Lighting the Way to the Home
Transmission System Basics: Optical Fiber and Optical Cable

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Abstract

Legacy system operators, such as telco and cable television (CATV) networks, are very familiar with the design and performance attributes of networks incorporating optical cables. However, pursuit of fiber-to-the-home (FTTH) deployments is currently most common among entities that have little to no experience in the design, construction, or operation of this type of telecommunication system. Basic component knowledge is essential to make informed decisions. Optical cable is one of the basic building blocks necessary to establish the physical infrastructure for an FTTH network.

This paper will discuss technical differences between common optical fiber and optical cable designs used in today's optical telecommunications infrastructure and typical applications where each is utilized. The primary focus of this paper/presentation is to educate individuals with limited experience in optical telecommunications.

Overview

The diversity of information available from a modern telecommunications network is changing the day-to-day routine of individuals in both the business and private sectors. The consumer appetite for newer, faster, and easier services continues to drive growth of broadband portfolio offerings. The Internet has become the de-facto communications platform for the "Y2K generation," and many businesses depend on this communications medium for their survival. Individuals exposed in the commercial sector to the benefits of a modern telecommunication network have directly influenced the proliferation and demand for similar quality of service (QoS) levels in the private sector. Reliable, high-capacity networks are required to properly support the demand for advanced telecommunication services such as high-speed Internet access, video teleconferencing, and video-on-demand (VoD) in residential applications. To remain competitive, service providers engaged in providing these services, as well as more traditional voice, video, and data applications, must ensure their networks are correctly positioned for both current and future demands. Failure to adapt to dynamic market conditions may create QoS issues that can directly impact relations between suppliers and customers. Access network applications routing optical fiber directly to the home (FTTH), business (FTTB), or other emerging applications (FTTx) will provide the transmission capacity necessary to provide reliable telecommunication services to the subscriber. The significant advantages of extending an optical network directly to the home or business are twofold. First, establishing this type of communications media link meets today's fast-paced demands. Second, deploying optical fiber to the home positions the network to easily adapt to anticipated future growth requirements.

The primary "building block" for constructing an FTTH network is the optical cable that links individual users with an optical fiber-based connection. Optical fiber is a proven and extremely capable transmission media. Optical transmission systems have demonstrated reliable operation for more than 20 years. The first applications for optical cables were primarily to replace trunk and backbone routes that required much larger copper cables. To put this into perspective, one mile of single fiber optical cable weighs approximately 28 pounds. A mile of copper cable with the same information carrying capacity would weigh 33 tons. Optical cables are extremely capable and lightweight, have extremely high data-carrying capacity, and provide future upgrade capability which all give optical fiber systems a decided technological advantage over other transmission media.

So why wasn't the entire copper plant replaced wholesale by optical fiber? In initial deployments 20 years ago, the primary obstacle was the cost differential relative to performance requirements for routing copper versus optical fiber throughout the entire network. With the passage of time, transmission performance requirements have steadily increased, and a commercially competitive market has driven down the cost differential between optical fiber and copper media. The end result is that an optical fiber solution is now economically viable and technologically necessary to meet broadband service demands.

Growth of the optical network into the FTTx space also alters the pool of potential service providers. The larger, nationally recognized telephone and cable television companies, while more familiar with the design and operation of optical telecommunications, have not yet completed any significant FTTH deployments. Recent trends demonstrate that smaller, regionally focused municipal organizations have been the most active in the design and deployment of FTTH networks. In many cases, these organizations are "newcomers" to optical telecommunications without a base of personnel experienced in optical fiber engineering. This situation can present challenges to select products and materials to outfit a proposed network. The number of different network solutions has grown and become more specialized as the optical telecommunications industry has matured. As with any progressive, technology-based industry, there has been a series of advances in design, materials, and system operations. Many solutions are "cutting edge;" but also directed to enhance specific applications. The sometimes forgotten limitation of such specialization enhancements is that optimizing one attribute typically degrades the performance of another. This situation can cause issues when "enhanced" products are not used properly. The true benefits and limitations of any solution must be understood and applied correctly. The challenge is to understand the technical performance requirements of the network under consideration and match up the best optical transmission products to meet them. An understanding of the basics can ease the burden of making these types of decisions. The purpose of this paper is to provide a basic foundation of optical fiber and optical cable information.

Communicating With Light – Optical Fiber Makes It Possible

The basic concept of operation utilized by today's modern telecommunication systems was proposed more than 100 years ago. Optical communication was first demonstrated in 1880 by Alexander Graham Bell when he successfully demonstrated the operation of his "photophone" and proved that information could be transmitted with light.[1] However, Bell's system relied upon the sun as the system's source of light and the signal was transmitted "line of sight" through the air. Thus, correct system operation of the photophone was entirely dependent on prevailing weather conditions. Further progress in the optical communications discipline was limited until a more reliable transmission light source could be identified. The development of Helium-Neon lasers in 1960 provided the stable light source upon which optical communications technology could now be advanced. The next technological hurdle was to develop a component/method to guide light over long straight distances and around bends in a controlled manner. Corning Incorporated was first to develop a workable "optical waveguide" design composed of fused silica glass in 1970.[2] The design of the optical waveguide, more commonly termed "optical fiber," was refined, and related work was undertaken to develop methods to deploy optical fiber in a communications network. By the late 1970s, the first practical optical fiber-based communication systems began operation. Since the first significant deployment, optical fiber technology has grown and matured. In today's networks, two optical fibers can transmit the equivalent of 625,000 telephone calls at one time. Optical fiber has been deployed in backbone and distribution networks since the late 1970s, and if all the optical fiber currently installed were placed end to end, it would reach from the Earth to the moon and back more than 160 times.[3] The promise of extending optical fiber closer to individual users in FTTH applications will only serve to significantly increase the amount of optical fiber installed.

The Basics of Optical Fiber

From a material standpoint, optical fiber is composed of ultra-pure silica, which is almost 200,000 times more pure than window glass. Optical fiber is extremely strong and very flexible. An optical fiber has the bending strength to provide reliable, long-term operation when placed in bends as small as one inch in radius. The tensile strength (resistance to longitudinal stress) is comparable to that of the strongest materials, including steel.[4] Even though the dimensions of an optical fiber closely approximate that of a human hair, its theoretical strength is extremely high and its durability has been proven in a variety of adverse environments.

The general makeup of an optical fiber is very simple. There are three basic components. Starting from the center of the optical fiber and working outward, an optical fiber consists of (1) the core region, (2) the cladding region, and (3) the coating region (see *Figure 1*).

