SILKROAD

Technology White Paper

SilkRoad Refractive Synchronization Communication™

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Version 1.0

Contents

Overview

The reflective and refractive properties of light have been known for millennia. The wave and particle theories of light have been developed within the past few centuries, with Maxwell's Field Equations providing a mathematical description of the behavior of light. Plank hypothesized the existence of the photon, and Einstein won his Nobel Prize for the photoelectric effect, which showed that the energy of light is proportional to the wavelength of light and not its intensity. His further work led to the theory of relativity, with its concept of four-dimensional space-time.

SilkRoad's technology is based on the relativity theory of Einstein, combined with a new interpretation of Maxwell's electromagnetic field equations. SilkRoad's Chief Technical Officer, Dr. James R. Palmer, has reformulated Maxwell's equations to solve for wave motion when light passes from one medium to another with non-zero optical index (Maxwell assumes the optical index is zero). In Dr. Palmer's solution, the real part of the optical index (n) and the imaginary part of the optical index (k) in all three orthogonal axes are positionally time dilated in relativistic time. Based on Dr. Palmer's new view of the physics of light, SilkRoad has patented *SilkRoad Refractive Synchronization Communication*™ *(SRSC*™*)* a set of physical principles that can be applied to fiber optic communication. Dataquest's Ken Kelly describes this new technology as "so simple as to be marvelous."

A brief comparison of SRSC™ to Dense Wave Division Multiplexing (DWDM) illustrates the implications of Mr. Kelly's comment:

Characteristic	**SRSC™**	**DWDM**
# of Lasers	1	16 to 90
# of Wavelengths	1	16 to 90
Data Location	1 Beam	16 to 90 beams
# of lenses	0	100s
Laser Mode	TEM_{00}	Multimode

The simplicity of the SRSC™ single laser system fosters high reliability and relatively uncomplicated solutions for add/drop, system redundancy, and other network requirements. This White Paper describes the scientific and engineering basis for this advanced capability.

1. Introduction

An Enlightened History

SilkRoad approaches photonic technology with a true respect for the physics that has brought us to this point. Our work with physical principles and field equations has led to a new understanding of the characteristics of light which, when applied to fiber optics, allow light signals to carry more information at greater distances than ever before.

Reflection and modulation

The road to our current optical theories began with Greek, Egyptian and early Chinese writings. Some of the first uses of optics were by means of reflection. It was found that reflected and concentrated sunlight could redirect heat and light for military and other purposes.

One of the most noted uses of this type of light modulation was during the battle of Thermopylae, when the Spartans reversed their shields to focus reflected sunlight onto advancing enemy troops. This disoriented the troops to such a degree that a weaker Spartan army was able to win the battle. Later, Tiberius Caesar ruled Rome from the Isle of Capri, using mirrors to flash information to and from the mainland of Italy. In neither case was direct modulation of sunlight undertaken; only the intensity of the sunbeam was changed.

Refraction of light

Galileo, Johannes Kepler, and René Descartes all made contributions to the understanding of light. In 1637, Descartes discussed optics and reported the law of refraction in his famous *Discours de la Méthode* (Discourse on Method). In 1620, the Dutch astronomer and mathematician Willebrord Snell independently discovered the law of refraction that is now named after him.

Snell's Law mathematically represents the angle of both reflected and refracted light traveling from one uniform material through another. Refraction is a simple principle (Figure 1.1) that is well understood. The ability of a man to spear a fish or of a hunting bear to pull a salmon from a stream requires a basic understanding of refraction.

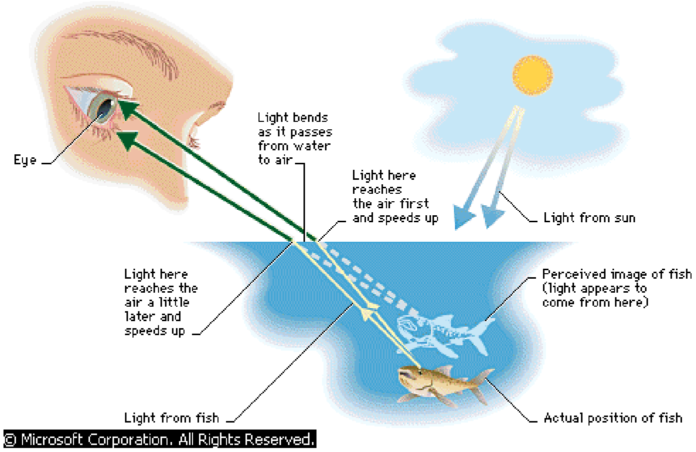


Figure 1.1 Refraction of Light

A wave or a particle?

During the late 1600s, an important question emerged: is light a swarm of particles, or is it a wave in some transparent medium through which it can freely move? English physicist Sir Isaac Newton was a proponent of the particle theory. At about that same time, Huygens developed the wave theory.


Sir Isaac Newton

Huygens' wave theory could not explain optical polarization, because waves that scientists were familiar with moved in parallel with, not perpendicular to, the direction of wave travel. On the other hand, Newton had difficulty explaining the phenomenon of interference of light. His explanation forced a wavelike property on a particle description.

Newton's great prestige, coupled with the difficulty of explaining polarization, caused the scientific community to favor the particle theory. This bias remained even after English physicist Thomas Young analyzed a new class of interference phenomena using the wave theory in 1803.The controversy would continue until Maxwell formulated his field equations.

