variations depending on temperature, wind and ice hazards have little effect on the physical length of optical fibers in the cable, unless the conditions are extreme.

The typical span in 110, 220, and 400 kVAC overhead power lines in Poland is 300–400 m, and the sag is 3.5–6 m according to [13].

For a 320 m span and a 5 m sag: $L_A = 319.568$ m, and $L_A/L_S = 0.99865$. Counter-intuitively, the actual (strain-free) length of the cable installed in a single span L_A is shorter than L_S, although the difference is low and equals 0.135% only. The extension of the cable exceeds the length added due to the catenary arc formed by the suspended cable. For the following cable and installation specification:

- $HF = 1.035$ (fiber overlength: 3.5%),
- number of spans in a cable section 10,
- route length of a cable section $L_R = 10 \times L_S = 3200$ m,
- cable spare lengths $2 \times L_{SP} = 2 \times 30$ m (see Fig. 7 and subsection 4.4),
- cable vertical runs $2 \times L_V = 2 \times 25$ m,

we get:

- length of cable in 10 spans: $3200 \times 0.99865 = 3195.68$ m,
- length of cable in a cable section: 3305.68 m ($RF = 1.033$),
- length of fiber in a cable section: 3421.38 m,
- $HF \times RF = 1.0692$ (6.92% difference between lengths of fiber and route).

HF in several ADSS cables exceeds 1.04 and the pylons are higher in mountainous terrain, so the difference between measured fiber length L_F and route length L_R may exceed 8%. Even if the location of the fault is referenced to a splice at the beginning of a cable section, it may be difficult to identify span requiring inspection.

4.4. Spare Lengths of Cables and Fibers

These segments allow to perform maintenance without adding a new section of the cable and an extra splice.

The spare length of a duct or aerial cable L_{SP} is preferably stored on each side of the splice and is coiled on brackets in a manhole or on a pole (Fig. 8). If the cable passes an area that is difficult to access with a utility vehicle carrying the equipment necessary for cable splicing, the line may incorporate considerably longer spares, 200 m or more, stored in underground enclosures to allow cable splicing at an accessible location.

Fig. 8. Spare lengths of aerial fiber optic cable accompanying a joint closure box: OPGW on a 400 kV high voltage power line (left) and ADSS on a low voltage line (right).

5. Use of OTDR for Fault Location

An extensive and detailed description of OTDR operation, as well as an interpretation of fiber traces is presented in [14]. E-book [15] is another publication covering this subject, but is considerably less detailed.

The most common kind of fiber cable fault is a localized damage, such as fiber breaks or severe bends, causing high losses in optical fibers. Such failures typically result from excavation and drilling works, as well as from vehicles hitting poles or cabinets. They constitute more than 80% of all fault, usually occur rapidly and affect all fibers in the cable [16].

Fault diagnostics with the use of OTDR include trace acquisition from one end of the affected line to save time. The most common fault, as mentioned earlier, is either a reflective break of the fiber, or a non-reflective and localized loss with uneven values in different fibers. The location of all fiber events is identical and testing multiple fibers brings no improvement in this regards. However, it confirms the type of the fault, e.g. damage of only some of the fibers in the cable suggests a rodent, a shot or a lightning strike.

A specific type of a fiber fault consists in the failure of a contaminated connector or a sharply bent fiber carrying a high-power optical signal in a transmission system employing EDFA amplifiers (up to 0.5 W or +27 dBm) or Raman amplification with powerful (multiple watts) pump radiation injected into the fiber. This kind of fault occurs at the ODF or inside a joint closure located relatively close to a line terminal. It results in the fiber coating overheating and burning out, followed some time later by a break of exposed glass fiber. Both the fiber break and damaged connector are highly reflective events. Other fibers and connectors are not affected.

