Deploying Long Distance L-Band on Existing Fiber Infrastructure

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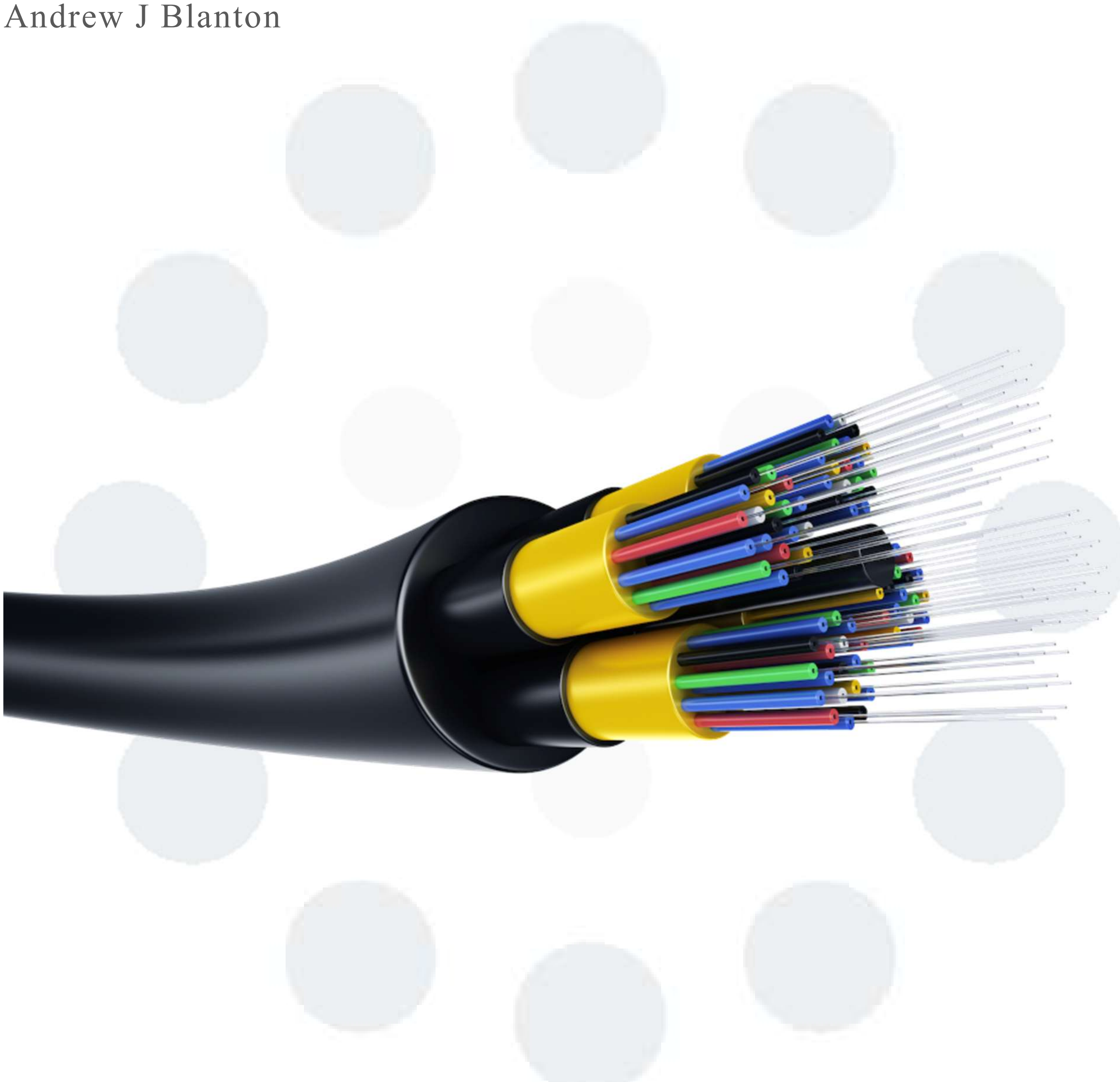

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Summary

The importance of the Internet and data transmission has grown exponentially in the modern era. The Internet is the backbone that connects the global community and is vital for many aspects of life. Large corporations, such as banks, hospitals, government facilities, cell phone providers, etc., require long distance private networks for critical operations. The networks that connect these homes and businesses are commonly referred to as Middle Mile Networks or MMN's. These networks are unique because they pool substantial amounts of data from remote areas and transmit it over long distances, sometimes hundreds of miles. Accomplishing this efficiently and reliably requires high end electronics, a hardened and robust medium (such as fiber optic cable), and specially trained engineers and operators. Nationally the conversation regarding access to the Internet, also known as broadband, has migrated from a want to a need. In the Infrastructure Investment and Jobs Act (IIJA) congress allocated approximately $65 billion for broadband with $1 billion going to MMN's and over $42 billion going to last mile providers (Pub. L. 117-58, 2021). Millions of new users trying to transmit data globally will require upgrades to the MMN's technology and physical infrastructure. An analogy would be trying to introduce millions of new drivers to the current Interstate highway system, it simply is not engineered for that kind of growth and would require obvious and significant improvements, the same is true for MMN's. While there are many upgrades that need to happen, this paper will focus on the specific challenge of deploying long distance L-band on existing fiber infrastructure.

Background

MMN's serve two distinct types of customers with the common goal of transmitting substantial amounts of data over long distances. The first type of customer is a last mile provider, or Internet Service Provider (ISP), which serves many end customers, collects the data locally and desires to transmit it to a large interconnection point sometimes hundreds of miles away. These large interconnection points or telecommunications hotels are secure buildings that allow companies to connect to each other and exchange data, this is also where the on/off ramp for the internet is located (PCMag, n.d.). The second type of customer is a large company that needs to securely and privately transmit data over a long distance. This data may connect business locations, pool customer data at centrally located points, or connect to a public telecommunications hotel. Examples of this type of customer include hospitals transmitting patient data, banks transferring money, courts storing case information, and cell phone companies connecting customer calls. Much of this data is considered critical and requires maximum efficiency and reliability. Achieving these standards requires physical path redundancy, sophisticated electronics, and large bandwidth data tunnels. In order for MMN's to meet the added demands and maintain existing services many will look at deploying electronics that open additional light waves. Current market projections indicate a significant increase in 400+ Gigabit per second (Gbps) port speed devices. The graph below highlights the increased demand for port speeds from 400 Gbps to greater than 3.2 Terabit per second (Tbps) in the data center environment. These demands driven by Artificial Intelligence (AI) and increased global connectivity will require MMN transport (Weckel, A & 650 Group, 2025).

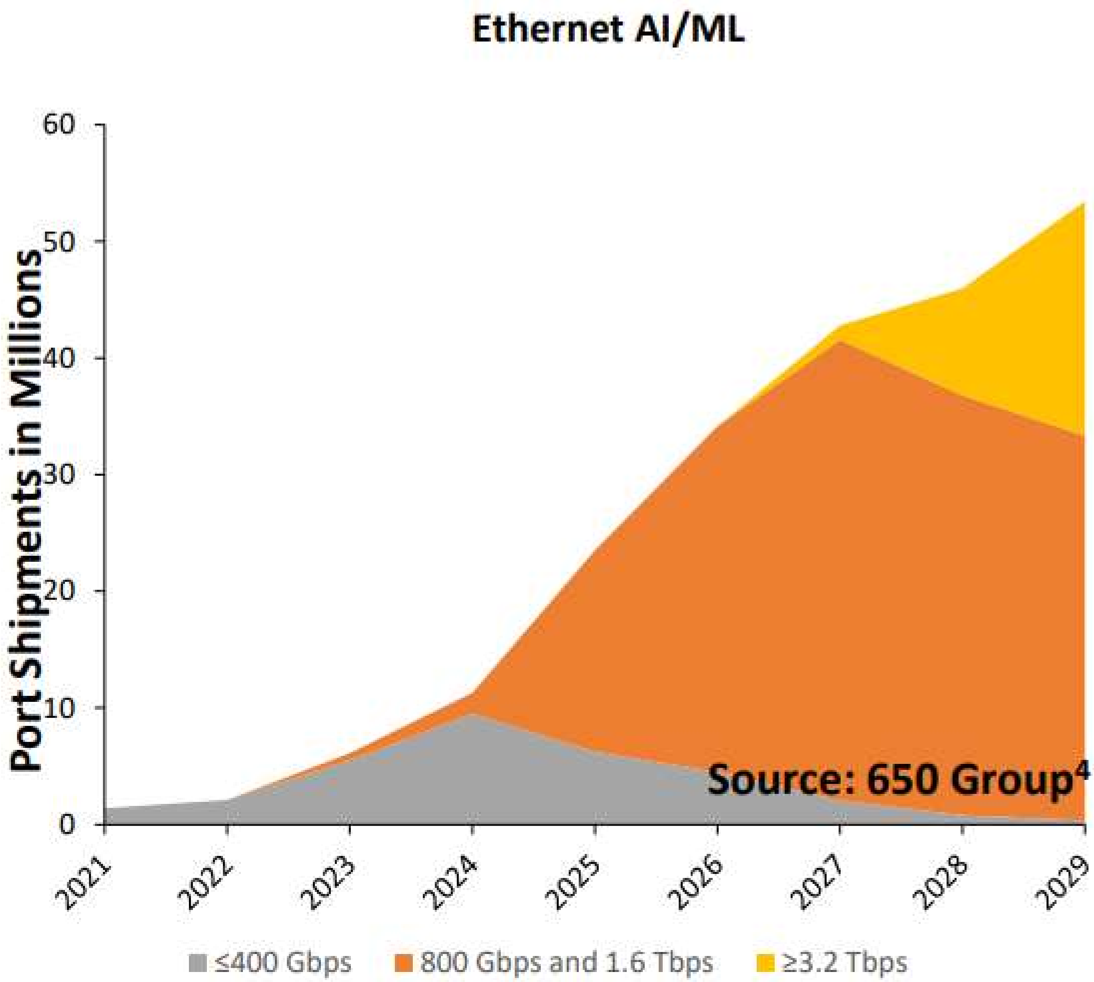

Figure 1: (Weckel, A & 650 Group, 2025)

To accommodate the higher bandwidth needs current MMN operators can deploy L-Band (1565 – 1625 nanometer (nm)) optics over top their existing C-Band (1530 – 1565 nm) networks (Casey, 2023). MMN operators use Dense Wave Division Multiplexing (DWDM) technology that utilizes the aforementioned wavelengths to combine multiple signals onto a single fiber and then demultiplex, or separate, the signals on the other end (Ribbon, n.d.).

