Field measurements on in-service optical fiber

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Cuvinte cheie. *Fibră optică, atenuare, dispersie, pierderi de transmisie, OTDR.*

Rezumat. *Lucrarea trece în revistă principalele mecanisme de atenuare şi distorsionare în fibra optică, evidențiază contribuțiile absorbției şi dispersiei semnalului optic la pierderi de transmisie, introduce parametrii sistemului de măsură bazat pe recepția împrăştierii inverse.*

Keywords. *Optical fiber, attenuation, dispersion, transmission loss, OTDR.*

Abstract. *This paper briefly shows out the main processes in the optical fiber that lead to attenuation and distorsion of the optical pulse, highlights absorption and dispersion effects upon the fiber budget loss, picturises parameters and performances of the backscattering based testing system .*

1. Introduction

There is a bunch of measurements an in-service optical fiber has to undergo in order to the end-user determines the actual overall optical transmission capabilities. The main measurements qualifying an optical fiber for information transmission purposes are:

- End-to-end optical link loss;
- Attenuation rate per unit length;
- Attenuation contributions to splices, connectors, couplers;
- Length of fiber or distance to an event;
- Attenuation discontinuities or fiber linearity loss per unit length;
- Optical return loss

Some measurements may require access to both ends of the optical fiber, other require only one end. Particularly, in-service optical fibers are subjected to on field testing programs from one end so as time to travel from one end of the fiber cable system to the other is saved. Installation, Maintenance and Restoration are the main tasks where on field testing is required.

2. Field test

The exact items of the on field testing program on optical cables are selected from a comprehensive list of measurements in accordance with system design, system criticality and contractual relationship between system owner, system user, system installer and optical cable and components supplyer.

Installation testing is intended to ensure that fiber cables comply manufacturer's specifications, no damages resulted during transportation and placement. Also, tests show out the quality of cables splices and cable terminations and that the fiber cables subsystem meets the requirements of the optical transmission system.

Maintenance testing is periodically required to demonstrate that fiber cables system suffered no

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defects of the cables, splices or connections. High capacity or critical systems may need automated testing devices employed to check the integrity of the system every minutes or so and alert immediately a degradation or an outage of the fiber cable.

Cable restoration ensues to identify the cause of outage (transmitter, receiver, cable, conectors) and to locate the fault in effect in the cable. After fiber cable revitalizing, testing is performed to prove the quality of the repaired system.

When verifying the fiber network, network topology and equipment should be taken into account. One major item to measure is the end-to-end optical link loss. The fiber link comprises the source, the optical transmission guide and the detector. The transmission link includes the source-to-fiber coupling loss, the fiber attenuation loss, the loss of all of the components along the line (splices, connectors, pasive components, etc.)

End-to-end optical link loss ranges from a minimum value up to a maximum value.

The minimum loss value is the ratio of the maximum optical power the transmitter injects into the fiber to the maximum received optical power signal with the communication still in force. The maximum loss value is the ratio of the minimum optical power at the fiber input end to the faintest received optical power whilst maintaining communication.

The transmitter data sheet provides both the maximum T_{MAX} and the minimum T_{MIN} power level figures. Minimum transmit power represents the worst case transmit power for a device, the device is guaranteed to provide at least that much power.

The receive sensitivity gives the user the faintest power level R_{MIN} the optical receiver can sense with a given noise level to operate correctly. The receive dynamic range provides us with the maximum power level R_{MAX} that optical receiver can handle.

Accordingly:

- The minimum end-to-end link loss $B_{MIN} = T_{MAX} - R_{MAX}$;
- The maximum end-to-end link loss $B_{MAX} = T_{MIN} - R_{MIN}$.