The field equations

As a result of Young's and Huygen's efforts, an entire wave theory of light existed in mathematical form before the British physicist James Clerk Maxwell began his work on electromagnetism. Maxwell postulated that electric and magnetic fields affect each other in such a way as to permit waves to travel through space. The equations he derived to describe these electromagnetic waves matched the equations that many scientists already relied on to describe the behavior of light.


James Clerk Maxwell

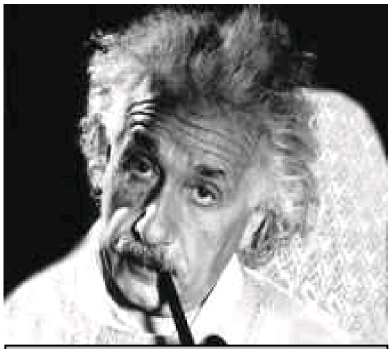
Maxwell's equations, however, were more general in nature. They described electromagnetic phenomena other than light, predicting the behavior of waves throughout the electromagnetic spectrum. In addition, Maxwell's theory calculated the correct speed of light in terms of the properties of electricity and magnetism. Later, when the German physicist Gustav Hertz detected electromagnetic waves at lower frequencies, as Maxwell's theory had predicted, the basic correctness of the field equations was confirmed.

Maxwell's work still left unsolved a problem common to all wave theories of light: an electromagnetic field can be pictured as a continuous wave phenomenon, and, when it travels, each of the infinite number of points, in every small part of space, must also move. It remained for Planck and Einstein to resolve this part of the developing theory of the behavior of light.

The photon

In 1900, Max Planck provided the missing link in this theoretical structure. He proposed the existence of a light quantum - a finite packet of energy that became known as the "photon." In the Standard Model, photons are described as "bosons," to distinguish them from a second category of particles in the Standard Model, the "fermions". Fermions are the building blocks of atoms, such as protons, neutrons and electrons. Bosons are the quantum particles associated with the force fields that act on the fermions.

Einstein's theories of light



Albert Einstein

Planck's theory remained controversial until Einstein showed how it could be used to explain the photoelectric effect, where the speed of ejected electrons is related not to the intensity of light, but to its frequency. This was consistent with Planck's theory, which also suggested that a photon's energy is related to its frequency. Over the next two decades scientists recast all of optical physics to be consistent with Planck's theory.

Einstein also discovered that light in a vacuum travels at a consistent speed that is independent of the speed of the observer. In other words, the speed of light is the same for someone traveling at several thousand miles an hour as it is for someone standing still. This led to the theory of relativity within four dimensional space-time.

The Laguerre Gaussian Principle

The Laguerre Gaussian principle predicts that light does not travel in the typical waves described by Huygens. Instead, photons follow space-time curves that are more helical in nature. The characteristics of the photons that travel down these curves change based on the "Laguerre order" that the curve occupies in the wavelength.

The Laguerre Gaussian principle demonstrates that the angular momentum of orbit and the spin of a photon allow more than one photon to occupy the same three-dimensional space in time. This principle is one of the landmarks in understanding how light occupies the four dimensions of Einstein's theories.

The ability to impose Laguerre orders on an optical beam results from the optical stability of the laser and the beam forming optics. In 1936, Beth first demonstrated the angular momentum that is imparted to an elliptically polarized beam of light. Beth's experiments demonstrated that each Laguerre order had increased angular momentum according to $\pm \mathbf{L}\hbar\nu$, where $\mathbf{L}$ is the Laguerre order. Prior conventional wisdom had been that photons had an angular momentum of $\pm\hbar\nu$.

By inducing Laguerre orders in a non-isotropic, non-homogenous medium, the orders of the Laguerre can be separated. This allows control of the angular momentum of the photons, taking advantage of the difference in real part of the optical index (n) and imaginary part of the optical index (k) in all three orthogonal axes to time dilate their positions in relativistic time.

In such fashion the orbit and spin of the photons in each order exist in the same place, with relative speed, but not in the same time relative to one another. Consequently each order, having its particular angular momentum, travels in its own relativistic time, without any interaction with the other photons on the other orders of the Laguerre.

A visionary future for fiber optic communications

SilkRoad is using this new approach to optical physics, developed by our Chief Technical Officer, Dr. James R. Palmer, to build the next generation of telecommunications equipment.

Dr. Palmer has been an outstanding contributor to optical physics throughout his career. The Recipient of a Rudolf Kinslake Medal in Optical Engineering, Dr. Palmer has been a lawyer, a teacher, an engineer, and a research scientist in optical physics. His publications have been used in colleges and universities around the world, and his contributions to optical physics form the basis of many of the technological applications SilkRoad is using today.

2. Technology

A Single Wavelength Approach

SilkRoad's patented technology, SilkRoad Refractive Synchronization Communication™ (SRSC™), is based on well-known but rarely utilized principles of optical physics.

Based on these principles, telecommunications systems will utilize a transceiver that uses only one wavelength. By using a single wavelength with a very narrow spectral bandwidth, systems become easier to scale to all types of users and data formats. A single wavelength approach is a simpler way of managing information, and allows a light signal to travel further down an optical fiber than a multiple wavelength signal.

Optical Refractive Synchronization

The process of refraction is the change of energy, direction or speed of a light beam that is propagating through a medium. Snell's Law predicts a continuous bending of the light beam and a subsequent change of speed of the light that is proportional to the index of refraction of the material.