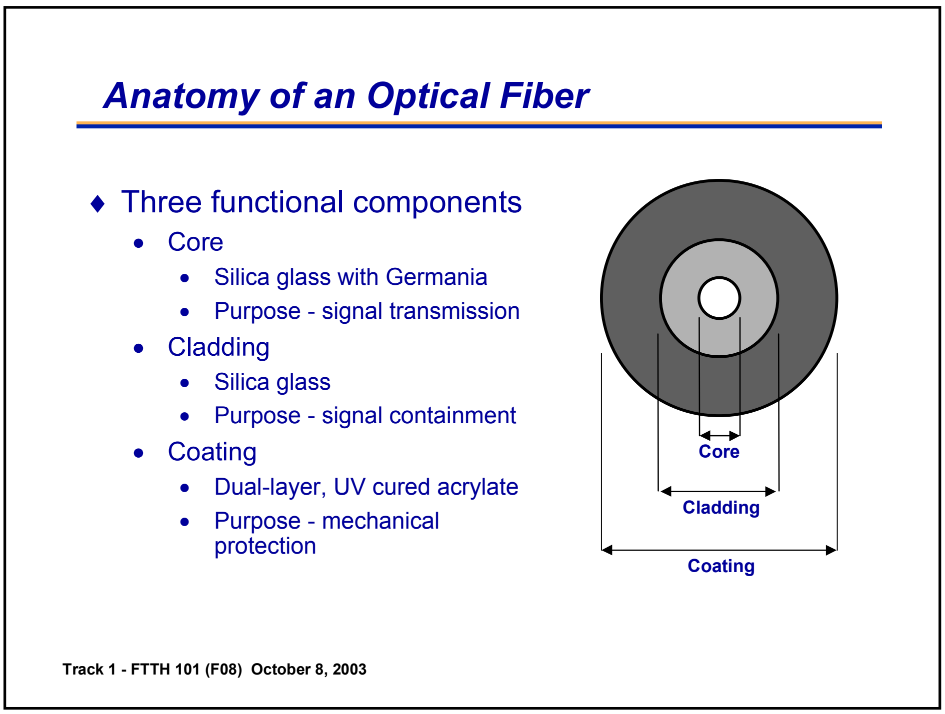

Figure 1: Optical Fiber

These three regions can be defined as follows:

Core The core is the region of the optical fiber through which the optical signal travels from origin to destination. While both core and cladding are composed primarily of silica glass, the overall material composition of each is different from the other. This difference in material properties directly relates to the manner in which each interacts with the optical signal. The primary parameter that characterizes the light transmission performance of the optical fiber is termed the “index of refraction” (IOR). The IOR of the core is maintained at a specific value by the controlled addition of Germania glass dopant (GeO_2) to the silica glass (SiO_2). Germania increases the IOR of the core relative to the cladding. The transmission signal remains in the core region due to the IOR difference between the core and the cladding. The physical size of this region varies between fiber types and dictates the capacity and transmission distance limits. The most typical core sizes for commonly used optical fibers are approximately 62.5, 50, and 8 micrometers. (While the correct terminology is “micrometers,” this unit of measure is sometimes referred to by the term “micron.” A micrometer is abbreviated using “μm.” For reference, 1 μm equals 1 x 10^{-6} meters.)

Cladding The cladding region surrounds the core and is typically composed of pure silica glass without any additives. The functional purpose of the cladding is to contain the optical transmission signal in the core region. When an optical signal is launched into the core, it will preferentially remain in the core because the difference in the IOR between the core and the cladding makes the cladding act as a mirror to prevent the optical signal from leaking out. This principle is called "total internal reflection," following Snell's law. The most typical cladding outer diameter size is approximately 125 μm.

Coating The cladding region is surrounded by a protective plastic coating comprising two distinct acrylate layers. The inner layer is soft and acts as a shock absorber. The outer layer is hard and abrasion resistant. The two layers combine to provide protection for the silica glass optical fiber from mechanical stresses and surface damage. The most typical coating outer diameter size is approximately 245 μm.

Since its initial development in the 1970s, a number of different fused silica glass optical fiber designs have been utilized in telecommunication networks. There are two general classifications of optical fiber types: multimode and single-mode. Multimode optical fiber was the first type of optical fiber to be developed/commercialized and has a core that is much larger than that of single-mode optical fiber. As its name suggests, multimode fiber can simultaneously transmit the optical signal over multiple stable pathways, or what are termed “modes,” inside the core. Single-mode optical fiber, with its much smaller core area, supports stable optical transmission on only one stable mode. *Figure 2* compares the two fiber types.

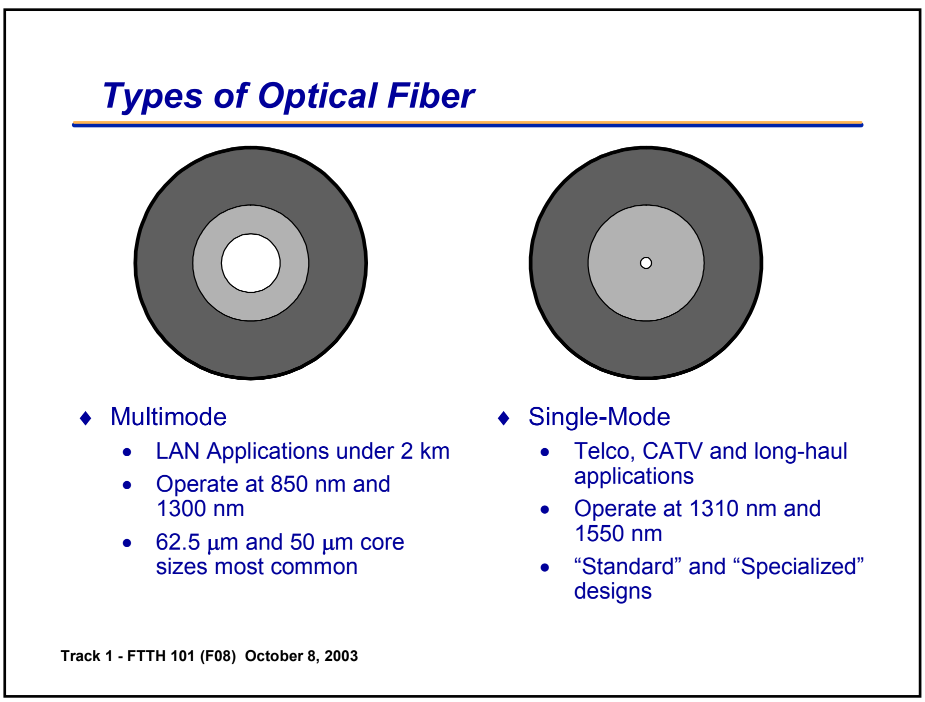

Figure 2: Multimode and Single-Mode Optical Fiber

While the larger core size of multimode optical fibers may give the perception of higher information-carrying capacity than single-mode optical fibers, in fact, the opposite is true. It is not possible to dedicate specific modes to different transmission signals for simultaneous transmission over multimode optical fiber. In practice, the multimode optical fiber carries one transmission signal over multiple pathways simultaneously, and that characteristic results in transmission distance limitations. Over equivalent distances, multimode networks are much more performance limited than comparable single-mode networks. Under typical operating conditions, multimode transmission signals are impacted by attenuation and dispersion (the details of which will be discussed in a later section of this paper) more rapidly than single-mode transmission signals. This combined attenuation and dispersion advantage of single-mode optical fiber allows for more information to be transmitted over longer distances. Accepted industry literature further characterizes the difference between optical fiber types in different telecommunication applications. The "Commercial Building Telecommunications Cabling Standard (TIA/EIA-568-B.1)," published by the Telecommunications Industry Association/Electronic Industries Association (TIA/EIA), recommends a distance limitation of no more than 2000 meters for a multimode optical fiber backbone. TIA/EIA–568-B.1 also recognizes that single-mode optical fiber is capable of 30 times the distance reach of multimode optical fiber.[5] The anticipated system demands, involving distance and data rates, for a typical FTTx application make single-mode optical fiber the logical choice for this type of network.