Problem Statement

MMN operators deploying L-band across existing fiber optic networks will experience a new set of constraints associated with fiber characteristics that were not as prevalent for the current network. Operators have deployed networks using 1310nm and 1550nm for over 40 years (Binamira, A 2025) and the challenges are well known. L-band experiences greater effects from macro bending, ramen scattering, and other constraints and these will be explored in this paper.

Technical Foundation

A basic understanding of fiber optic transmission principles will assist in understanding the specific issues associated with L-band deployment. The concepts covered are fiber optic transmission, modulation, and molecular scattering/absorption.

Transmission

Fiber optic cables are constructed of silica glass stretched until it is similar in size to a human hair. This is surrounded by another layer of glass known as the cladding. Finally, the cable has multiple layers of various protective coatings (CXtec, 2023).

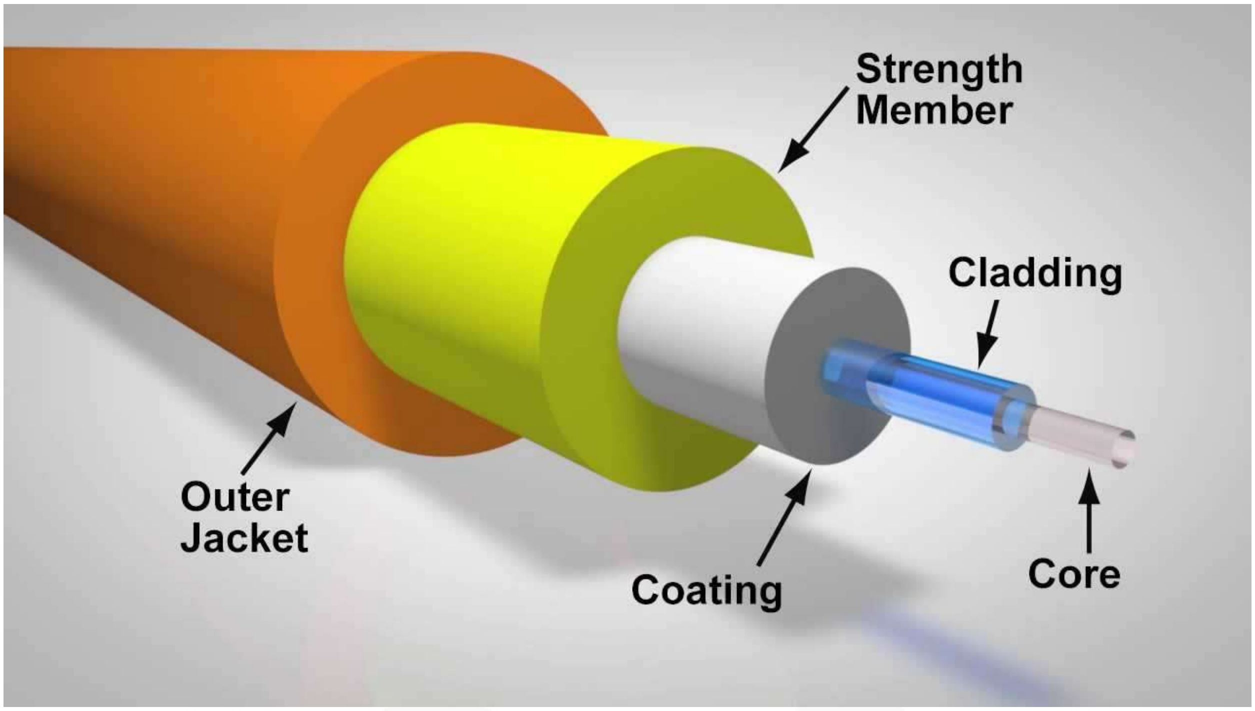

Figure 2: (Thorlabs, n.d.)

The most common fiber used to transmit data over long distances, excluding underwater marine operations, is compliant with ITU-T standard G.652, accounting for nearly 95% of all currently deployed fiber optic cables. ITU-T standard G.652.A was released in 1984 and featured a water peak at 1383nm, this was due to the presence of hydroxyl ions as a result of the manufacturing process. The water peak caused signal loss at 1383 nm to such a degree that no usable transmission could be accomplished at that specific wavelength. By 2003, the latest standard G.652.D was released and no longer included the water peak at 1383nm. The graph below highlights the water peak and shows the natural attenuation of different wavelengths (*G.652D fiber*, 2025). Attenuation is a loss in signal strength measured in decibels per kilometer (dB/km). If signal loss is too great, communication between either end is broken (GeeksforGeeks, 2025).

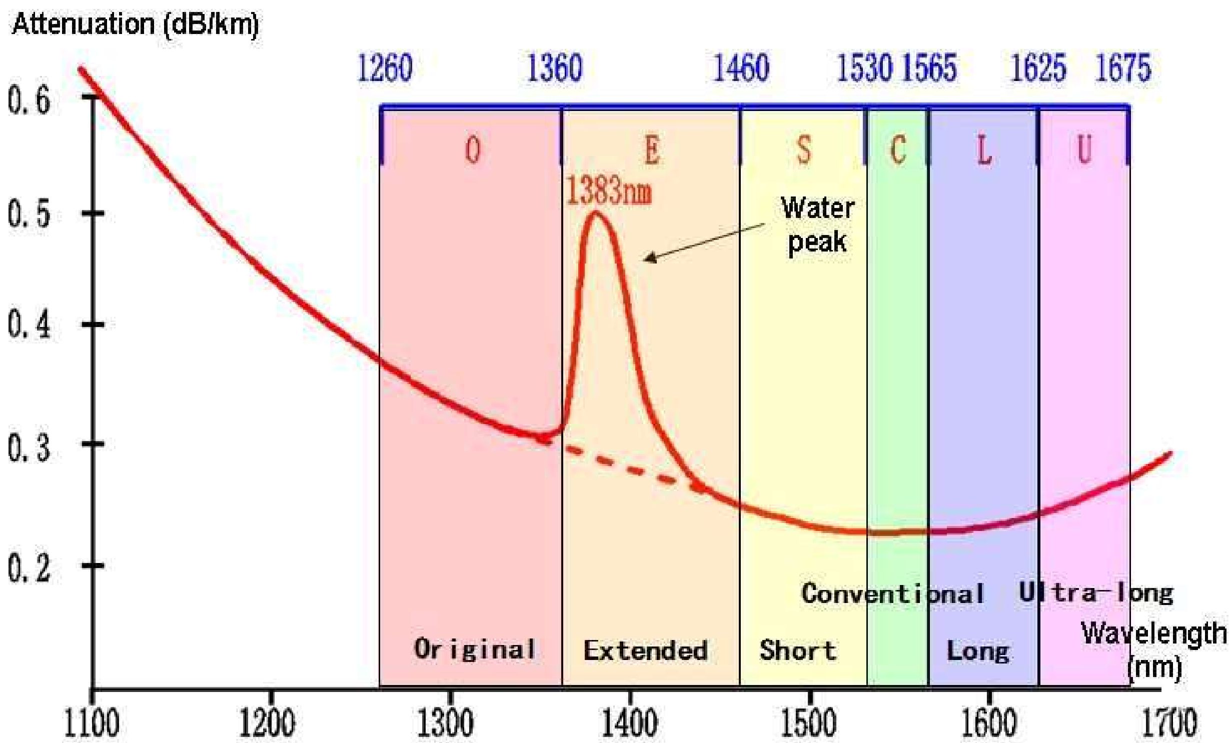

Figure 3: (G.652D fiber, 2025)

Transmitting data across fiber requires the use of photons or light, an electromagnetic wave. These waves are transmitted through the core with minimal loss through the principle of Total Internal Reflection (TIR). TIR occurs due to the interaction of the light as it travels between the core and the cladding. Specifically, TIR is when the incidence angle meets or exceeds the critical angle required to push the refractive angle greater than or equal to 90 degrees. Refraction is the bending of light, more specifically, it is a directional path change of a light wave due to interference by a material which causes a velocity change in the wave. Every material has a calculable index of refraction for a light wave determined by dividing the speed of light c (3×10^8 m/s) by the measured speed the light wave travels through the material. For materials that allow faster light wave propagation the refractive index is lower. The refractive index equation is n = c/v, where n equals the refractive index, c equals the speed of light in a vacuum, and v equals the measured speed of light through the material in question. When light passes through two different materials the resultant light is both reflected and refracted (Libretexts, 2025). An example would be standing over a pond of water and looking at a fish swimming in the water. The fish appears to be in a different physical location than it actually is due to refraction, which happens because the light passes through both the water and the air, having different refractive indices. The resulting refraction can be manipulated based on the two materials chosen and their respective refractive indices. A light traveling from a material with a higher index of refraction to a material with a lower index of refraction will cause the resultant light to travel at an angle greater than the incident angle (original angle) and the opposite is true, figure 1 depicts this principle graphically.