When light passes from a modulator into an optical fiber, the beam encounters an abrupt change in the index, polarity or phase of the medium. The physical nature of the medium controls the amount of energy out of the medium, the ability of the light to pass through the medium, and the amount of energy being absorbed. This behavior of light is central to *Optical Refractive Synchronization.*

Optical Refractive Synchronization is the basis for SRSC™. Dr. Palmer hypothesized the following as a basis for this technology:

- That Maxwell's field equations can be solved for the change in the electric field through a change of the index of refraction where k (the imaginary part of the index of refraction) does not equal zero.
- That the expansion of Snell's Law to include five dimensional behavior of light over space-time is necessary to account for the behavior of light passing from one medium to another. This provides a theoretical basis for controlling, predicting and utilizing these properties of light in transceivers.
- That the properties of light act both as a particle, as postulated by Newton and Planck, and as a wave, as demonstrated by Huygens and Young.
- That light travels in a helical path as described by the Laguerre Gaussian formulation.

Dr. Palmer's paper, "*Optical Refractive Synchronization, Coherent Information in a Waveguide*" describes this principle, in detail, through mathematical models.

Solutions to Maxwell's field equations

Optical Refractive Synchronization is an elegant mathematical description of the behavior of light as it travels from a medium of one index of refraction to a second medium of a different index. In order to understand the process, it is necessary to solve Maxwell's equations in a unique fashion consistent with the standard concept of Einstein's theories of the behavior of light.

Dr. Palmer reformulated Maxwell's equations into a closed form solution to function within a time domain. This solution conforms to empirical values for birefringent materials. In Dr. Palmer's formulation, the x and y components of the electromagnetic wave vectors are **a function of space** and, most importantly, **are a function of time.** In order for *Optical Refractive Synchronization* to work, space must be dealt with simultaneously in all three orthogonal dimensions as a function of time.

This means the imaginary part of the index of refraction, k, does not equal 0. Furthermore, k_x, k_y, and k_z are not equal and have non-zero values. The Standard Model of electromagnetic fields, as described by Maxwell in two dimensions, must be expanded to five dimensions as a function of time.

The angle of incidence in Snell's Law

Snell's Law describes refraction by mathematically predicting the angle of transmitted light after it passes through the boundary between two media. Dr. Palmer has expanded this principle with *Optical Refractive Synchronization,* by increasing the number of sources passing through the medium, controlling the refractive index, then maintaining and predicting changes to this index over time and space.

As light is passed through an electro-optical crystal, optical modulation can be performed. The ability to change the refractive index abruptly and, therefore, the electric field, allows the signal to be modulated onto a light beam by a radio frequency (RF) signal applied to the electrodes on the crystal. This application of RF onto a light beam creates an amplitude modulation. The light beam then passes through two optical waveguide paths in the crystal at the frequency of the radio signal. Optical modulation is achieved, therefore, through the refraction of the optical signal.

By combining the frequency spectrum of various sources and optically modulating each signal with a specific RF subcarrier frequency that has an appropriate sampling frequency and amplitude ratio, one can synchronize a number of different signals and coherently place them onto a single laser beam (Figure 2.1). This is *Optical Refractive Synchronization*.

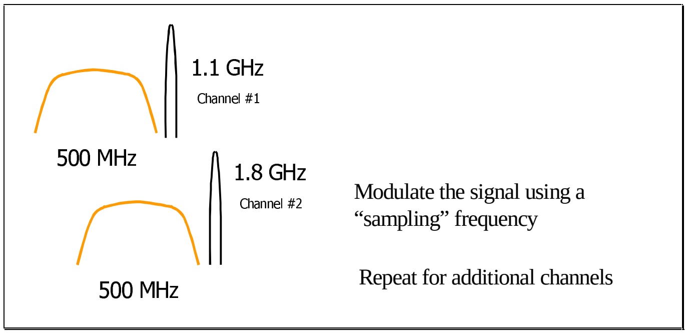


Figure 2.1 Output in Frequency Space–Multiple Frequency

Controlling particles and waves with the Laguerre Gaussian principles

One of the most useful aspects of *Optical Refractive Synchronization* is the ability to predict the transport paths of photons over helical light waves as described in the Laguerre Gaussian principles. Using these principles, it has been determined that photons travel the Laguerres with an angular momentum of orbit and spin that is characteristic of each Laguerre order on the wave.

Two photons can therefore occupy the same three-dimensional space in time and not collide or interfere with each other if they are excited by distinct Laguerre orders. Photons traveling on different Laguerres within the same wavelength will have different spin and energy properties from other photons traveling in that same path (Figure 2.2).

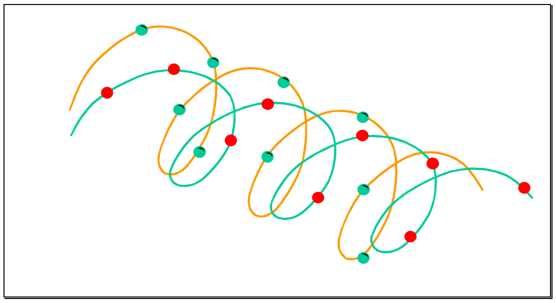


Figure 2.2 Visual Representation of Laguerres

SilkRoad uses these principles, combined with Snell's Law, to transport multiple channels of information on a single wavelength. In addition, the same wavelength can be made bi-directional using the slight shift in ellipsometric phase that is characteristic of the different Laguerre orders.