All OTDRs used for diagnosing telecom networks are capable of automatically analyzing the fiber trace for discontinuities exceeding a set threshold, e.g. 0.10 dB. Such events are automatically listed, along with their type and parameters (loss, reflectivity, fiber distance to event). The fiber trace and the associated event table may be saved to a file or may be uploaded to a remote server. However, the distance displayed is the fiber length L_F between the OTDR's port (or a reference connector, when a launch fiber is employed) and the event. This value must be converted to cable length L_C, using Eq. (2), and next to distance between the fault and the closest easy-to-find objects, such as manholes, cabinets or poles with the joint closure.

The staff tasked with testing the fiber are often subcontractors servicing multiple networks, and do not have any precise data (n_{eff}, HF, route documentation) necessary for precise location of the fault. This information must be provided by the network operator from his OSS or cable network database.

5.1. Instrument Uncertainty in Distance Measurement

The distance uncertainty is usually specified by OTDR manufacturers as a sum of:

- 0.001–0.005% of distance measured (1–5 m for 100 km),
- cursor resolution (0.1–20 m depending on pulse width).

For a distance of 100 km and the pulse width of 1 μs (100 m), the uncertainty defined using this method is below 25 m. With a longer pulse of 10 μs (1000 m), the uncertainty is higher due to the shape of the pulse, optical receiver's impulse response, operator's skill, software used, etc. For a 10 μs pulse we can reasonably expect an uncertainty of approx. 75 m. Still, this is only 0.075% of the fiber distance measured.

The distance measurement error resulting from ignoring the cable helix factor is in the 0.15–4% range, while the spare lengths and vertical runs of cable and undulation of cable may incorporate a comparable error.

5.2. Refractive Index of Optical Fiber

There are two parameters of the optical fiber that are important for fault location using OTDR:

- effective refractive index n_{eff} for calculating fiber length between the OTDR's optical port and the fault,
- attenuation limiting the maximum length of the fiber which may be tested.

The geometry, attenuation, dispersion and mechanical parameters of telecom-grade fused silica fibers are standardized under ITU-T [9], [17] and IEC [18], [19]. The fiber's effective refractive index n_{eff}, defined as the ratio of one-way transmission delay τ in the fiber multiplied by the speed of light in vacuum to the fiber's physical length L_F is not standardized:

$$n_{eff} = \frac{c\tau}{L_F} \,. \tag{15}$$

In general, n_{eff} of multimode fibers (1.47–1.50) is higher than of single-mode fibers (1.46–1.47) because of the lower difference in the refractive index between the core and the cladding, as well as frequent incorporation of depressed (fluorine-doped) inner cladding in single-mode fibers.

Other names of this parameter include index of refraction (IOR) [20], effective index of refraction (EIOR) [21], effective group index of refraction [22], and group refractive index [23].

Specifications provided by fiber manufacturers include values of n_{eff} at intended operating wavelengths [22], [23] with a decent resolution, e.g. $n_{eff} = 1.4682$. The estimated consistency of n_{eff}, resulting primarily from its dependence on the fiber mode field diameter (MFD) and its production tolerance, typically ±0.4–0.5 μm, as well as the tolerance of OTDR operating wavelength [21], approx. ±20 nm, amounts to approx. ±0.0003. The variations observed with changes in temperature (for fibers in primary coating) and aging are negligible. A margin for other factors like rounding must be added, increasing n_{eff} uncertainty to 0.0001. However:

- n_{eff} is wavelength-dependent due to chromatic dispersion of the fiber, resulting in a difference between values at 1310 nm and 1625 nm of up to 0.002 for the ITU-T G.652 or G.657.A single-mode fiber (for the worst case scenario),
- cable specifications often fail to include n_{eff}, as the fibers in the cable can vary.

The uncertainty in measurement of fiber distance L_F resulting from the uncertainty of n_{eff} is proportional to the measured value. Two scenarios are important here:

a) the user has entered the n_{eff} found in the data sheet of the fiber under test,

b) the n_{eff} value from OTDR factory settings or from previous measurements is used.

The review of available datasheets indicated that n_{eff} values of commercially available single-mode fibers for terrestrial networks, conforming to ITU-T G.652.D, G.654.E, G.655.C/D/E, and G.657.A1/A2 standards, are within the following ranges:

- 1.4606–1.4710 at 1310 nm if the fiber is designed for operation at this wavelength,
- 1.4620–1.4700 at 1550 nm.