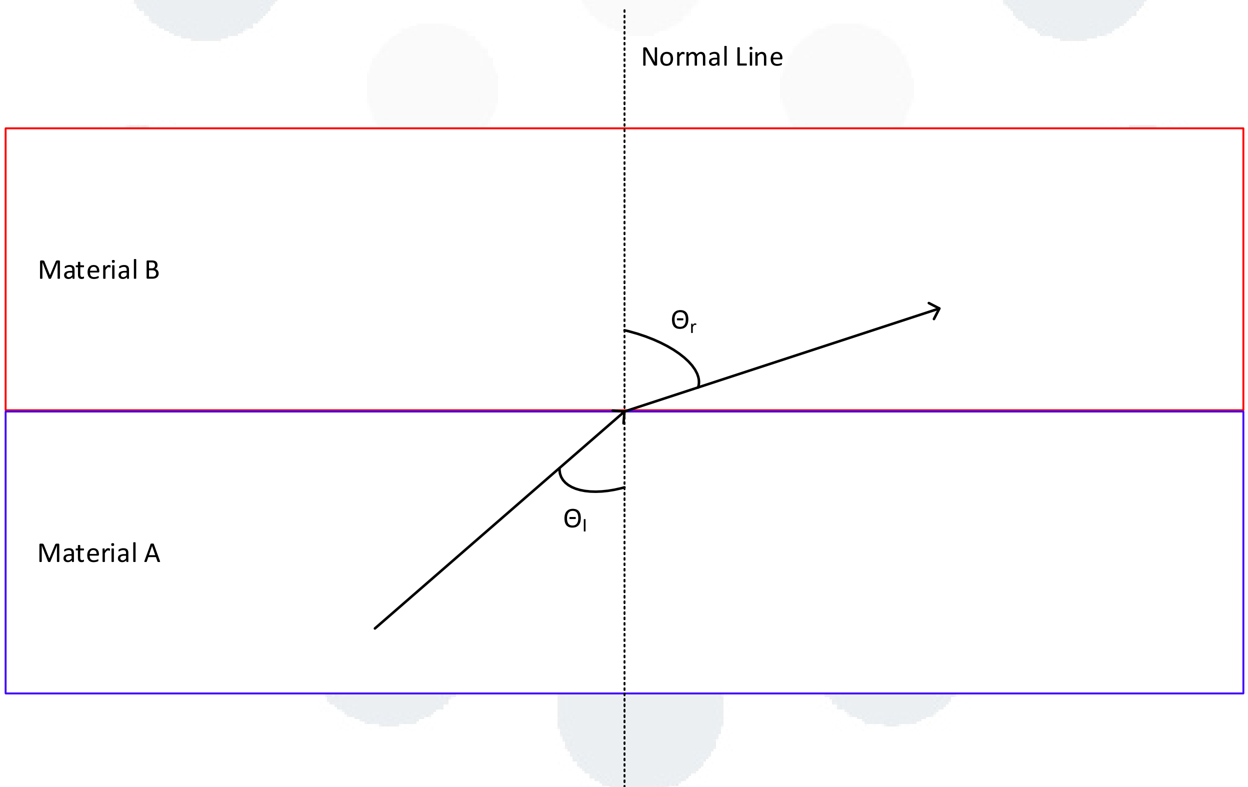

Figure 4: Depicts a refractive angle greater than the incident angle due to a lower refractive index of Material B than Material A

The resultant refractive angle is calculated using Snell's Law. Snell's Law states that $n1\sin\Theta1 = n2\sin\Theta2$, where n1 equals the index of refraction of material 1, Θ1 equals the incidence angle or angle of the light wave propagating material 1 in relation to the normal line, n2 equals the refractive index of material 2, and Θ2 equals the refractive angle in relation to the normal line (Libretexts, 2025). By rotating the incident and refractive light waves respective to each other the keen observer will note there is a point when the incident wave angle is still possible, but the refracted wave exceeds 90 degrees from the normal line and is reflected into the incident material, thus Total Internal Reflection.

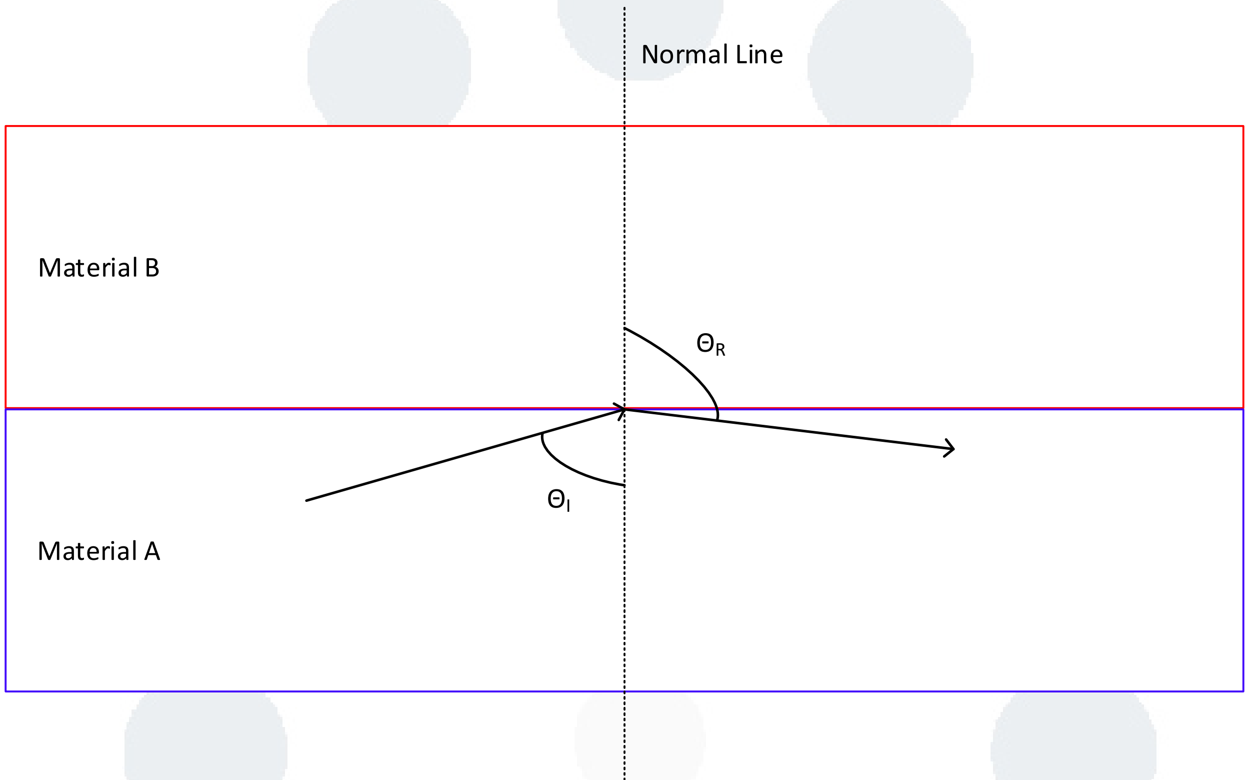

Figure 5: Incident and resultant waves depicting Total Internal Reflection.

In fiber optic cabling TIR is achieved by using a core material with a higher refractive index than the cladding material that surrounds it. In the above figure 2 the core is represented by material A, and the cladding is represented by material B. TIR allows the light wave with the data encoded in it to travel along the path without exiting the fiber. The angle when this first begins to occur is called the critical angle and is defined by the refractive angle equaling 90 degrees to the normal line. For a signal to be transmitted to the other side the optic at one end must launch the light wave at or greater than the critical angle.

Modulation

For discernible transmission of data to occur the devices on either end of the fiber optic cable must agree upon and be able to read ones and zeros, or bits, from the beam of light, this is done by manipulating or modulating the wave. The sinusoidal wave equation, $y(x,t) = A\sin(kx - \omega t + \varphi)$, identifies three of the four variables that can be modulated to allow identification of bits on either side (Libretexts, 2020).

- Amplitude, A
- Frequency, f ($f = \omega/k$)
- Phase, φ

Polarization is the fourth variable and will be discussed later, the other variables in the equation are:

- Height, y
- Distance, x
- Time, t
- Angular Frequency, ω

The simplest form of modulation is On/Off keying or Amplitude Shift Keying (ASK). At every agreed upon moment in time the detector records a 1 or 0 depending if the light is on or off, or if the wave is at maximum amplitude or not. Figure 5 shows a signal that is either on or off, while Figure 6 shows an example where the amplitude is shifted down slightly (Rhode & Schwarz, 2020 UASK). The slight shift in Figure 6 requires less power and time but has a much smaller margin for error. The contrast of effects requires a delicate balance that engineers and designers are tasked with optimizing.