Transverse Electromagnetic Waves (TEM$_{pq}$) and SRSC™ Technology

Light emitted by most lasers contains several discrete optical frequencies, separated from each other by frequency differences associated with discrete modes of the optical resonator (Figure 2.3). The spectral characteristics of a laser, such as line width and coherence length, are primarily determined by the longitudinal modes: Beam divergence, diameter and energy distribution are governed by the transverse modes. It should be noted that lasers are multimode oscillators unless specific efforts are made to limit the number of oscillating modes.

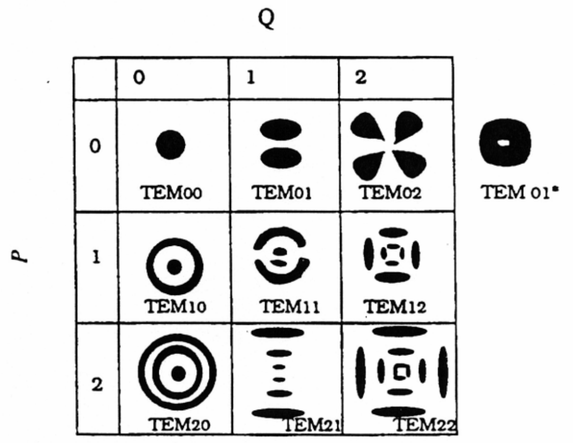


Figure 2.3 Modified Matrix of Typical Transverse Mode Patterns in Laser Output Beams

With SRSC™ technology, SilkRoad is able to use a standard DFB laser TEM$_{00}$ propagation mode to achieve maximum transmission distance down a given fiber. Utilizing the *Palmer Reverse Thermal Wave Laser Transform Control* (PLTC) system, SilkRoad can maintain this control throughout the system and into the fiber, giving an SRSC™ signal longer span length and greater signal integrity.

SRSC™ Compared to DWDM

The SRSC™ single wavelength transceiver is simple and easy to deploy in any network from the computer desktop to the long-haul telecommunications networks.

Until recently, a DWDM system (Figure 2.4) that uses 16 to 40 lasers (wavelengths) has been one of the best technologies available for expanding the capacity of fiber-optic cable.

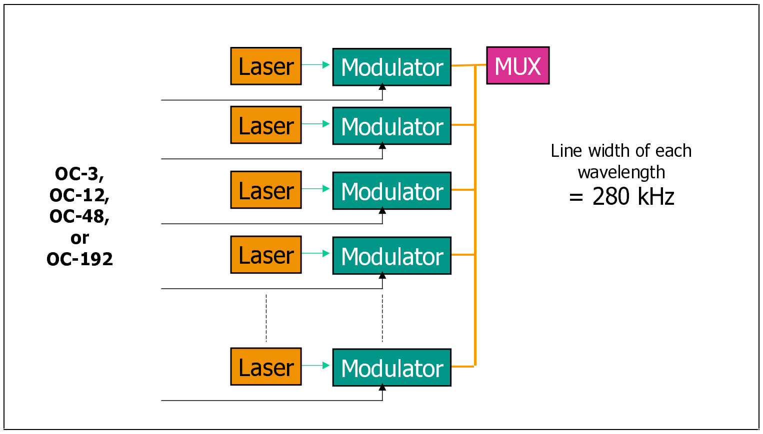
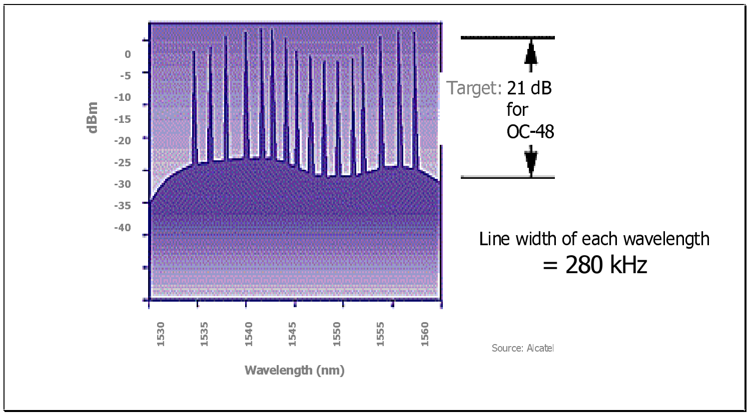


Figure 2.4 A Typical DWDM Schematic

Although DWDM is the basis for many current and planned photonic products, the technology has some inherent limitations. DWDM transmitters are often configured to modulate the signal into the laser cavity, which changes the output modes of the cavity and broadens the spectral output (Figure 2.5). However, increasing the signal strength of this type of DWDM transmitter to minimize spectral broadening has limited benefit. Higher power eventually introduces an undesirable condition called “mode hopping” or “chirping”, which decreases both signal quality and transmit-receive distance. Even when DWDM systems employ external optical modulators instead of direct modulation into the laser cavity, other limitations, such as four-wave mixing, arise.



Source: Alcatel

Figure 2.5 A DWDM Wavelength Span

A particular limitation of DWDM is the decrease in frequency separation as the number of wavelengths in a given band increases. This close spacing leads to an increase in the error rate and a consequent reduction in the transmission distance. Transmission distances improve with the use of EDFAs, but the four-wave mixing problem remains as a barrier to significant bandwidth improvement.

DWDM also requires complex equipment and software for the add/drop and signal regeneration/amplification functions. In DWDM, these functions depend on conversion from optical to electronic formats to perform the add/drop or regeneration/amplification, and reconversion from electronic to optical signals for continued transmission.