The optical loss budget, for a –10dB minimum transmit power and –32dB minimum receive sensitivity, is B_{MAX} = 22dB, the highest optical power available for the fiber cable network. All of the losses must be subtracted out from this power, such as cable attenuation, connector loss and splice loss. Cable attenuation is the most significant loss factor. Typically, the optical power loss in the fiber cable ranges from 0.22 dB/km to 0.5 dB/km. A 0.4 dB/km fiber deprives a 20km network of 8 dB. Each connector removes 0.75 dB off from the optical power and each splice draws out additional 0.1 dB from the power in the fiber. Six connectors and four splices decrease the power with further 4.9 dB hence a 9.1 dB link margin remains for repair splices, safety margin and transmission. If we spare 0.5 dB for repair splices and 3 dB for the safety margin, the excess power available for the transmission itself is 5.6 dB. At this point, the positive optical loss buget figure shows out that the fiber network sample in this instance delivers the requested performance over the life in-service.

An appraisal of the optical loss budget is particularly useful when field measurements on in-service fiber cable network ensue to determine the available transmission quality. Significant differences off from loss budget calculations could demonstrate additional losses generated by faults or fiber breaks.

Optical fiber are made of pristine silica glass yet they absorb a tiny fraction of the light guided through them. Material absorption is high in ultraviolet region due to electronic resonance and in the far-infrared region beyond 2000nm due to vibrational resonance but is low within the 500 nm to 2000 nm window. Certain impurities cause strong absorption but the glass itself has some absorption. The most important impurity yielding fiber loss is the OH ion which has a fundamental vibrational absorption peak at 2730 nm. The overtones of this OH-absorption peak are responsible for the dominant peak near 1400 nm and a smaller peak near 1230 nm. In state-of-the-art fibers, the peak near 1400 nm can be reduced to below the 0.5 dB level. Rayleigh scattering is a fundamental loss mechanism originating from density fluctuations into the silica during manufacture. Resulting local fluctuations in the refractive index scatter light in all directions, the atoms act like tiny reflective particles reflecting light off so it escapes from the fiber core and is lost from the signal. The shorter the wavelength the higher the amount of scattering, therefore visible wavelengths are scattered much higher than the infrared. Light leakage occurs when light escapes from the fiber core into the cladding. Large amount of light escape from a tight fiber bending as the hitting angle is smaller than the total internal reflection angle.

Absorption and scattering are extremely small in optical fibers, total attenuation accumulates when light travels through many kilometers of fiber. Normally, attenuation is measured by comparing the strength of the input signal to the output. Attenuation is cumulative and uniform through the entire length of the fiber. The characteristic attenuation is measured in decibels (dB) per unit length, usually decibels per kilometer (dB/km).

Bandwidth and information capacity are crucial in communications, the more information one wants to convey the faster the signal has to change. Optical fiber has a flat attenuation curve at all signal frequencies in the normal operating range very much differently to an electrical wire which shows out a higher attenuation the higher the frequency. There are other effects to limit the optical fiber transmission capacity. An electromagnetic wave interacts with the bound electrons of the fiber, basically a dielectric, the medium response depends on the optical frequency. This is reffered to as chromatic dispersion, a frequency dependence of the refractive index. The fiber medium absorbs the electromagnetic radiation through oscillations of bound electrons at resonance frequencies. Fiber dispersion is critical in propagation of short pulses because different pulse spectral components travel at different speeds. In the normal dispersion regime the blue-shifted components of the optical pulse travel slower than the red-shifted components of the same optical pulse. The dispersion increases steadily with the distance the pulse goes through the fiber so as the optical signal is stretched out for each kilometer it travels. The dispersion-induced pulse broadening will limit the transmission speed. For example, a 2 Gbit/sec signal might be able to travel 400 km but a 10 Gbit/sec signal would be limited to 100 km. Using multiple cladding fiber it is possible to design dispersion-flattened optical fibers having low dispersion over a wide wavelength range 1300 nm to 1600 nm. An important feature of chromatic dispersion is that optical signals at different wavelengths propagate at different speeds inside the fiber because of the mismatch in their group velocities. This feature leads to a walk-off effects which makes two optical pulses to travel the same fiber core without any interactions between them.