Figure 5: On/Off keying example where amplitude 100 is on and 0 is off (Rhodes & Schwarz, 2020)

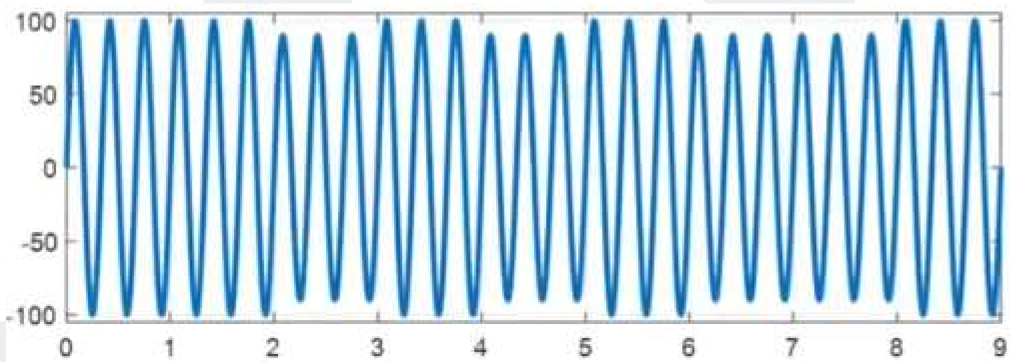

Figure 6: Amplitude keying example where 100 is on and 90 is off (Rhodes & Schwarz, 2020)

Frequency Shift Keying (FSK) is similar to ASK but is not commonly used for MMN's because it is not optimal in high bandwidth environments (Rhode & Schwarz, 2020 UFSK).

A phase change in a wave occurs when the wave is shifted linearly along the time axis and is expressed as degrees (Captain Physics, 2024). The figure below shows a wave Ch1 in red and the resultant wave Ch2 in blue if it is 90° (left) and 180° (right) out of phase.

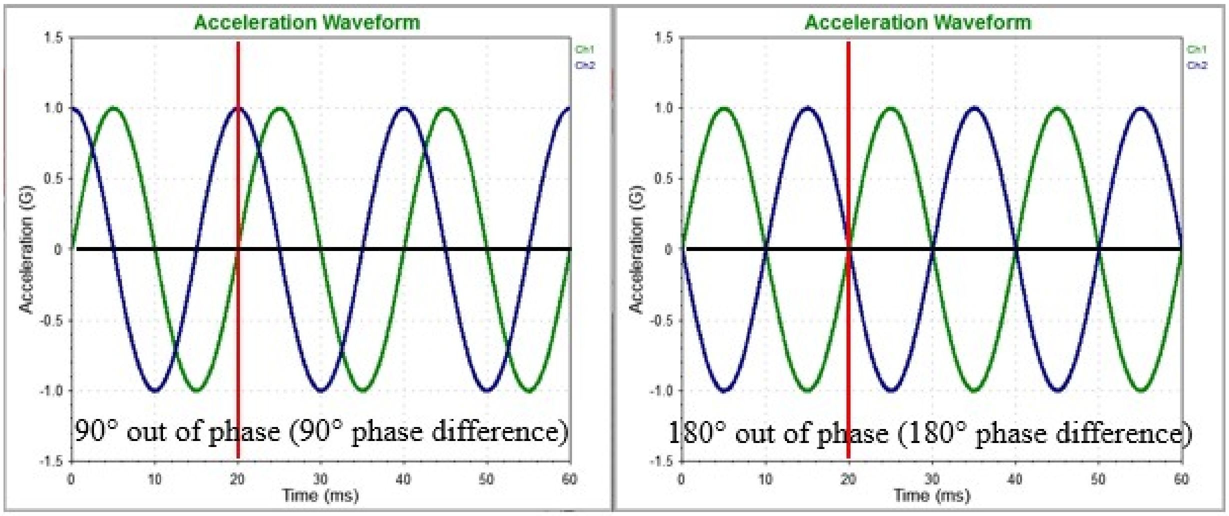

Figure 7: (VRU, 2023)

The detector will see the shift in phase and record a 1 for that bit, conversely if there is no change in phase it will record a 0, this is known as Phase Shift Keying (PSK). PSK is considered superior to ASK in MMN networks because it is less sensitive to noise and is more efficient resulting in higher bandwidth capabilities. Noise is a general term to describe a multitude of changes that occur to a wave as it traverses fiber, one of those being attenuation or a degradation of the amplitude of the wave. If the transmitting end sends a signal at a specified amplitude the receiving end will have to be able to discern what that amplitude is after traveling down the fiber to correctly determine if the signal is meant to be a 1 or a 0. Because PSK does not rely on the received amplitude to discern the signal, attenuation plays less of a role (*Phase Shift Keying (PSK) – BPSK, QPSK & Variants*, n.d.).

The aforementioned PSK is actually known as Binary PSK (BPSK) because it results in two possible answers, a more advanced form of PSK is known as Quadrature PSK (QPSK). QPSK shifts the wave into one of four phases resulting in four possible states or answers. The resultant four states each represent a pair of bits because that is the maximum possible combinations of two bits (Keim 2016).

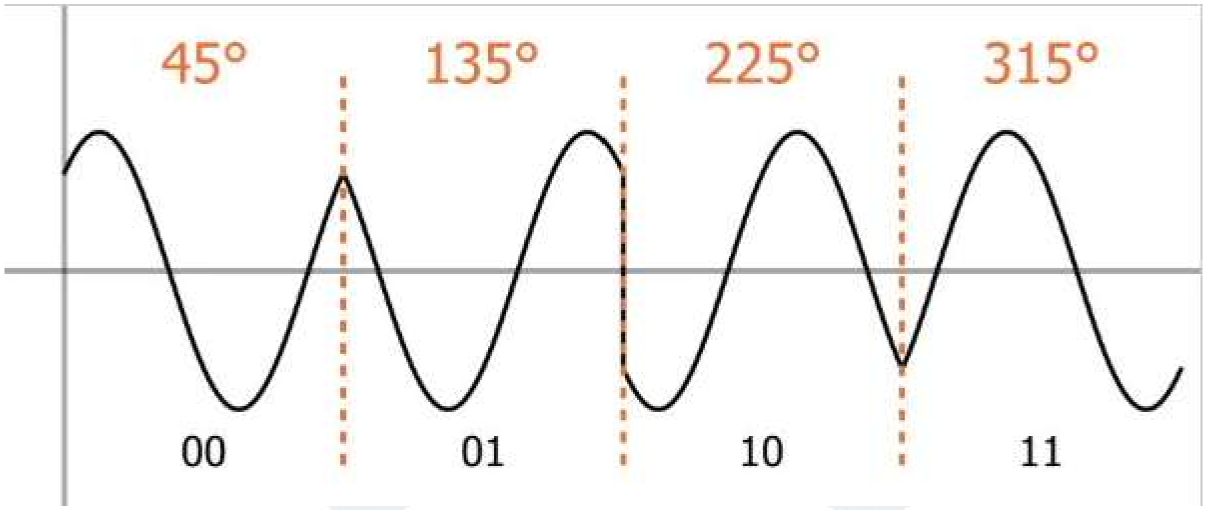

Figure 8: Depicts two-bit values for each of the four phases in QPSK (Keim, 2016).

The most advanced form of modulation currently in production is Quadrature Amplitude Modulation (QAM). QAM combines ASK and PSK to create more possible states of a wave that can be detected by a receiver. By measuring four amplitudes within four phases there are sixteen possible answers, with sixteen distinct answers four bits can be communicated at every data collection point, Figure 9 gives a cross-sectional view of those points (Notes, n.d.).

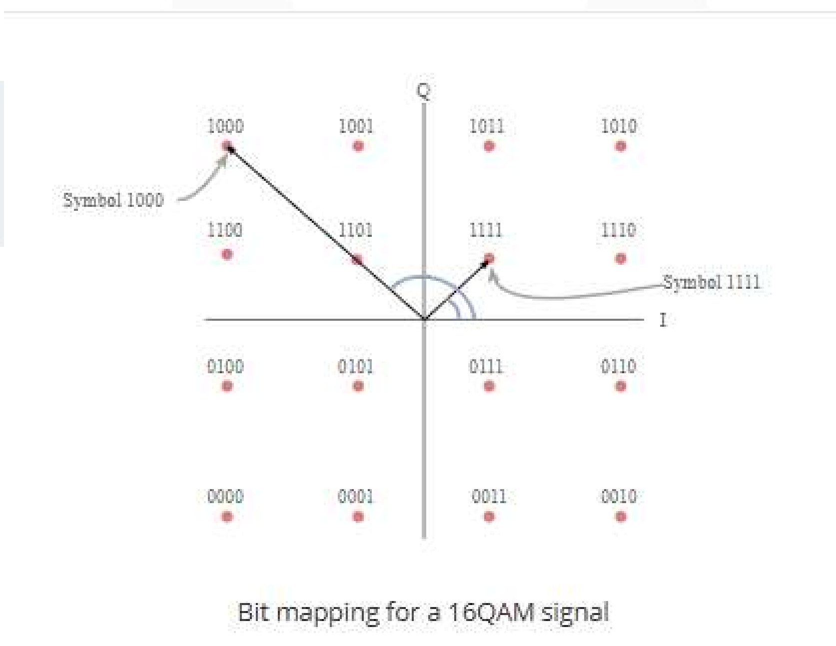

Figure 9: (Notes, n.d.)

As the number of phase and amplitude evaluation points goes up, so does the possible number of bits that can be transmitted by each, inversely the more evaluation points make the signal more susceptible to noise.