The difference between extreme values is about 0.010, so the combined error in setting the n_{eff} in the second case increases to ±0.0110. Using a n_{eff} value for a wrong wavelength, e.g. 1550 nm instead of 1310 nm, may increase this error up to ±0.0130.

During the measurement of fiber distance of $L_F = 100$ km, the uncertainty expected in scenarios (a), (b), and (b) with data for wrong wavelength is 68 m (0.068%), 748 m (0.748%), and 884 m (0.884%), respectively. This error in scenario (a) is comparable with distance measurement uncertainty specified by manufacturer of the OTDR.

5.3. Fiber Refractive Index and Cable Helix Factor

For reliable distance measurements, the value of n_{eff} provided by the fiber manufacturer must be set in the OTDR for each wavelength at which fiber testing is planned. The range is at least 1.4–1.6, giving a possibility of introducing a large error by entering wrong n_{eff}, and it may be expected that the value will be reduced to 1.00 due to the recent introduction of low-latency photonic bandgap fibers with a hollow core, designed for data center applications [24]. Fibers with n_{eff} values as low as 1.02 were developed recently as well.

Many OTDRs allows to input cable HF or equivalent fiber overlength as a percentage value [20]. This parameter is wavelength-independent.

Because n_{eff} is usually specified at two or three wavelengths, such as 1310 nm, 1550 nm and sometimes 1625 nm for single-mode fibers, the value at another wavelength, e.g. 1650 nm, may be estimated by linear interpolation or extrapolation [21].

The default value of HF is 1.000 (0.0% fiber overlength). If the OTDR has no HF setting function, a solution is still possible – after setting n_{eff} equal to the n_{eff} of the fiber multiplied by HF, the instrument will show the length of cable instead of fiber.

5.4. Measurement of Cable Helix Factor

The length of an outdoor cable with a rigid strength member, except for the OPGW made of stranded wires, is marked accurately on the sheath by the factory (maximum tolerance of cable length is 0–1% of length markings, while the typical tolerance equals 0.2%). This allows to calculate HF from the fiber length L_F measured with OTDR and cable length L_C between markings at both ends of the length under test, using Eq. (2). However:

- the HF value established using this method is valid only for a given type and size of cable. It varies considerably for otherwise equivalent cables from other suppliers,
- HF is much less consistent than fiber n_{eff}.

6. Distance Correction for Fault Localization

The techniques enabling a more precise localization of fiber cable faults include:

- conversion of the measured fiber length to cable length using the helix factor,
- accounting for spare, vertical and indoor lengths of cables,
- using the route factor which is useful only for long, uniform lines,
- referencing distance to the nearest splice instead of ODF.

Effective use of these methods requires access to OSS information, i.e. a valid database of cable routes and network facilities, including buildings, manholes, poles, street cabinets, splice and termination locations, cables (type, HF value, fiber type, count, and n_{eff}), together with their geographical locations and fiber IDs. Additionally, the OSS shall store the reference OTDR traces of all fibers, measured from both ends of the line, for comparison with the test data acquired before and after servicing.

With a decent set up and well-maintained OSS, the system is capable of calculating the actual location of a fault after entering a raw distance to the fault measured with OTDR, and of presenting this location on a map together with nearby objects, such as manholes or buildings for reference.

Unfortunately, this is not always possible, as the maintenance of infrastructure data is costly and labor-intensive. In such cases, manual or semi-automated correction of distance to a fault may be the only option.

The best way is to set the OTDR up with HF of the cable to be tested. Alternatively, cable length L_C may be calculated from the measured fiber length L_F using Eq. (2).

This method has no use when the line is made up of two or more different types of cable, unless corrections for each part are made separately, which is complex and with inherent error risk.