Modal birefringence becomes an issue when short optical pulses are transmitted over long lengths. Real fiber demonstrates small anisotropies of the refractive index along fiber orthogonal directions. Accordingly, the light launched into the fiber with a fixed state of polarization changes its polarization in a random fashion because the two components travel at different speeds due to different group velocities. The smaller mode index axis is the fast axis because of the larger group velocity the light propagates that direction. Similarly, the larger mode index axis is called the slow axis. The pulse becomes broader at the output end as the group velocities change randomly in response to random changes in fiber birefringence. The extent of signal broadening can be estimated from the time delay spanning between the two polarization components during propagation of the optical pulse. This is the Polarization-Mode Dispersion effect which is important for long-haul optical communications systems.

3. OTDR tester

The most accurate way to measure the overall losses of the optical fiber is to inject a known level of light into one end and measure the level of the light at the other end. Light sources and power meters are recommended by ITU-T (G651) and IEC 61350 to measure the insertion loss. This method requires access to both ends of the fiber which is not always possible or productive.

Optical Time Domain Reflectometer (OTDR) technique provide the user with fully tests on a fiber from one end only. An OTDR tester can detect, locate and measure events any place in the fiber link. The OTDR detects a small signal returned back to the OTDR in response to injection of a large signal. If Rayleigh scattering is uniform along the entire length of the fiber then discontinuities in the Rayleigh backscatter can identify anomalies in transmission along the fiber length. The backscattering factor S describes the ratio between backscattered power and the scattered power. Typically S is proportional to the square of the fiber numerical aperture. Backscattering depends on input power, pulse width, bacvkscattering coefficient, distance and fiber attenuation. Dopants in the fiber leverage scattering and thus higher levels of attenuation. An OTDR can measure the levels of backscattering accurately and uses it to measure small variations in the fiber characteristics at any point along its length.

The light bounces off from two optical transmissive materials interface. Fresnel reflection can take place at a joint, connector or mechanical splice, at a non-terminated fiber end or at a break. The magnitude of Fresnel reflection depends upon the incident power and the relative difference between the two refractive indexes. Reflected light from a fiber-to-air boundary is 4000 times the backscatter level. The OTDR must have an outstanding sensibility to process signal powers that low.

The OTDR launches optical pulse into the fiber through a laser diode and pulse generator. The returning light power is separated from the injected pulse using a coupler and fed to the photodiode. The returned optical pulse is converted to electric signal, amplified and sampled and then displayed on a screen. Laser diode supplies an optical pulse wavelength of 1310 nm & 1550 nm for single mode fiber and 850 nm & 1300 nm for multimode fiber.1625 nm laser diode is also used when live traffic measurements occur in order to avoid interference with 1310 nm and 1550 nm traffic. The pulse generator feed the fiber with light pulses from 10 mWatt to 1 Watt. The pulse width spans from 2 nsec up to 20 microsec at reccurence of a few kHz. The pulse frequency is limited to the rate at which the pulse return is completed before another pulse is launched into the fiber. The light goes through the coupler/ splitter and into the fiber under test. The OTDR measures the time delay between the outgoing pulse and the incoming backscattered pulses. The backscattered signal power level is sampled over time. Measured samples are plotted on an amplitude scale with respect to time relative to timing of the launch pulse. The time domain information is converted to distance based on the refractive index input data. The refractive index is reciprocal to the group velocity of the light in the fiber hence a time-to-distance formula operates. If the refractive index is inaccurate the resulting distance is in error.

4. Summary

On-field effective budget optical measurements on in-service fiber cables claim access to one fiber end. Testing program on optical fiber cable comprises a list of measurements in accordance with network design, system criticality and contractual relationship between parties. The most important item to measure on an optical fiber is the end-to-end fiber link loss or the fiber loss budget. Absorption and dispersion effects into the fiber contributes to intrinsec loss while fiber tight bending, splices, connectors and optical components add extrinsic loss.

The OTDR technique meets the requirement to access one fiber end only. The OTDR is a versatile device designed to detect the backscattering level along the fiber link. It measures backscattered signals much smaller than the launched signal into the fiber.

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