Access applications are best supported by a single-mode optical fiber solution. The next challenge is to determine which single-mode optical fiber design is best suited for the specific application under consideration. A basic understanding of the optical transmission principles and limitations is necessary to assist in making an informed selection.

Digital Transmission over Single-Mode Optical Fiber

Telecommunications over an optical fiber network are achieved by transmitting a sequence of light pulses between two locations. Electronic devices on either end of the network encode and decode these signals into useful voice, video, or data information. The primary function of the optical fiber is to carry each pulse of light from origin to destination without significantly distorting the signal. As the optical signal propagates along the optical fiber, two limiting effects, attenuation and dispersion, adversely impact the transmission quality and ultimately restrict the maximum reach of the system. These effects can be generally described as follows:

Attenuation Refers to the reduction of signal strength as the light pulse moves down the optical fiber away from the transmitter. Ultra-pure silica glass is an excellent transmission medium; however, it is not perfect. The optical signal will lose some of its strength due to scattering and absorption effects. Scattering is caused when a portion of the optical transmission signal interacts with the glass crystal structure at the atomic level and reflects outside a stable transmission pathway. Absorption is caused when a portion of the optical transmission signal interacts with natural trace impurities (such as water and metal ions) in the core region. The signal loss is typically quantified on a log scale in terms of decibels (abbreviated dB) and normalized to a reference distance, usually a kilometer. The attenuation rate is wavelength dependent and is less than 0.4 dB/km in the most frequently utilized single-mode optical fiber wavelength bands (the 1310 nm and 1550 nm operating bands). A typical spectral attenuation curve showing the attenuation variation versus wavelength is shown in *Figure 3*. Published standards define the bounds of these operating regions. The most common single-mode optical fiber wavelength operating ranges (original or "O Band," 1260 nm to 1360 nm, and the conventional or "C Band," 1530 nm to 1565 nm) are indicated in *Figure 3* for reference. In addition, technological advancements have enabled favorable advancements in the "water peak" attenuation zone is identified in *Figure 3*. The water peak region of the spectral attenuation curve, in the vicinity of 1383 nm, has historically demonstrated elevated attenuation due to hydroxyl ions entrapped in the glass structure. Recently, single-mode optical fiber designs have been released that demonstrate low attenuation performance in the water-peak region of the attenuation curve (refer to the dotted line in the water peak region in *Figure 3*). This level of performance enables a larger percentage of the optical spectrum to be available for telecommunications applications. This enhanced attenuation attribute does not directly benefit operation in the more traditional 1310 nm and 1550 nm operating windows, but it does provide for future increased capacity in the water-peak region of the spectral attenuation curve. The most likely application utilizing this band would be coarse wave division multiplexing (CWDM). For FTTH applications, low attenuation in this operating region would better position the network for future upgrade. The true value of this level of performance depends upon the design/operation priorities of the transmission network under consideration.

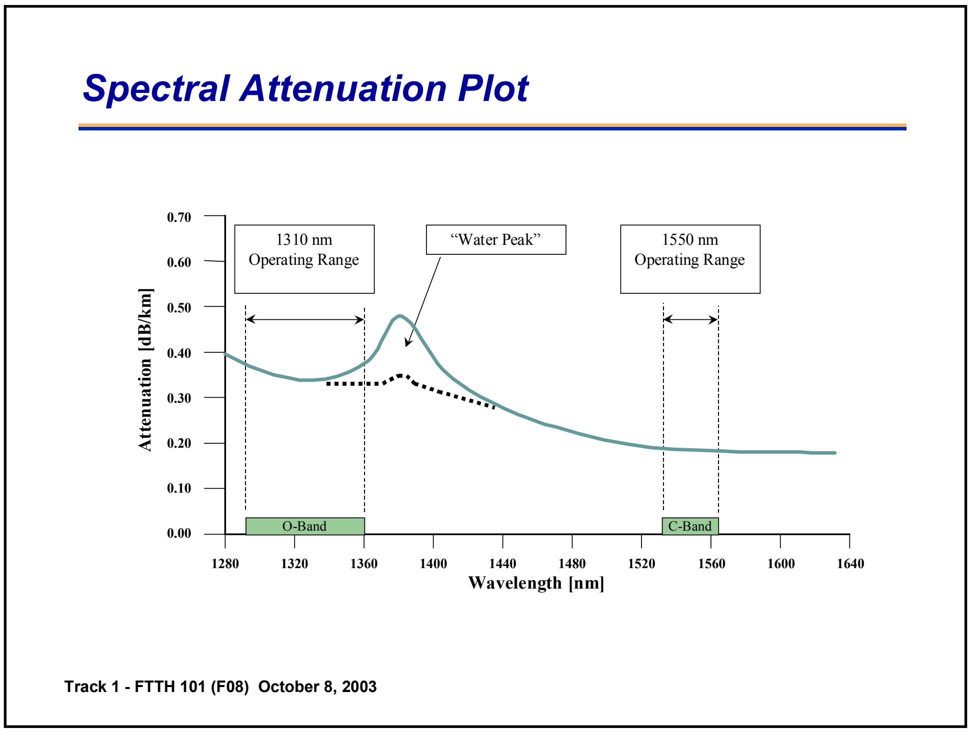

Figure 3: Single-Mode Attenuation Curve

Dispersion

In general, "dispersion" refers to the effect that causes the optical signal to "spread out" as it travels along the optical fiber. In single-mode fiber, a specific type of dispersion termed "chromatic dispersion" is the predominant factor. Chromatic dispersion occurs because each optical pulse is composed of light at more than one discrete wavelength. Ideally, each pulse would be "square" and composed of a single wavelength that is shown in the "Theoretical" example in *Figure 4*. In reality, each pulse is curved and made up of several wavelengths due to limitations in the optical transmitter. This is shown in the "Actual" example in *Figure 4*. Like attenuation, optical transmission speed in the optical fiber is also wavelength dependent. As the light pulse travels down the optical fiber, each wavelength component of the pulse travels at its associated speed. As the transmission distance increases, the different wavelength components separate and the pulse broadens. Since the pulses are transmitted in sequence, the leading edge on one pulse will approach the trailing edge of the pulse ahead of it. This is not a problem until the leading edge of one pulse overtakes the trailing edge of the pulse ahead of it. Once this "overlap" condition occurs then transmission errors start—typically indicated by bit errors. This condition is depicted in the "Impact of Chromatic Dispersion" example in *Figure 4*. It leads to errors at the receiver because individual pulses can no longer be distinguished from one another. The chromatic dispersion is typically quantified in terms of picoseconds (abbreviated as "ps," and 1 ps = 1 x 10^{-12} sec) at each wavelength under consideration. Like attenuation, chromatic dispersion is also normalized to a reference distance, usually a kilometer.