The use of route factor (RF) is recommended only for long, uniform lines with one type of cable, uniform installation rules, straight routes, and even so, specific "jitter" resulting from the conversion of discrete spare and vertical lengths of cables to a fraction of total cable length is experienced, meaning that the accuracy of this method is low. The length of route to fault L_R may be calculated from measured fiber length L_F using Eq. (1).

Referencing to the nearest splice is the best approach when combined with use of cable helix factor for conversion of fiber distance to cable distance. While a complete single mode fiber optic link may have a length of up to approx. 120 km, the cable section extending between splices is typically up to 4 km long, and most often 2.5 km or even less. Consequently, errors in the measurement of distance to fault stemming from an unknown or improperly set HF and n_{eff} are proportionally reduced.

The suggested fault location procedure is as follows:

- acquire a fiber trace and set the cursor at the beginning of a fault (spike or fall on the fiber trace),
- look for the nearest splice before the fault and measure the distance between them,
- verify whether this distance is smaller than the length of the cable section. If not, this means that the nearest splice was missed due to very low (apparent) loss, and another fiber shall be tested,
- convert the measured splice-to-fault fiber distance to cable distance, using Eq. (2),
- use this cable distance to find the relative location of the fault with respect to the nearest objects in the route documentation, e.g. the fourth manhole after the one with a joint closure. The spare lengths of cable must be included.

In a duct network with a 2000 m cable section, cable with $HF = 1.015$ (1.5% fiber overlength), 0.2% uncertainty of HF (0.002), and spare length of cable near the joint closure $L_{SP} = 20$ m, the expected error in a fault location process relying on this procedure is approx. 5 m. Without corrections for HF and spare lengths of cable, the error may reach 50 m under the same conditions.

7. Conclusions

Precise location of a fault in an outdoor fiber optic cable using an OTDR is crucial for enabling fast and efficient cable repairs and for restoring the fiber connections. The use of OTDR allows to locate a fault from a distance of 100 km or more, with the accuracy in order of 100 m, therefore enabling to begin servicing without losing any time on looking for the actual fault location.

The methods of estimating the locations of fiber cable faults, as presented in this paper, shall be useful in achieving this goal, especially when a fully featured network OSS is not implemented. The use of the parameter of fiber optic cables discussed in this paper, i.e. the helix factor, is always essential.

References

[1] IEC 60304 Ed. 3,"Standard colours for insulation for low-frequency cables and wires", 19821 [Online]. Available: https://webstore.ansi.org/Standards/IEC/IEC60304Ed1982

[2] ANSI/TIA-598-D-2014, "Optical Fiber Cable Color Coding", *Telecommun. Industry Association (TIA)*, 2018 [Online]. Available: https://global.ihs.com/doc_detail.cfm?document_name=TIA%2D598&item_s_key=00134525

[3] IEC 60794-1-31 Ed 2, "Optical fibre cables – Part 1-31: Generic specification – Optical cable elements – Optical fibre ribbon", 2021 [Online]. Available: https://webstore.iec.ch/publication/30731

[4] H. Murata, *Handbook of Optical Fibers and Cables*, 2nd Ed. New York: Marcel Dekker, 1996 (ISBN: 9780585268972).

[5] IEC 60794-1-20, "Optical fibre cables – Part 1-20: Generic specification – Basic optical cable test procedures – General and Definitions [Online]. Available: https://webstore.iec.ch/publication/3479

[6] Patent WO 03/083518 A2, "Optical fiber cable with controlled helix-plus-EFL values and methods therefor", 2003 [Online]. Available: https://patents.google.com/patent/WO2003083518A2

[7] Patent US 6859592 B2, "Optical fiber cable with controlled helix values", 2005 [Online]. Available: https://patentimages.storage.googleapis.com/ce/c8/a1/926b52d292150c/US6859592.pdf

[8] IEC 60794-1-31 Ed 2, "Optical fibre cables – Part 1-31: Generic specification – Optical cable elements – Optical fibre ribbon", 2021 [Online]. Available: https://webstore.iec.ch/publication/30731