The final variable that can be modulated to transmit data is polarization. A wave transmits light oscillating in all directions. By applying a screen or filter to the light a resultant wave that only oscillates in a single direction can be achieved, this is typically done in a horizontal or vertical direction and would be referred to as horizontally or vertically polarized light (Captain Physics, 2024). The below figure depicts unpolarized light passing through a filter and the polarized light that comes out. Sunglasses with UV protection use a film with vertically aligned molecules to filter out horizontally oriented light, improving visual acuity especially from glare.

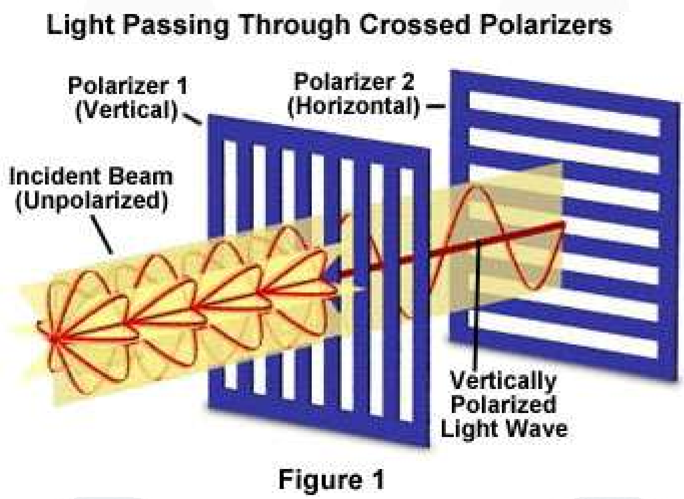

Figure 10: (Polarization of Light, n.d.)

Polarization adds a three-dimensional component to modulation. Combining amplitude, phase, and polarization allows for increased data transmission but the added complexity decreases the margin for error.

Molecular Scattering/Absorption

One of the most significant sources of natural attenuation comes from molecular scattering, in particular Rayleigh scattering may account for up to 96% of overall attenuation (*Optical fiber,* n.d.). The periodic table identifies elements based on the number of electrons they have and is organized in rows based on the valence shell.

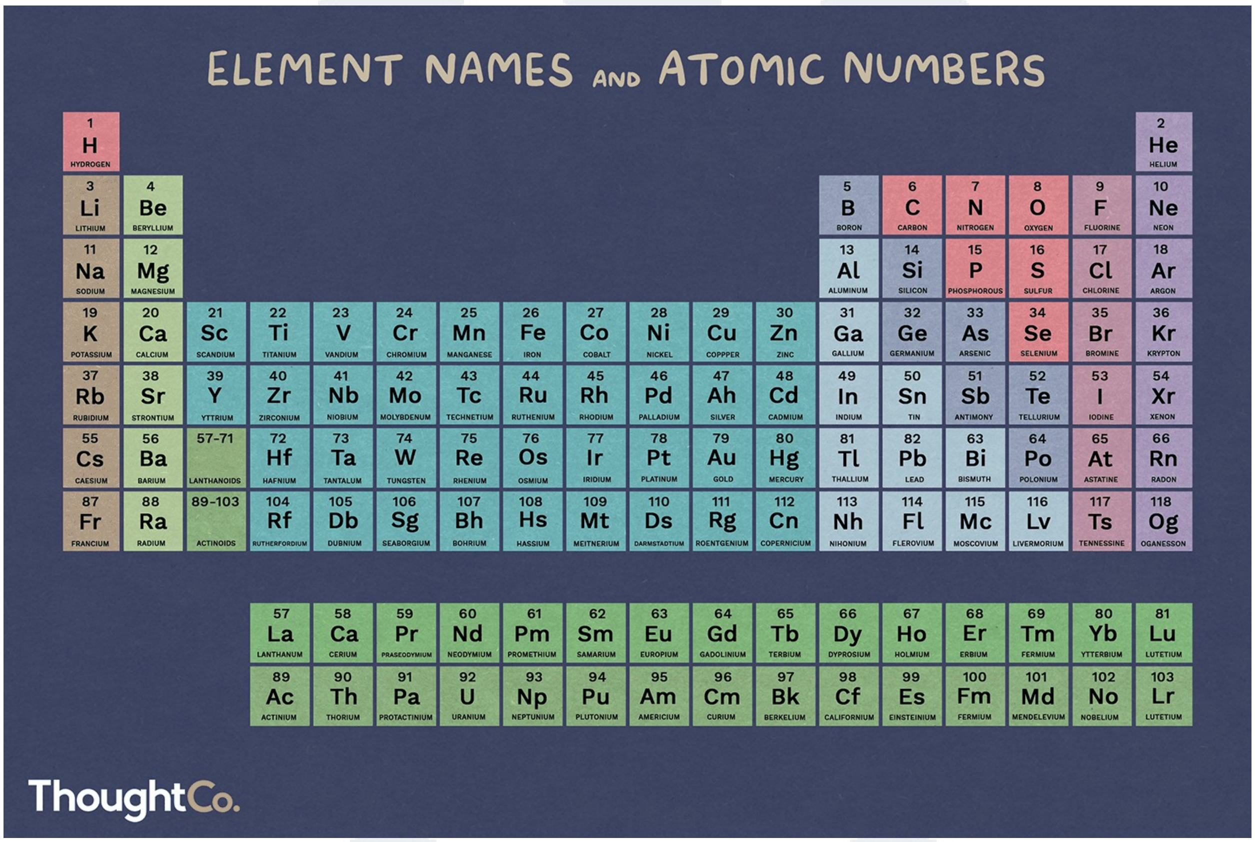

Figure 11: (ThoughtCo, 2024)

The Bohr model of the atom explains electrons as moving in a shell a certain distance from the nucleus with each shell being able to hold a maximum number of electrons and the shells building upon each other (Admin, 2023).

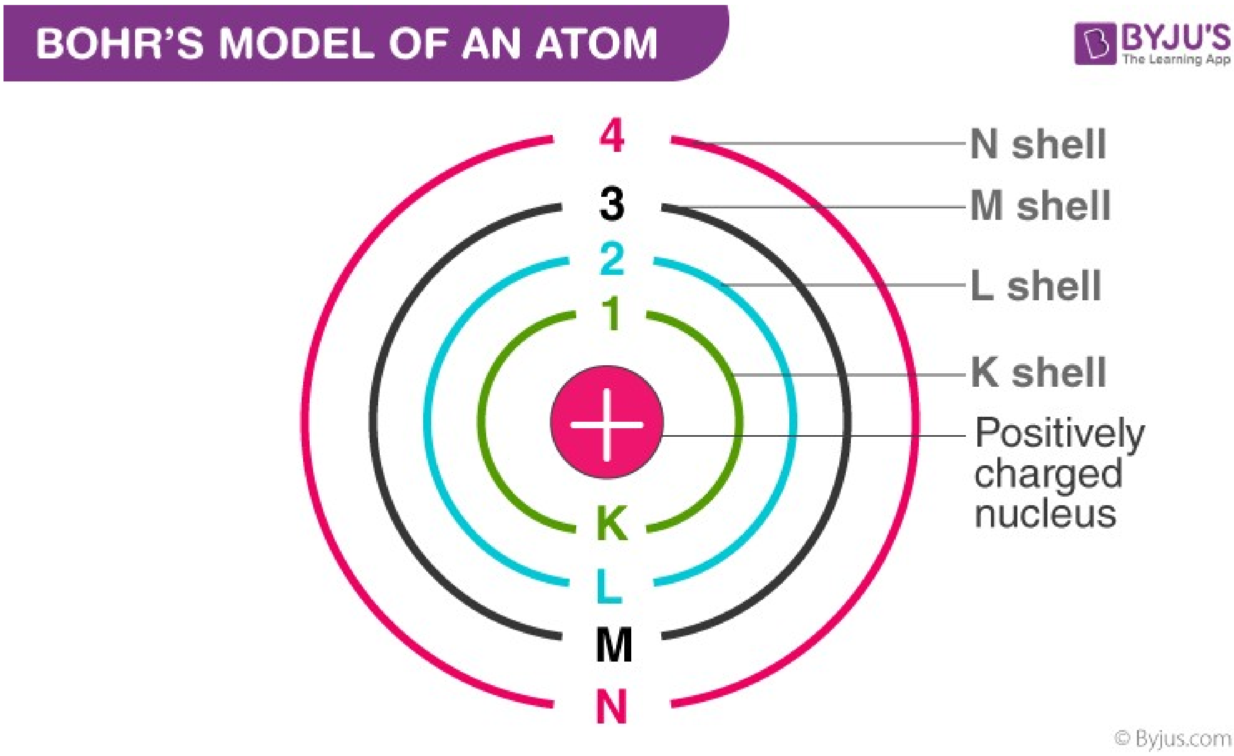

Figure 12: (Admin, 2023)

The first four shells can hold 2, 8, 18, and 32 from nearest to the 4th level, respectively. For example, Phosphorus is 15 on the periodic table, meaning it has 15 electrons surrounding the nucleus. This means the first valence shell is full with 2 electrons, the second is full with 8 electrons, and the third has 5 electrons.