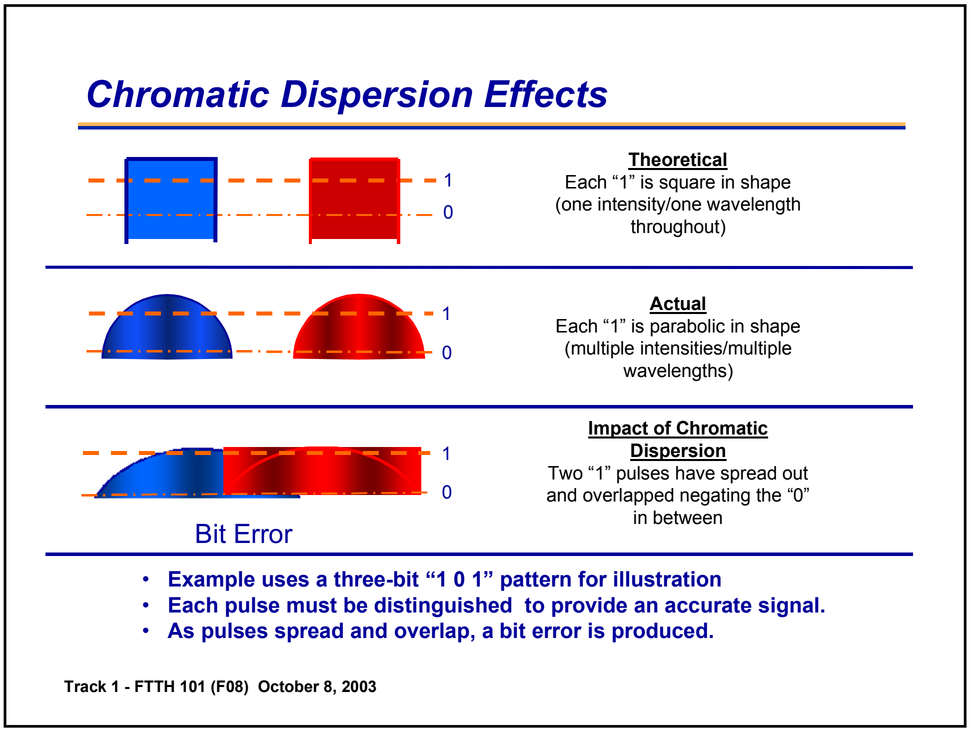

Figure 4: Impact of Chromatic Dispersion on Optical Transmission

The limitations imposed by attenuation and chromatic dispersion have directly influenced the development of a variety of different single-mode optical fibers. Enhancements have been developed that have optimized performance in certain target applications; however, improving the performance of one attribute typically places limitations on others. This results in a situation that requires more detailed knowledge of the optical fiber performance (or system design) to properly match the correct single-mode optical fiber design to each application. A review of the most significant single-mode optical fiber designs is now presented to better prepare system operators.

The most common single-mode optical fiber is technically termed as "dispersion-unshifted." This design has been the telecommunications workhorse for many years and is also known as "standard single-mode fiber." This optical fiber is optimized for use in the 1310 nm operating wavelength range and is also capable of supporting transmission in the 1550 nm operating wavelength range. System operation at 1310 nm was the first single-mode transmission range significantly explored. System operation at 1550 nm evolved because this operating range provided lower signal attenuation than operation at 1310 nm, and therefore longer reach could be achieved. The downside of operating a 1550 nm system on standard single-mode optical fiber was that the chromatic dispersion was more than five times higher than operation at 1310 nm. The low-water-peak attenuation optical fiber previously discussed is also considered a dispersion unshifted design. The chromatic dispersion properties of the low-water-peak optical fiber would be equivalent to the standard single-mode optical fiber previously discussed, and this performance is specified in published standards documents.[6] The introduction of system requirements for extended transmission distances and higher data rates have raised the operational significance of chromatic dispersion performance in the 1550 nm operating range. These requirements led to development efforts to improve chromatic dispersion performance in this operating range.

To address the higher chromatic dispersion observed in standard single-mode optical fibers in the 1550 nm region, a design was developed to shift the low chromatic dispersion performance to coincide with the lower attenuation region in the 1550 nm region. The first versions of this single-mode optical fiber were termed “dispersion-shifted” and required a more complex waveguide design.[7] There were two significant consequences of this design. First, the new waveguide design was more challenging to manufacture, and, second, acceptable performance in the 1310 nm region could not be guaranteed. The advent of wave division multiplexing (WDM) obsoleted this fiber design (due to the impact of multi-wavelength, non-linear effects) and resulted in the follow-on development of a next-generation product, technically termed “non-zero dispersion-shifted” single-mode optical fiber. Like its dispersion-shifted predecessor, the non-zero dispersion-shifted design was a complex waveguide design that did not guarantee acceptable 1310 nm performance.

The non-zero dispersion-shifted single-mode optical fiber best supported long-haul telecommunications carriers because it could be used for 1550 nm WDM transmission over great distances when incorporated with erbium-doped fiber amplifier (EDFA) technology. Typical applications involved point-to-point transmission distances hundreds of kilometers in length. While this is one of the latest developments in optical fiber technology, it is not a good fit for most access applications. The medium/short distances and “tree and branch” style architecture of most access designs do not match up well with the strengths of this optical fiber in typical FTTH applications. The potential for specialized FTTH applications utilizing this optical fiber design may exist and would have to be considered on a case-by-case basis.

As a general consideration, a standard (dispersion-unshifted) single-mode optical fiber will meet the current and anticipated requirements of the majority of FTTx applications today. Selection of a single-mode optical fiber with a low-water-peak attenuation performance enhancement should also be considered as a viable option. The decision process for selection of the specific fiber type to be deployed should address availability, upgradeability, budget, and transmission equipment.

Optical Cable – Facilitating Deployment and Reliable Optical Fiber Operation

Before being deployed in an operational system, the optical fibers are incorporated into a composite structure of materials to minimize the risk of damage or shortened service life. This composite structure is termed an “optical cable.” The designs of optical cables are based upon similar designs for copper communications cables and are expected to have service lifetimes in excess of 20 years. These lifecycle predictions are based upon heat age testing and historical performance of the materials used in copper cable designs and, now that some optical cables have been field deployed for 20 or more years, the predictions are being validated with actual field performance.

The specific materials used in the construction of any particular cable depend on the application being addressed. Optical cables are designed to protect the optical fibers from damage due to the rigors of installation and from the demands of the surrounding environment; however, no single optical cable design is universally superior in all applications. To meet application-specific requirements, outside plant (outdoor), indoor/outdoor cables, and inside plant (indoor) cables must be designed for their intended installation environment. The consequences of optimizing a cable design for outdoor use can prove counterproductive to meeting the requirements for indoor placement and vice versa. For example, the most popular cable jacket material for outdoor use will not pass flame-resistance tests required for placement indoors. In general, optical cables installed in an outdoor environment are exposed to more severe mechanical and environmental conditions than cables installed in the protected, climate-controlled, indoor environment. Outdoor installations (usually lashed aerially, pulled through ducts, or directly buried in the ground), are subjected to combinations of ultraviolet (UV) radiation, standing water, cable-gnawing rodents, extreme temperatures, and other hazards specific to outdoor deployment. Indoor installations (horizontal, riser, or plenum applications) must conform to building codes and be flame retardant. Cables designed for indoor/outdoor applications strike a performance compromise between dedicated indoor and outdoor cables. Indoor-outdoor cable designs provide flexibility for utilizing one cable design but are more expensive and should only be utilized in transition applications to link dedicated outdoor cables with dedicated indoor cables.