From a systems point of view, the DWDM process is highly complex, requiring sophisticated optical components (several hundred of which require thermal control), extensive software processing (to monitor and control the output of the transmitter), and the constant attention of highly skilled technical maintenance personnel. Considering all of these drawbacks, the evolution of DWDM technology has today reached some serious roadblocks which only new optical physics technology can remedy.

The SilkRoad Solution

SilkRoad's patented SRSC™ technology is deployed as a single wavelength, multi-channel solution for optical transmission delivery systems. An optical telecommunications system designed under these principles shifts the focus, from multi-wavelength transmitters and receivers to transmitters and receivers that use only a single wavelength (Figure 2.6).

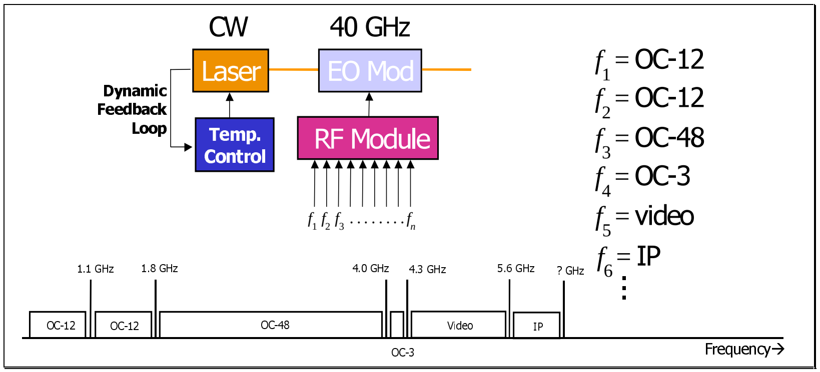


Figure 2.6 Channel Stacking with SRSC^{TM}

SilkRoad's core technological achievement, SRSC™, supports a fundamental performance leap beyond DWDM. Using only a single transmission laser on a single fiber, SRSC™ can support any fiber architecture or existing optical transmission medium, and requires less amplification and software control than DWDM. SRSC™ meets or exceeds all requirements of the International Standards Based Network and the International Telecom Union for OC-48 and OC-192 transmission protocols.

SilkRoad's solution relies on several proprietary and patented optical transmission techniques, including a unique form of external modulation and a laser cavity temperature control system. These technological innovations will ultimately support bi-directional, terabit per second transmission.

- External subcarrier frequency generation and modulation provides address-specific discrimination at the receiving node.
- The Palmer Reverse Thermal Wave Laser Transform Control (PLTC) system generates an extremely narrow line width of approximately $1\text{x}10^{-5}$ angstroms.
- An optical modulation technique provides for coherent transmission and retrieval of both analog and digital signals.
- The SRSC™ receiver that uses a modulating subcarrier frequency as a data channel identifier to demodulate and homodyne each coherent signal reaching the detector.
- A five (5) pico-second photo diode detects SRSC™ high frequency signals.

The SRSC™ design also incorporates a new and patented distributed feedback (DFB) laser, which achieves its very high transfer rate through a combination of line width narrowing, frequency mixing, and external modulation. These three features of the laser allow the signal to travel farther down an optical fiber than a multi-laser transmitter (such as DWDM) which requires beam amplification and reconstruction after shorter distances than an SRSC™ signal. The single laser simplicity of SRSC™ also allows for a reduction of the software required to control the network elements.

3. Product Architecture

Expanding the Possibilities

The architecture described in this section will provide a baseline understanding of current SRSC™ network products.

- The SRSC™ hardware platform consists of four (4) subsystems: the Interface Module, the Frequency Module, the Optical Module, and the Command & Control Module (which contains processor, control, and alarm sub-modules).
- The SRSC™ software platform also consists of four (4) subsystems: the Element Management System (EMS), the Configuration Management System (CMS), the Diagnostic Management System (DMS), and the Human Computer Interface (HCI).

The two platforms bind themselves together via a common electronic bonding method referred to as the operating system (embedded for hardware and operating system for software). This architecture is designed to conform to all standard mounting and power standards as well as meet NEBS and UTI-T standards.

This architecture focuses on the market demand for maximum bandwidth capability for existing fiber optic cable. Although standards convergence is a primary goal of SRSC™ architecture, additional building blocks are required to reach this objective. The SRSC™ technology scales from a simple point-to-point enterprise network to a long-haul, multi-ring network.

SRSC™ Hardware Platform

The SRSC™ hardware platform is designed in a group of subsystems. The subsystems and their functions are at equal levels of importance and are designed with high priority on interoperability (Figure 3.1).