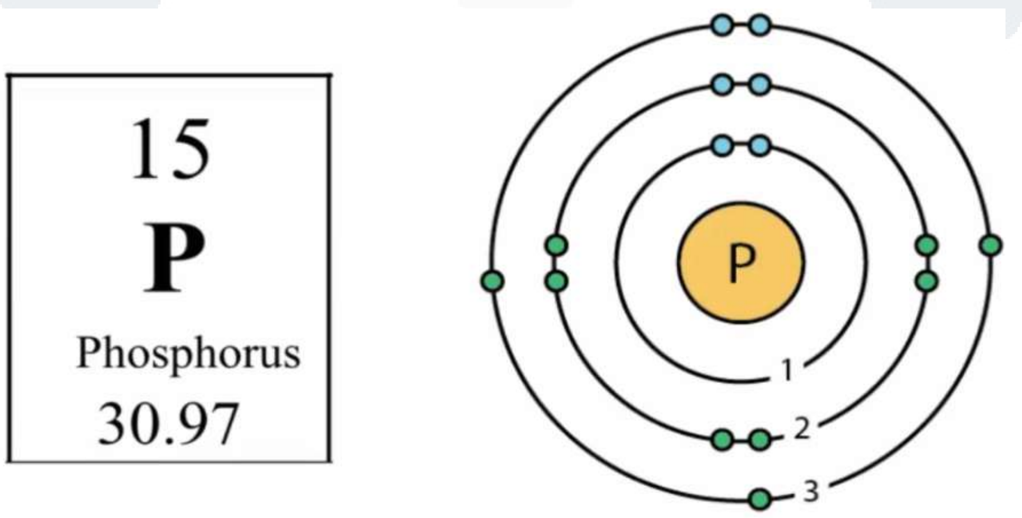

Figure 13: (Breslyn, 2022)

As photons interact with molecular systems, they will cause vibrations in the molecule. The molecule will absorb energy from the photon and will then re-emit or scatter energy in all directions. Using the Bohr model, when the molecule absorbs the energy from an interacting photon, an electron will be excited meaning it jumps to a higher shell level. At a later time, the electron will decay or return to its original shell level and emit energy in the form of a photon. In some cases, a molecule already in an excited state will interact with another photon causing a stimulated interaction, which can result in either a higher or lower energy photon being emitted. The effects from absorption and scattering have been characterized by several scientist including Brillouin, Compton, Raman, and Rayleigh. Most impactful for fiber optic transmission include Rayleigh and Raman. Rayleigh scattering is characterized by the wave emitted being the same frequency and in phase with the incident wave and is the reason the sky appears blue. Raman scattering is characterized by a wave that is either greater or lower in energy than the incident wave, meaning a change in frequency (Tipler & Llewellyn, 2008).

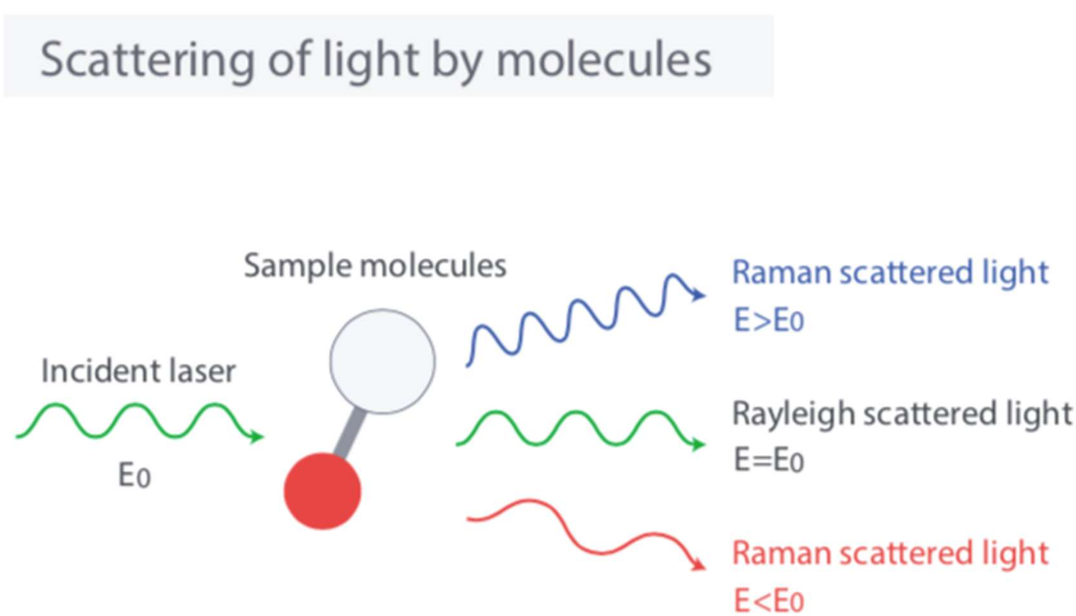

Figure 14: (Yohk, n.d.)

Rayleigh scattering occurs more frequently in fiber optic transmission but is less impactful per incident than Raman. This is because Rayleigh maintains frequency and phase, preserving the modulation and therefore the bits, but attenuation still occurs because waves are emitted in all directions including directions that will not experience total internal reflection and back towards the emitter, or back scatter. Raman can disrupt the original information more drastically, but when controlled it is used to amplify a signal.

Problem/Solution

Stimulated Raman Scattering (SRS)

Problem

Raman scattering is defined as Stokes or anti-Stokes, depending on the original state of the molecule and the energy of the wave emitted. In the case of Stokes, the excited electron does not immediately decay to the ground state and thus emits a photon at a lower frequency than the incident wave. Anti-Stokes occurs when the molecule is in excited state prior to the photon interaction and then after the interaction decays to a lower state than when it began, resulting in a wave with a higher frequency (PLC, n.d.)

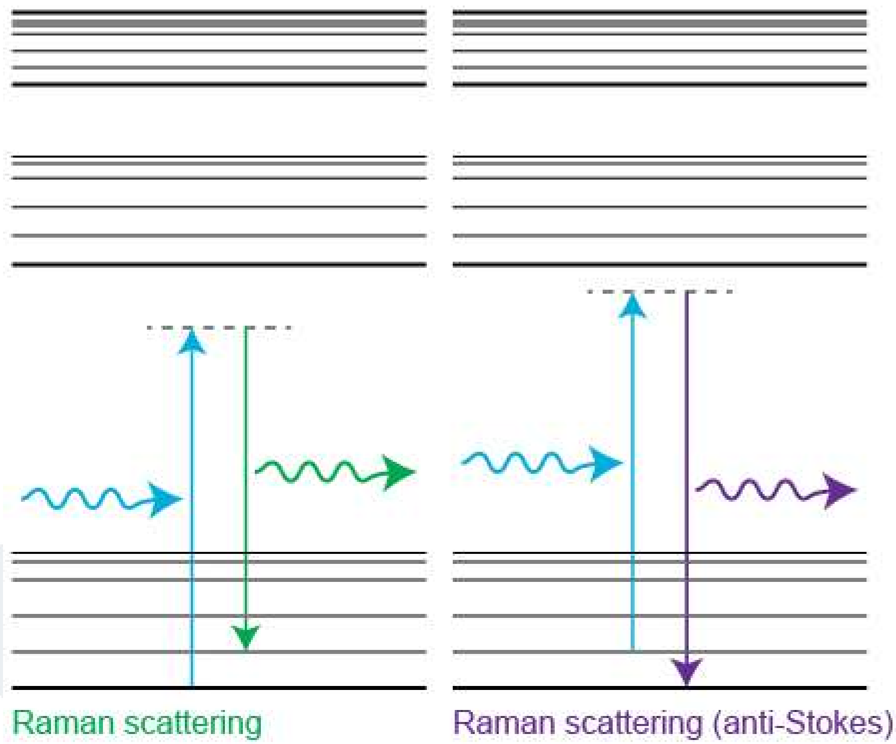

Figure 15: Highlights Stokes (energy loss) and anti-Stokes (energy gain) Raman scattering (PLC, n.d.)

When SRS occurs naturally in silica fiber the gain effect is undesirable because it transfers energy from the incident wave to another incident wave causing higher amplified spontaneous emission noise. This is more pronounced in a C-band and L-band combined network because the wavelengths are at the optimal distance apart to induce the power exchange. The peak of the Raman effect occurs at approximately 13 – 15 Terahertz (THz) or 100 nm separation (Zyskind & Bolshtyansky, 2011).

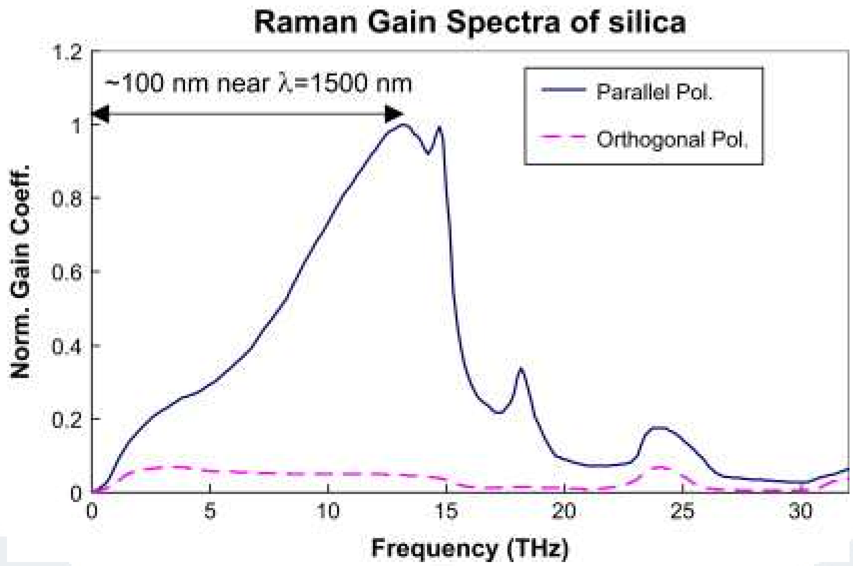

Figure 16: (Zyskind & Bolshtyansky, 2011)

Solution

SRS is a natural phenomenon; therefore, solutions are centered around avoiding the problem or mitigating the effects versus overcoming the problem itself. With the C-band using wavelengths between 1530 – 1565 nm and L-band 1565 – 1625 nm, there is no option to create channel spacing outside the affected area i.e., more than 100 nm a part. To limit SRS for as long as possible operators can start by using wavelengths near the center of the spectrum, starting with 1565 nm, and moving out in either direction as needed.