The diversity of optical cable products required to support an access FTTH network provides a practical example for the potential complexity of the selection process. A typical FTTH network schematic (regardless if it follows a passive optical network [PON] topology or a point-to-point [P2P] topology) closely resembles this type of design as depicted in *Figure 5*.[8]

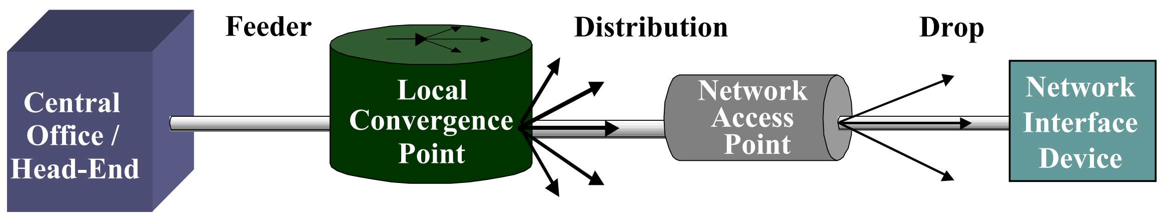

Figure 5: Network Design Example

At a minimum, there are at least three different cable products necessary to construct the physical plant of the network design depicted. First, a higher-fiber-count cable will be required for the “Feeder” and “Distribution” portions of the network to establish the optical fiber routing from the central office/head-end (CO/HE) to the network access point (NAP). Second, a cable containing one or two optical fibers will be required to link the NAP to the network interface device (NID) at the individual subcriber’s premises. Third, an interconnect cable assembly of some type will most likely be required to link patch panels in the CO/HE. Typically, this will be a “jumper” assembly with an optical connector installed on both ends of the cable or a “pigtail” assembly with an optical connector on one end. A typical application for a jumper is to interconnect an optical transmission route by plugging each connectorized end into separate pieces of hardware. A typical application for a pigtail is to establish a link between an unterminated optical fiber and a mechanical patch panel. The free end of the pigtail is fusion spliced to the optical fiber, and the connectorized end is plugged into the patch panel to complete the connection. Each of these cable products requires a different design. Several design options are available for each application type.

Similar to optical fiber, the maturity of the optical telecommunications industry has directly influenced the development of a variety of different optical cable designs. Enhancements, features, and benefits have been developed that have optimized performance in certain target applications; however, improving the performance of one attribute typically places limitations on others. Again, this results in a situation that requires more detailed knowledge to properly match the correct optical cable design to each application. A review of several significant optical cable design features is now presented to prepare system operators for selecting the right product for their specific application.

Optical Cable Design Considerations

The optical cable serves two functional roles vital to the deployment and survivability of the optical fiber in the field. First, the cable structure must provide an easily interpreted organizational element that facilitates positive identification of each optical fiber in the cable. This is particularly important in higher-fiber-count cables to ensure each optical fiber route is correctly connected.

Second, the cable structure provides protection for the optical fibers from mechanical and environmental forces created by installation, prevailing weather conditions, or unintentional man-made conditions (accidents) that could damage the optical fiber.

Some of the most significant basic cable design elements include the following:

1. Identification and organization
2. Tensile strength
3. Resistance to mechanical stress (bend, impact, compression, twist)
4. Temperature sensitivity
5. Waterblocking protection (outside applications)
6. Resistance to outdoor environmental hazards – ultraviolet (UV) radiation, rodents, chemicals, and lightning (outside applications)
7. Flame retardance (inside applications)

The first design element to be addressed, identification and organization, provides the ability to positively identify one optical fiber from another within any cable that contains multiple optical fibers. There are a variety of methods currently employed. Some of the more common methods are illustrated in *Figure 6*.

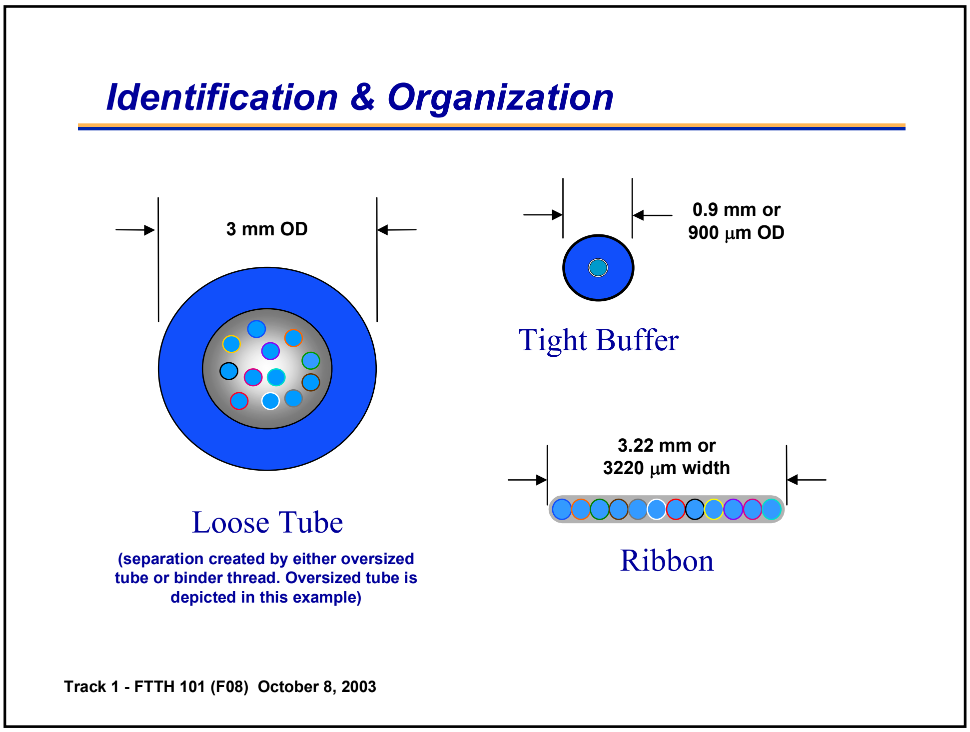

Figure 6: Identification Methods

To reduce the complexity of this process, the total number of optical fibers contained within a cable is subdivided into unique and separate subunits within the optical cable—most commonly 12 optical fibers per group in outside plant optical cables. The physical separation of each group of optical fibers is achieved by a variety of methods. The three most common identification methods for outside plant cables involve placing the group of optical fibers in a color-coded, oversized tube, wrapping the group of optical fibers with a color-coded binder thread, or linking the group of optical fibers together in a planar array commonly called a “ribbon.” A print statement on the ribbon itself typically differentiates individual optical fiber ribbons from one another. The optical fibers in dedicated inside plant cables typically have a layer of plastic that is extruded over individual optical fibers. The plastic layer is colored for identification purposes, and the thickness of the plastic layer is optimized to facilitate connectorization of the end of the cable. This design element of inside plant cables causes individual optical fibers to be larger in size than individual optical fibers in their outside plant counterparts. This is usually not an issue because typical applications for indoor cables do not require high fiber counts. *Figure 6* provides a relative size comparison for consideration.