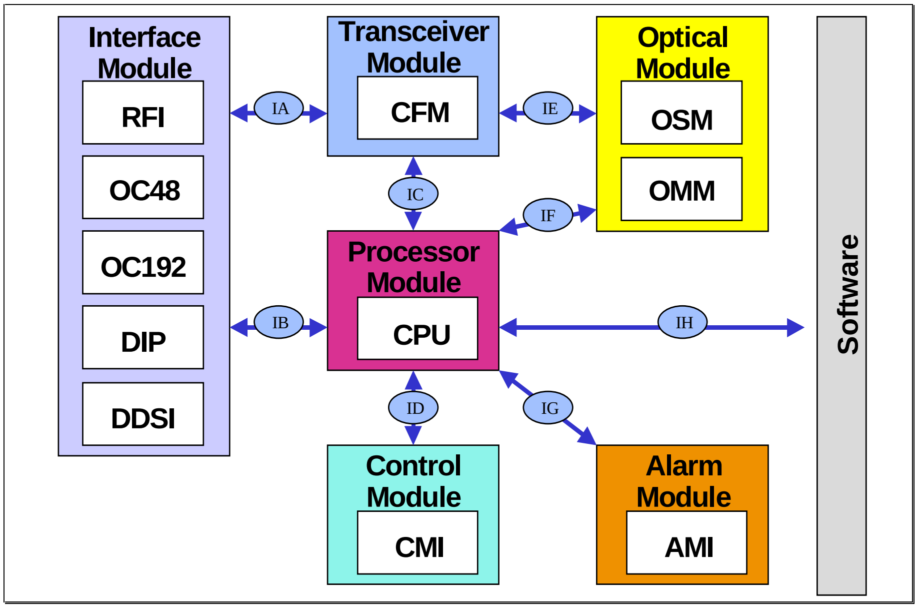


Figure 3.1 SRSC™ Hardware Platform

Command and control module

The command and control module consists of the processor module, alarm module, and control module, and contains the embedded operating system. This module interfaces with every aspect of the product as well as the software that controls and manages it.

Transceiver module

This module is responsible for preparing the signal to be transmitted and received over an optical medium. In this module, the signal is filtered to the preferred frequency range for the channel and a subcarrier is attached. After detection, the subcarrier is stripped and the signal shaped back to its original frequency range.

Interface control module

This module is responsible for interfacing external equipment and interoperability with external entities. Examples of interfaces include analog signals, OC-12, OC-48, OC-192, and digital signals. There are specific modules for the signal input and output.

Optical control module

This module contains the optical signal conditioning, distribution and control functions. It contains both the laser for transmittal and the detector to receive the signal. All channels are sent to this module for transmission, and are returned after detection to the transceiver module.

SRSC™ Software Platform

The SRSC™ software platform consists of a group of subsystems. The software platform is responsible for operation, administration, maintenance (monitoring), and provisioning (the industry acronym is *OAM&P*). There are four (4) major subsystems within the software platform (Figure 3.2).

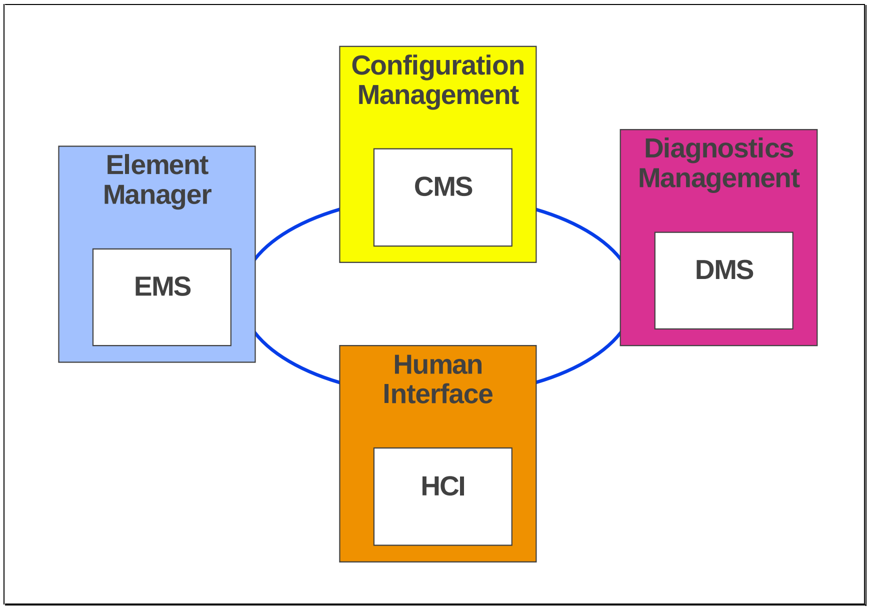


Figure 3.2 SRSC™ Software Platform

Element Management Subsystem (EMS)

The five requirements of an effective EMS are:

- Functionality: overall functional details within a system, interaction among multiple subsystems, interoperability, and traffic transport control.
- Usability: assessment of user profiles, human factors, consistency, learn-ability, and user documentation.
- Reliability: availability, robustness, exactness, correctness, security, and errors.
- Performance: capacity, speed, scalability, and efficiency.
- Supportability: distribution, installation, localization, administration, testability, service, legal aspects, maintenance, portability, and compatibility.

Configuration Management Subsystem (CMS)

CMS is responsible for the configuration of the network element within the full system. The configuration is primarily automatic with some administration.

Diagnostic Management Subsystem (DMS)

DMS is responsible for diagnostics within the product. Monitoring is on going with a full alarm and switch-over process within the software.

Human Computer Interface (HCI)

HCI is responsible for user/operator/administrator intervention within the system. Intervention may occur locally or remotely. The Graphical User Interface (GUI) is the core of this subsystem.

Simple Network Management Protocol (SNMP)

The SNMP interface is the primary interface for transport of information to and from the Network Element (NE) to the Element Management System (EMS) or Network Manager on the manager side of the Network Management System (NMS). SNMP concentrates on fault monitoring, fault reporting and the status of channel interfaces, thus providing basic network management capability (Figure 3.3).