Another mitigation technique would be to assign high-order modulation to C-band and lower-order modulation to L-band. Because the lower-order modulation has a higher Optical Singal-to-Noise Ratio (OSNR) tolerance it would have a better chance of effectively reaching the receiver (Shen, 2024). In other words, assign higher bandwidth channels that require high-order modulation like 16-QAM to the C-band and lower bandwidth channels that can use lower-order modulation like QPSK to L-band. Realistically, this may require the MMN operator to reconfigure an existing network on C-band to the newly deployed L-band, which is time-consuming, costly, and could possibly affect current service.

A final note about the SRS effects on L-band deployment. As channels are turned up or turned down there can be a notable change in interaction with other channels and cause temporary power fluctuations due to SRS amplification. This process is commonly known as rebalancing. Rebalancing can cause temporary outages or damage to optics. To mitigate effects an operator can deploy ghost channels, which are channels that do not have traffic on them but are deployed and ready to pass traffic. The advantage is no rebalancing occurs if new services need to be configured over the ghost channel, however the disadvantage lies in prior channel planning being required for proper deployment.

Macrobending

Problem

As a fiber optic cable is bent, either as a part of installation or due to outside temporary influences like wind, signal loss can occur and is referred to as macrobending. As fiber bends the incident angle is shifted towards the normal line and for waves traveling at or near the critical angle this could result in a shift out of Total Internal Reflection (TIR) and into Refraction and Reflection (R&R) (*Optical fiber loss and attenuation*, n.d.).

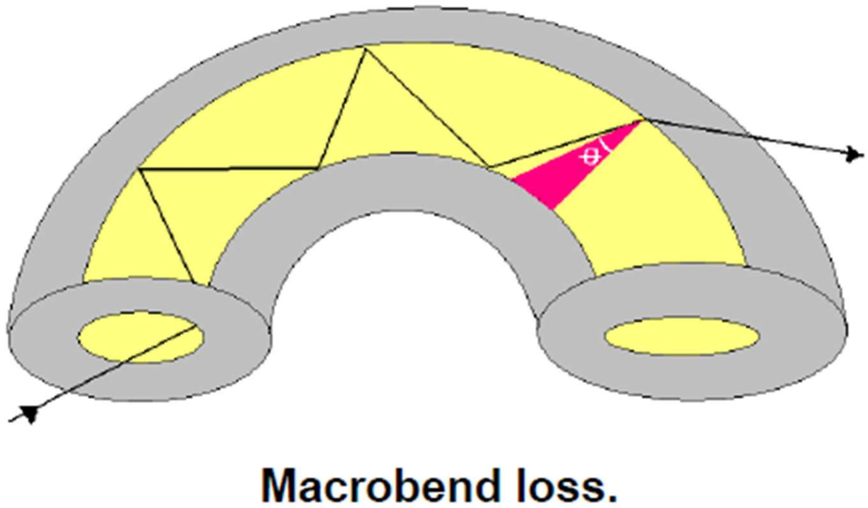

Figure 17: Depicts incident angle changes in bent fiber (Optical fiber loss and attenuation, n.d.).

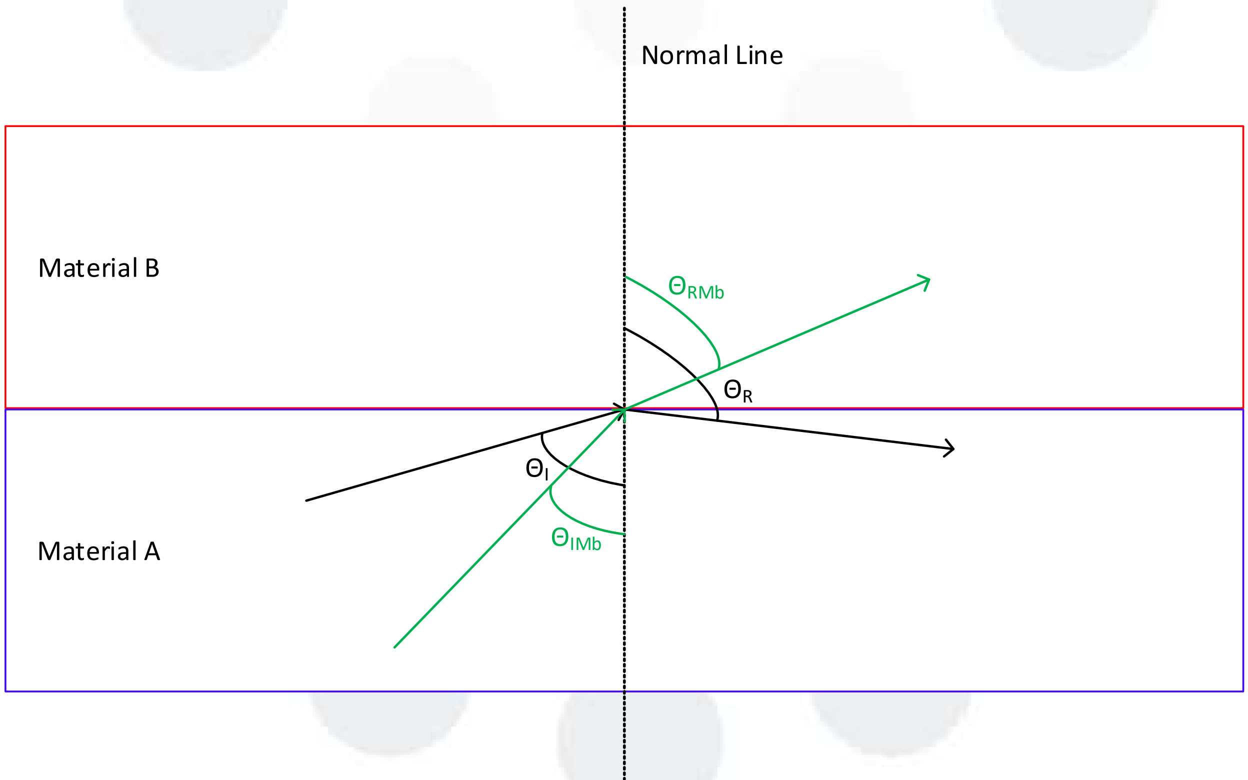

Figure 18: The black lines depict a light wave before Macrobending in TIR, and the green depict waves after macrobending out of TIR.

Figure 18 shows a green line representing the new incident angle after the fiber has been bent, like in Figure 17, resulting in ΘIMb and ΘRMb outside of the critical angle required to achieve

TIR. The Macrobending effect is more pronounced in the L-band because higher wavelengths require a higher incident angle to reach the critical angle, therefore, less tolerance for changes. Analyzing the equation for refractive index n=c/v, and incorporating the equation for velocity v=fλ, where v equals velocity, f equals frequency, and λ equals wavelength, shows the refractive index is inversely proportional to the wavelength (Question Video, n.d.). This principle is best visualized using a prism and light waves in the visible spectrum.

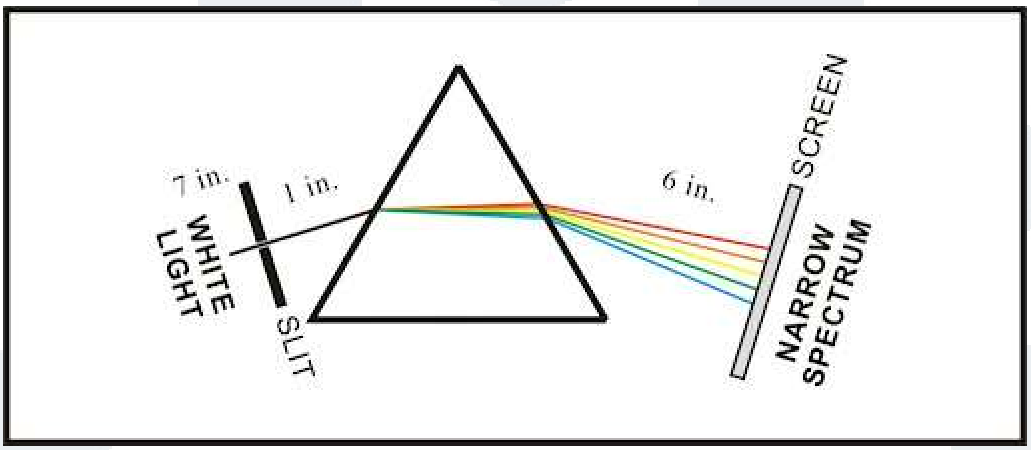

Figure 19: Shows red, a longer wavelength, bending less than blue (O'Connor, 2021).

What this means for existing fiber infrastructure is that loss due to macrobending observed in the lower C-band wavelength will be less than loss experienced in the higher wavelength L-band.