Standards are published to facilitate identification of individual subgroups or individual optical fibers. The primary method of optical fiber identification is color-coding. The industry-accepted color-code sequence is defined in "Optical Fiber Cable Color Coding (TIA/EIA-598-A)."[9] A colored ink or thermoplastic material is applied to the outer surface of the optical fiber. The basic 12-color sequence described in the standard is summarized in *Figure 7*.

Position Number	Color	Abbreviation
1	Blue	BL
2	Orange	OR
3	Green	GR
4	Brown	BR
5	Slate	SL
6	White	WH
7	Red	RD
8	Black	BK
9	Yellow	YL
10	Violet	VI
11	Rose	RS
12	Aqua	AQ

Figure 7: Optical Fiber Cable Color Coding

The next design element is tensile strength. The cable will most commonly be exposed to tensile loading when it is installed as it is unreeled and pulled into position by hand or motorized winch. Tensile protection is accomplished in the cable by using one or more types of strength elements. These can be aramid yarn, fiberglass rovings, or rods made of steel or glass reinforced plastic (GRP). These strength elements are placed along the longitudinal axis of the cable and are designed to support tensile loads applied to the cable to prevent the optical fibers from being exposed to the excessive strain. The GRP or steel rods also serve an anti-buckling function as cable materials contract longitudinally in cold temperatures.

The next design element is resistance to mechanical stresses. The optical cable must protect the optical fibers contained from a variety of mechanical stresses that may be encountered during installation and over the operating life of the network. External forces can apply flexure and twisting to the cable as it is pulled into place. During its service life, the cable can be exposed to crush or impact forces due to falling tree limbs or construction-related activities. Jacket materials with excellent durability properties, such as polyethylene (PE), are selected for use in outdoor applications. Additional impact and crush resistance can be included in a cable design by the addition of a steel tape armoring wrapped around the entire length of the cable. The arrangement, material selected, and thickness of the various cable components are designed to address these kinds of stress loading events.

Correct operation under different temperature conditions is also a significant design element. Outside plant applications have higher and lower temperature extremes than inside plant applications. The design of the cable must take into account the difference in expansion and contraction rates of the different cable components to prevent induced stress being applied to the optical fibers. Again, the arrangement, materials selected, and thickness of the various cable components are designed to address these kinds of stress loading events. In some cases, a specific design element has opposite effects on mechanical and temperature performance. Material thickness is one such example. Increasing thickness will provide increased mechanical strength; however, thicker materials are more susceptible to inducing expansion/contraction stresses under changing temperature conditions. Ultimately, the thickness must be optimized for both properties.

Application-specific design properties are also very important to the long-term survivability potential of the cable design. For outside plant applications, cables may be exposed to a variety of hazards, such as moisture and chemicals in underground applications, UV radiation from exposure to sunlight in aerial applications, and attack from rodents in direct-buried applications. Lightning can impact cables with conductive elements in either above- or below-ground installation conditions. For inside plant applications, cables must meet fire-code requirements imposed for the buildings.

Waterblocking protection is addressed by incorporating a material into the cable structure that inhibits the ability of a fluid to penetrate or travel inside the cable core. Today, the use of dry waterblocking technology is common. A "super-absorbent" material is inpregnated onto tapes and yarns and placed along the longitudinal axis of the cable. When exposed to water, the super-absorbent material holds the water in place by swelling in size and acting as a barrier to prevent moisture ingress into the cable. The dry waterblocking technology also simplifies craft practices because it reduces preparation time when working with the cable.[10] The use of dry waterblocking technology significantly reduces the amount of gel compound that was previously used for waterblocking protection. The process to remove this gel from the cable internal components is a much more time-consuming process than simply cutting out a dry tape or yarn.

A durable outer jacket material is utilized in outside plant applications to address chemical resistance and UV resistance concerns. Outside plant cables typically use a medium density polyethylene (MDPE) material for the outer jacket. MDPE provides excellent chemical resistance and sufficient material flexibility to facilitate cable routing for installation conditions that contain bends or changes in elevation. Carbon black is added to the MDPE to provide protection from UV exposure. The carbon black acts as a UV "reflector" and prevents the UV radiation from being absorbed into the MDPE and breaking it down. The combined effectiveness of the MDPE with carbon black additive results in proven performance in greater than 20-year service life.

Direct-buried optical cables may be damaged by burrowing rodents such as the pocket gopher, and aerial cables may be damaged by squirrels.[11] The primary damage mechanism occurs as these rodents use the cable for "dental maintenance" of their front teeth. The industry-accepted practice involving cable design to provide protection from this hazard is twofold. The first is to increase the cable's outer diameter so the rodent cannot place the cable inside its mouth, and the second is to incorporate one or more layers of metallic armor into the cable construction. The addition of armor serves both purposes and is the most common method used. Corrugated steel tape armor is the most common type of material used and is typically corrugated, then wrapped around the longitudinal axis of the cable and covered with an MDPE jacket.[12]

Lightning can cause damage in both aerial and underground installations. Cables with conductive elements (such as corrugated steel armor) may be adversely affected should a lightning strike occur in close proximity to the cable. The potential for damage to underground cables is dependent upon the conductivity of the surrounding terrain and frequency of ground strikes in the area.[13] Under "favorable" conditions, the outer jacket of the cable can be breeched due to arcing between the ground and the cable armor. This sets up the precursor for premature cable failure.

Flame resistance is a leading design element for inside plant applications. This design element highlights the fact that there is no "universal" cable design for all applications. The MDPE material, with all its excellent properties previously mentioned, is not flame retardant. Polyvinylchloride (PVC) is a widely used jacket material for inside plant applications; however, it is not ideal for outside plant applications. Optimizing this type of performance typically requires special material selection and testing/certification by an approved agency.

Standardized testing for these design considerations exists and is documented for dedicated outdoor cables, dedicated indoor cables, and indoor-outdoor cables.[14, 15, 16] The design considerations previously listed provide the system operator with an appreciation of the considerations necessary to select the proper cable for their application. In any case, the best approach is to begin by thoroughly understanding the challenges of the application at hand, establishing the priority of each design aspect, and selecting a cable product that matches up best with those priorities.

Cable Designs for Access FTTH Applications

To demonstrate the process for selecting cable designs, let's return to the Network Design Schematic in *Figure 5*. As previously stated, at a minimum, there will be a requirement for a multi-fiber optical cable, an optical cable for drop applications, and an interconnect cable (most likely a cable assembly with factory installed connector[s]).

First, consider the multi-fiber optical cable. Most FTTH network designs do not involve high-fiber-count (more than 144 fibers) optical cables. Optical cables utilizing optical ribbons are primarily intended for applications that require very high fiber counts. There are products commercially available that place as many as 864 optical fibers in the same cable. High fiber counts typically go hand in hand with "home run" style architectures that are currently not cost-effective with the majority of FTTH deployments. A loose tube cable containing individual single-mode optical fibers is more than capable of meeting current needs as well as positioning the network for future growth. A representative design is shown in *Figure 8*.