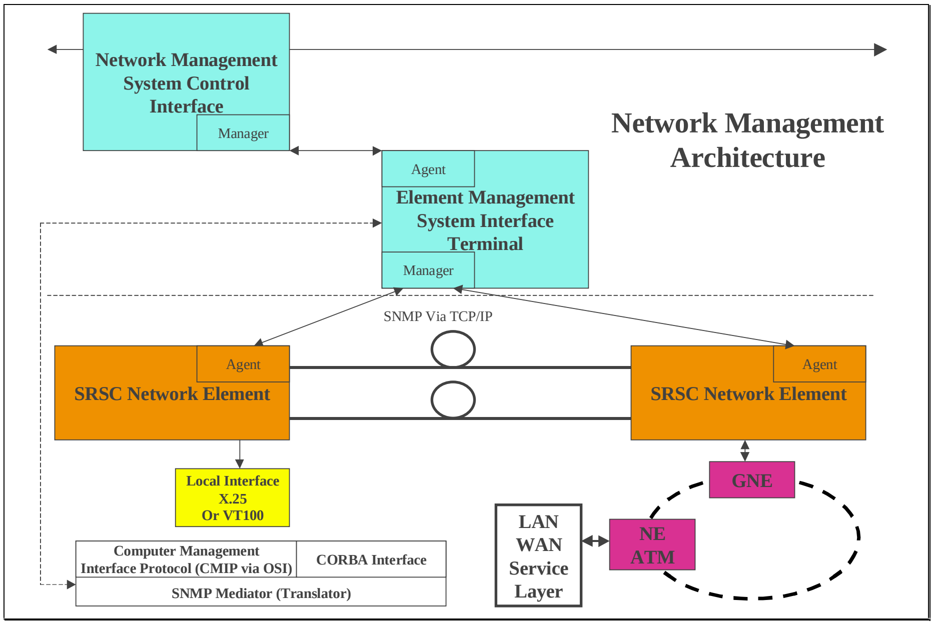


Figure 3.3 Network Management Architecture

Alarm Standards, X.721 and X.700 are used to develop the fault and alarm interface requirements. The key importance of this is the identification and development of the ASN.1 and GDMO object interfaces. These objects are defined by SilkRoad and developed on an as-needed basis, in accordance with proper telecommunications standards such as TMN/OSI or CORBA.

Types of SilkRoad Products

Core products based upon SilkRoad technology and system architectures provide a full network solution for our customers. These products work together to derive the maximum benefit from the SilkRoad SRSC™ technology. Used in combination, they provide a full network managed solution with high bandwidth over both long-haul and short-haul networks. With this technology:

- SilkRoad has a product line that employs SRSC™ technology to deliver multiple channels of information on a single wavelength.
- SilkRoad implements a means of optical and RF signal conditioning that eliminates the amplification and regeneration required in current DWDM technology.
- SilkRoad deploys a means of combining multiple SRSC™ signals over a single wavelength by optically shifting the ellipsometric phase of the optical signals.

SilkRoad SRSC™

The base products of the SilkRoad SRSC™ product line are optical channel transmission delivery products that tie together to transmit and receive multiple channels of information over a single wavelength.

The SilkRoad SRSC™ products take signals from multiple RF, digital, or analog sources, convert them into a standard analog format, and then modulate a subcarrier onto each signal. This set of signals is then externally modulated onto a narrow bandwidth laser, which is transmitted down any single mode optical fiber. At the receiver end, the signals are detected and returned to baseband without error.

SRSC™ products handle various types of inputs and provide the same signal received into our transmission product at the receiving or delivery end. These inputs can include optical signals, digital signals and analog signals (Figure 3.4).

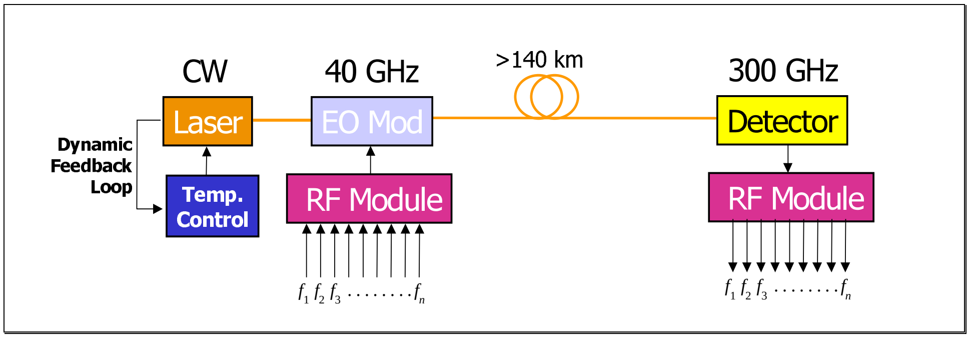


Figure 3.4 The SilkRoad SRSC™ Product Solution

The SilkRoad SRSC™ product line can be utilized for the transmission of a single channel or multiple channels. With the convergence of technologies and market segments, SilkRoad SRSC™ products can be deployed for telecommunications, interactive data transmissions, video, cable television and various enterprise applications. The scalability of the design lends itself well to local area network applications. When interfaced with electrical wave-guide information, computer cards using this technology can bring information directly to computers and set-top boxes for almost any application.

SilkRoad Optical Wave Concentrator (OWC™)

SilkRoad OWC™ products utilize Optical Phase technology in conjunction with SRSC™ technology to increase the amount of bandwidth that can be sent over one wavelength. The first phase SilkRoad OWC™ product is designed as an eight (8) sub-laser wavelength concentrator onto a single wavelength, but this number can be increased over time. SilkRoad OWC™ products work in conjunction with SilkRoad SRSC™ products.