Solution

The only obvious solution to macrobending is to remove or lessen the bends in the existing fiber plant. The in-depth discussion regarding the details of macrobending is to relay that conditions on existing fiber infrastructure will be worse for L-band. The diameter of intentional bends in the fiber can be increased to reduce loss. An example would be increasing the bend radius of a future coil by putting it on a larger rack. Also, temporary losses could be attributed to temporary bends that may occur during high wind events. An operator that identifies where these losses are occurring could implement mitigation techniques that restrict movement.

Birefringence

Problem

When orthogonally polarized light experiences a velocity difference between the vertical and horizontal polarization, it causes a phase delay, and birefringence occurs. Materials like the calcite crystal shown below are birefringent and cause the viewer to see two images where only one exists. (made the below image smaller)

Figure 20: Visual birefringence example (Wiersma, n.d.)

Mathematically, the speed difference is due to different refractive indices experienced as the wave travels at different angles through the material. The phase change can be calculated with the following formula, $\Delta\varphi = 2\pi/\lambda * BL$, where $\Delta\varphi$ is the phase change, λ is the wavelength, B is the Birefringence ratio (the difference of the observed indices of refraction), and L is the fiber length. Based on the equation the resulting phase change is inversely proportional to the wavelength, meaning longer wavelengths will experience less phase change through the same birefringent material (Engineering Funda, 2026). The change in wave state caused by birefringence is called Polarization Mode Dispersion (PMD). When the detector receives a signal, the orthogonal waves are added together to obtain the final information. If PMD occurs the waves will arrive at separate times resulting in pulse broadening, if the pulse broadening is wide enough to cause overlap with other waves, then bit errors will occur. Error rates are more prevalent in faster speeds because there is less room for pulse broadening as shown below.

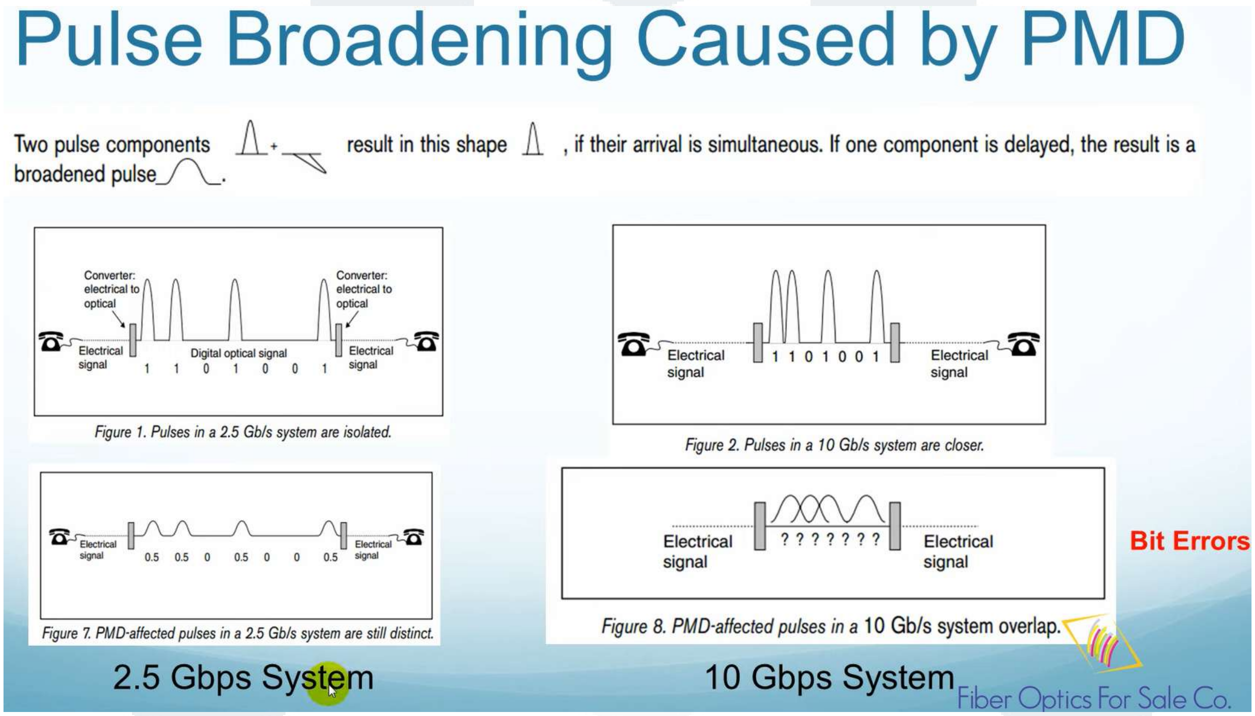

Figure 21: (Fiber Optics for Sale, 2012)

The physical cause of birefringence is elongation of the molecules. This could be caused by any number of physical or electromagnetic causes (Novel Device Lab, 2018). Examples include:

- Compression of the fiber optic cable
- Macrobending
- Microbending or small perturbations in the fiber
- Lightning, especially reactive with Optical Ground Wire (OPGW) (Tech, 2020)

- Fiber twists
- Cladding eccentricity, with the core of the fiber being shifted closer to one side of the cladding (Fiber Optics for Sale, 2012)

Solution

The first recommendation is to identify and remove the cause of the birefringence. This could include replacing sections of fiber that are damaged, increasing bend radii, or replacing OPGW with All-Dielectric Self Supporting (ADSS) or another fiber type. It is important to note that not all causes of birefringence are constant and may have a temporary effect. This can be frustrating to diagnose in real world applications, and could be caused by any number of outside factors like wind, temperature, storms, etc.

The second recommendation would be to move higher-order modulation to L-band and lower-order modulation to C-band. The phase change is less in longer wavelengths; therefore, L-band will experience less PMD than C-band will. This is counter to the solution for Stimulated Raman Scattering and should be thoroughly considered before making changes. An overall characterization of the fiber will help find the right balance between these.

General Solutions

Optical Time-Domain Reflectometer (OTDR) Testing

OTDR results can provide a window into the health of the fiber and where issues may lie. If the operator is able to obtain OTDR result during temporary events, like climate events common to the area, they will be able to better predict the reliability of a new connection. Simultaneously testing fiber at the extreme ends of the C and L-bands, approximately 1550 and 1625 nm will reveal SRS loss and Macrobending that may not be observable with just one or the other (VIAVI, 2021).

New advances in OTDR technology may be able to unlock knowledge about fiber conditions vital for deploying L-band. Phase-sensitive OTDR's could provide additional information about the behavior of light waves as they travel through the fiber and better pinpoint areas where the aforementioned problems are occurring. Additionally, MMN operators are beginning to incorporate built-in OTDR's into their network equipment, this has the potential to provide real-time information and catalogue data about prior events.

Overall Attenuation Mitigation

The most impactful results start with optimizing the overall attenuation of the fiber network. The other techniques discussed in this paper are intended to fine tune an already optimized network. Specifications for G.652.D compliant fiber are variable depending on the manufacturer and the specific product, but for 1625 nm are commonly in the 0.20 dB/km range. With certain L-band products requiring a maximum 0.25 dB/km, there may only be a 0.05 dB/km allowance for splicing and other attenuation. This makes it vital that MMN operators test each section of fiber and take steps to clean fibers or redo splices that do not meet specifications. Some sections of fiber may need to be replaced if the fiber has degraded beyond repair.

A common and often times significant source of attenuation comes from the equipment inside Points of Presence (PoP). Demarcation of fiber includes splicing outside fiber to inside fiber, then splicing to a bulkhead, and finally connecting using a jumper cable. All of these can add attenuation to the overall system and for extreme cases could be removed in favor of splicing the outside fiber directly to the jumper cable.

Routing, Modulation, Band, and Spectrum Allocation (RMBSA)

In late 2023 the paper "ISRS impact-reduced routing, modulation, band, and spectrum allocation algorithm in C+L-bands elastic optical networks" was published in the *Optical Fiber Technology* journal. This paper takes a deep dive into the intricacies of designing a network experiencing serious degradation from SRS, using the aforementioned parameters. This is an excellent resource to further investigate and mitigate effects of SRS (Shen, 2024). It is also a good reminder that these four parameters affect each other and should be evaluated holistically. Routing refers to the distance between network nodes, modulation has already been defined, band refers to the wavelength chosen, and spectrum allocation refers to the number of wavelengths or channels used to meet the bandwidth demands. Delicately balancing each of these individually and accounting for how they interact with each other could tip the scale of reliability and connectivity.

Conclusion

Long Distance L-band deployments on existing fiber infrastructure introduce new challenges not previously experienced when deploying lower band technology. With tighter tolerances in light attenuation and finer margins for higher-order modulation, a new set of tools need to be added to the MMN operator's toolbox. There is no perfect answer but rather a group of finely tunable variables that if accounted for properly can lead to a successful and reliable L-band deployment. Conversely, minor effects can cause significant heartache to operators and lead to intermittent outages or complete signal loss.

While finding ways to use the currently installed fiber optic plant is more financially responsible it is not free. Similarly, when more cars are built, the Interstates must be widened and reinforced. When more people need to eat, farms must be made more efficient. And when more people need to use the Internet, Middle Mile Networks must be invested in. Connecting all Americans, maintaining their future bandwidth needs, and growing AI will require higher speed Middle Mile Networks. These networks will need to install new fiber, replace existing fiber, and implement higher bandwidth technology like long distance L-band on existing fiber infrastructure.

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