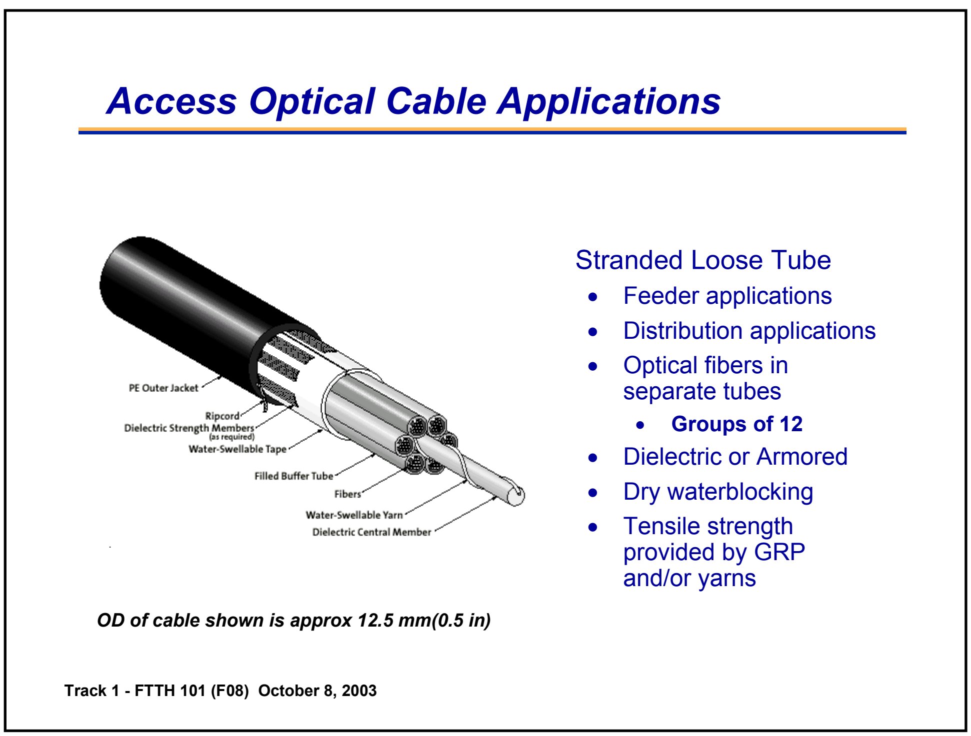

Figure 8: Example of Feeder/Distribution Optical Cable

This cable design, called a "stranded loose tube" cable, provides ease of identification of individual optical fibers as they are grouped in color-coded, 12-fiber subunits. Tensile strength is provided by dielectric strength elements and a dielectric central member. This design has been proven in the field and has been successfully deployed and operated for years in different outside plant environments. It utilizes dry waterblocking technology to protect against the ingress of unwanted moisture and, as an option, can incorporate steel tape armor for added mechanical strength. It can be deployed aerially, be directly buried in the ground, or be pulled into conduit. This design meets all design elements previously discussed for feeder/distribution applications in the outside plant environment.

Now, consider the drop cable application. Unlike the feeder/distribution functional requirements, this application requires a very low optical fiber count—typically one or two optical fibers. Neither a ribbon cable design nor a stranded loose tube design are practical for this application; both designs are simply too big and too costly to serve in this function. Some of the key design elements for this type of optical cable are a smaller outer diameter and capability to support both direct burial and aerial self-supported installations. Also, unlike the feeder/distribution application, drop cables are typically deployed in short lengths (less than 150 feet) and may be treated as a "consumable" material that would be replaced rather than repaired. It is also desirable for these optical fiber drop cables to readily integrate with existing installation hardware and established installation practices associated with copper drop cables. Another consideration related to its copper predecessors occurs if the optical fiber drop cable includes any metal subcomponents. Since these cables are typically located in close proximity to physical structures, provisions for grounding and bonding any electrically conductive elements within the cable structure must also be addressed. Specific requirements typically vary and usually depend on the local building codes of the specific region. These design elements alone create different application requirements and alter selection requirements from those pertinent to the feeder/distribution applications previously discussed. Two representative designs for an optical fiber drop cable are shown in *Figure 9* and *Figure 10*.

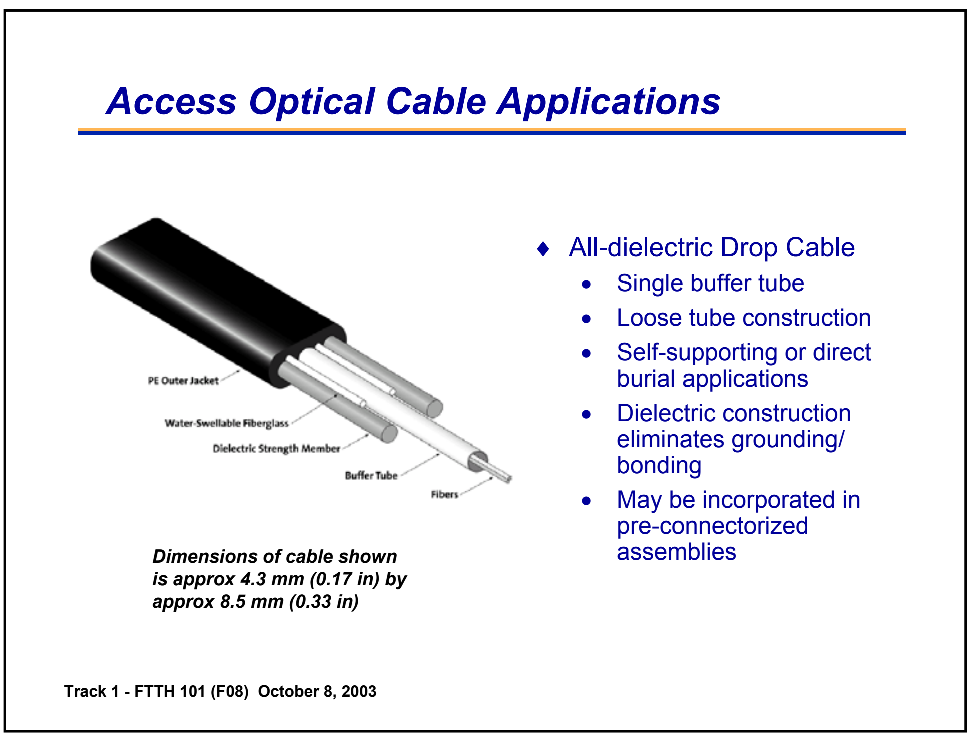

Figure 9: Example of Optical Drop Cable (All-Dielectric)