[9] ITU-T G.657, "Transmission media and optical systems characteristics – Optical fibre cables – Characteristics of a bending-loss insensitive single-mode optical fibre and cable", 2016 [Online]. Available: https://www.itu.int/rec/dologin_pub.asp?lang=s&id=T-REC-G.657-201611-I!!PDF-E&type=items

[10] ITU-T L.89, "Design of suspension wires, telecommunication poles and guy-lines for optical access networks", 2012 [Online]. Available: https://www.itu.int/rec/T-REC-L.89-201202-I

[11] Installation Instructions – AFL Optical Ground Wire (OPGW). AFL, ACS-WI-805.06, 2012. [Online]. Available: https://www.bidnet.com/bneattachments?/689129089.pdf

[12] S. Karabay, E. A. Güven, and A. T. Ertürk, "Performance testing of an optical ground wire composite", *Materials and Technol.*, vol. 47, no. 1, pp. 119–124, 2013 [Online]. Available: http://mit.imt.si/izvodi/mit131/karabay.pdf

[13] D. Złotecka, "Nadmierne zwisy linii WN jako przyczyna awarii w systemach elektroenergetycznych", *Przegląd Elektrotechniczny*, vol. 94, no. 10, pp. 143–147, 2018 [Online]. Available: http://pe.org.pl/articles/2018/10/33.pdf [in Polish].

[14] D. R. Anderson, L. Johnson, and F. G. Bell, "Troubleshooting optical-fiber networks: understanding and using your optical time-domain reflectometer", 2nd Ed. *Elsevier Academic Press*, 2004 (DOI: 10.1016/B978-0-12-058661-5.X5020-4).

[15] J. Laferriere, G. Lietaert, R. Taws, and S. Wolszczak, "Reference guide to fiber optic testing", *Viavi Solutions*, vol. 1, 2018 [Online]. Available: https://www.normann-engineering.com/support/white_papers/fiberguide1-bk-fop-tm-ae.pdf

[16] R. Dutta and G. Rouskas, *CSC/ECE 791B – Survivable Networks Introduction*, North Carolina State University, Raleigh, N.C., USA: Spring, 2008.

[17] ITU-T G.652, "Characteristics of a single-mode optical fibre and cable", 2016 [Online]. Available: https://www.itu.int/rec/T-REC-G.652/en

[18] IEC 60793-2-50, "Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres", 2015 [Online]. Available: https://webstore.iec.ch/preview/info_iec60793-2-50%7Bed5.0%7Den.pdf

[19] IEC 60793-2-10, "Optical fibres – Part 2-10: Product specifications – Sectional specification for category A1 multimode fibres", 2019 [Online]. Available: https://webstore.iec.ch/publication/62020

[20] OTDR – Optical Time Domain Reflectometer User Guide, EXFO Inc., 2019 [Online]. Available: https://trsrentelcoimagerepository.azureedge.net/trswebsitedata/Specs-Manuals/max740c%20manual-10779-11014.pdf

[21] "Explanation of the sources of variation in optical fiber effective group index of refraction values", *Corning Inc.*, AN4091, 2020 [Online]. Available: https://www.corning.com/content/dam/corning/media/worldwide/coc/documents/Fiber/application-notes/AN4091.pdf

[22] Corning SMF-28 Ultra Optical Fiber Product Information. PI1424, 2014 [Online]. Available: https://www.corning.com/media/worldwide/coc/documents/Fiber/SMF-28%20Ultra.pdf

[23] "AllWave optical Fiber – Zero Water Peak: The industry's first zero water peak single-mode fiber for reliable full-spectrum performance (data sheet)", *OFS Fitel*, ID: fiber-117, 2017 [Online]. Available: https://fiber-optic-catalog.ofsoptics.com/documents/pdf/AllWave+-ZWP-Fiber-159-web.pdf

[24] "AccuCore HCF Fiber Optic Cable and Assemblies (data sheet)", *OFS Fitel*, 2020 [Online]. Available: https://www.ofsoptics.com/wp-content/uploads/AccuCore-HCF-Fiber-Optic-Cable-Assembly-web.pdf

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