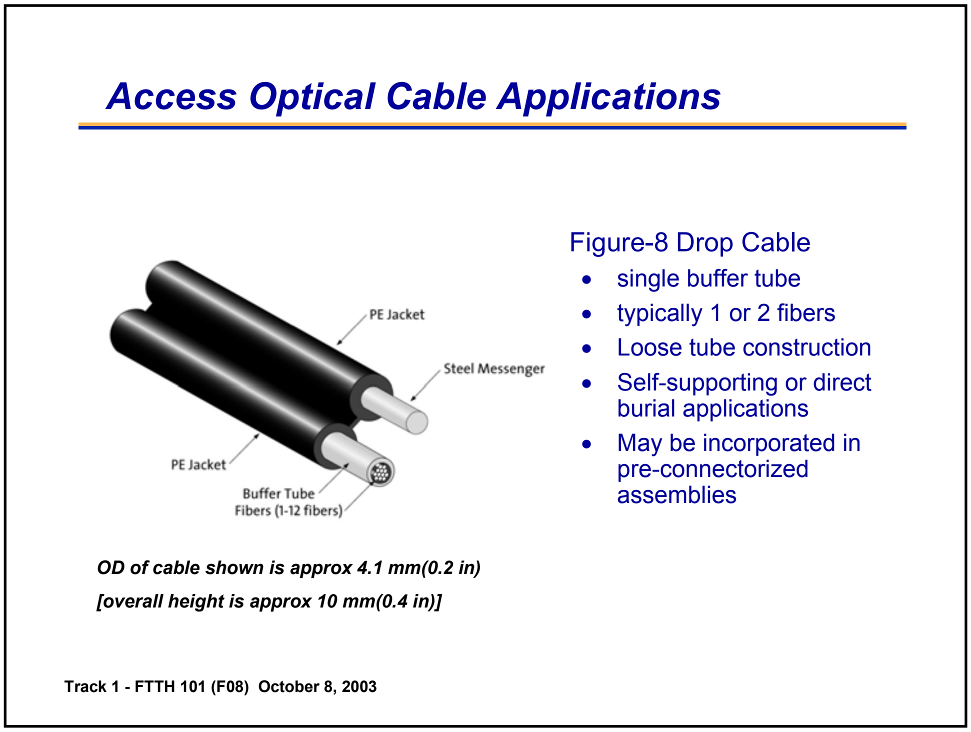

Figure 10: Example of Optical Drop Cable (Integral Steel Messenger)

The cable designs shown in *Figure 9* and *Figure 10*, both termed "optical drop" cables, provide a simple method to route one or two optical fibers to the customer premises. This design provides one oversized tube to house and protect the optical fiber(s). The steel messenger wire that is connected to the cable by a web of plastic jacket material provides tensile strength. This design fulfills the requirement for a small, cost-effective cable that is only needed to span relatively short distances. It can be deployed aerially and is self supporting. Also it can be directly buried in the ground should that application be necessary. This design meets all design elements previously discussed for drop cable applications in the outside plant environment.

The last application, for an interconnect cable assembly product, requires a different cable design still. Like the drop application, this application requires a very low optical fiber count—typically one optical fiber. Unlike the drop application, this application requires even shorter lengths and a focus on facilitating connectorization of the optical fiber. Neither a ribbon cable design nor a loose tube design supports this application well; therefore, a tight-buffered cable is typically chosen for this application. When used in the CO/HE as a patch cord, this product must meet flame-rating requirements dictated by local building codes. That is why this product utilizes a PVC outer sheath instead of the MDPE sheath utilized by the feeder/distribution and drop cable products. Again, the specific design elements pertinent to the required functionality create different application requirements and alter selection requirements. A representative design is shown in *Figure 11*.

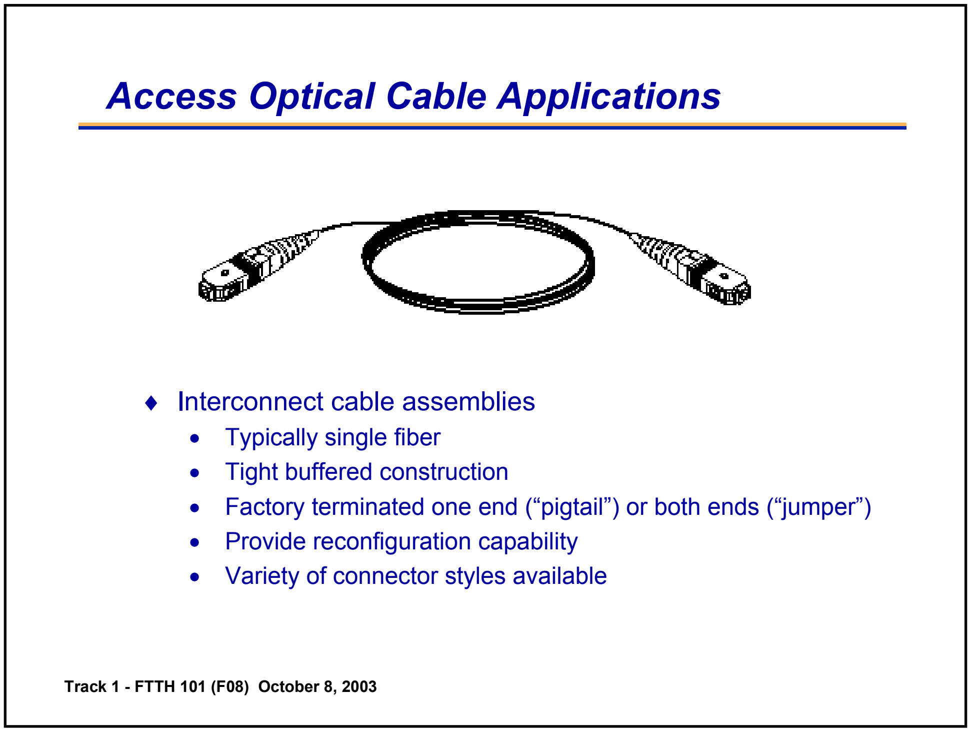

Figure 11: Example of Interconnect Cable Assembly

This product design, termed an "interconnect cable assembly," incorporates a tight-buffered optical cable and provides for a simple solution to complete optical fiber routes using mechanical connectors. These assemblies are commonly used to connect patch panels in the CO/HE and provide testing and reconfiguration capability. Short pigtail assemblies, with a connector on one end, can be fusion spliced to terminate cable ends downstream of the CO/HE. In short lengths, these units will perform properly in the outside plant when installed using the manufacturer's recommendations. This design fulfills the requirement for a small, easily connectorized cable solution that is only needed to span short distances.

Conclusion – Knowledge Is Power

Choosing the correct solution from the variety of optical telecommunication products available today can be a daunting task. The industry has matured, resulting in both general and specialized products for the system designer's "toolbag." The FTTH deployment example discussed in this paper shows that the newest optical fiber product is not necessarily the best for the application under consideration. The key to success is understanding the application at hand and matching products with the best performance for those applications. In general, the performance requirements for most FTTH access telecommunication applications can be met using standard single-mode optical fiber incorporated in proven cable designs.

The basic "big picture" considerations can be applied universally. For optical fiber and optical cable, they can be summarized as follows.

To select the proper optical fiber, at a minimum, the system designer must understand the following:

1. The intended data rate
2. The maximum point-to-point transmission distance

3. The transmission wavelength range(s) to be employed
4. Whether digital signals, analog signals, or a combination of the two will be carried on the network
5. The anticipated system upgrade plan

To select the proper optical cable, at a minimum, the system designer must understand the following:

1. The maximum number of fibers required in a single cable
2. The type of installation (aerial, direct buried, duct, or indoor)
3. The expected mechanical and environmental stress loading on the cable plant once installed
4. The product "craft friendliness" that directly impacts deployment efficency/speed of deployment.

Different optical fiber and optical cable designs offer distinct advantages when they are used in the applications for which they are intended. Careful consideration of system operating parameters, handling and installation requirements, and resistance to potential mechanical and environmental hazards are vital to the long-term reliability of any FTTH network. When properly selected, system operators will ultimately succeed in "lighting the way to the home."

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