The product detector used in SilkRoad OWC™ is different than the SRSC™ product detector, although they are based on the same architecture.

The only application of SilkRoad OWC™ products is to concentrate more than one SRSC™ signal set onto one wavelength. SilkRoad OWC™ products consist of a transmitter and a detector and integrate a customer solution into a single product.

SilkRoad Optical Signal Conditioner™ (OSC™)

The SilkRoad regeneration unit is a self-contained network element unit that has the ability to take a multi channel SRSC™ optical signal input, reconvert it to the RF form, and remodulate it back onto the fiber. There are two implementations of SilkRoad OSC™ products: one with the use of Optical Phase technology in conjunction with SRSC™ technology; and one with SRSC™ technology only.

SilkRoad OSC™ products work primarily as signal regenerators for distance applications. These products provide our customers with a low cost means of boosting the signal to the original characteristics of the generated signal at the last central office location in the network.

Beyond that, the products can be used for improved signal management in the network by filtering out unwanted signals and transferring the proper signals further down the network. OSC™ implementation can potentially accept multiple SRSC™ signals from various sources and redistribute only the necessary signals further down the network.

SilkRoad OSC™ products regenerate signals in a self-contained and self-powered unit (Figure 3.5), and can therefore be deployed in sub-marine and long-distance land applications

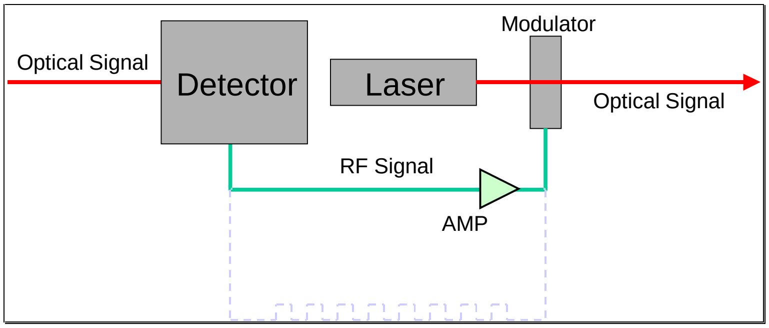


Figure 3.5 The SilkRoad OSC™ Solution

SilkRoad OSC™ products are controlled and managed via the service channel on the SRSC™ spectrum and work with the same software systems as SilkRoad SRSC™ products. The modular design concepts and architecture in SilkRoad products are continued in SilkRoad OSC™ products. OSC™ products have an optional filter bank that can be used for signal management to combine wavelengths from various sources and distribute only those that are needed further down the network.

Reliability Standards

The standard Mean Time Between Failures (MTBF) is divided between data failure and equipment failure. For optical transmission channel delivery products the standards are as follows:

- Bit Error Rate (BER) rates of less than10^{-15}
- System MTBF 50,000 hours

A key factor in ensuring these standards is component and subsystem selection and testing. A calculated BER and MTBF for each subsystem component is calculated with these standards in mind. Stringent reliability testing is always required for the overall communications system, in addition to component verification.

4. Network Architecture

Dispensing with Known Limitations

SilkRoad's solution for long-haul networking combines the transport and switching layers that are normally divided in DWDM and SONET systems. The merging of these layers increases reliability, speed, and bandwidth while decreasing equipment costs and infrastructure requirements compared to a SONET/DWDM system.

Our network is a high bandwidth solution that combines a long-haul express network and a local loop network into a similar architecture. Most current long-haul networks are using or considering the use of DWDM for optical transport and SONET for electrical switching. However, most users realize that both SONET and DWDM have significant drawbacks and that these networks are costly to build and maintain.

Most of the proposals for bolstering the performance of optical-based systems have assumed the use of multiple wavelengths to provide expanded bandwidth. Optical Cross Connect (OCX) has been suggested as a solution to free the loop of SONET.

However, any multiple-wavelength system, such as DWDM with an OCX network environment, brings a set of fundamental problems that must be addressed:

- DWDM requires costly optical components, thermal control, software control, and maintenance for reliable long-haul signal transport.
- DWDM prohibits boosting of the signal level to reach greater distances due to chirping interference.
- DWDM fails to meet bandwidth goals without major infrastructure and data management costs.

SRSC™ echnology avoids these problems, allowing for lower initial costs and greater long-term flexibility for capacity growth. Figure 4.1 shows SilkRoad's approach to the future of transport technology, eliminating any need for the SONET layer.

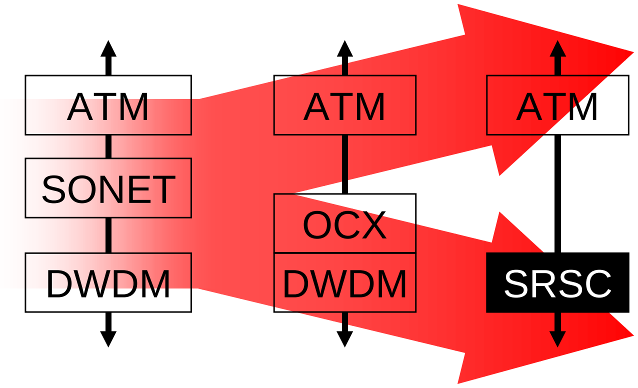


Figure 4.1 The Future of Switching

While DWDM hopes to eliminate the SONET layer by using OCX, SilkRoad's SRSC™ dispenses with both SONET/multiple-wavelength transmission and cross connect technology to deliver the performance that DWDM has not yet been able to achieve.

More processing at the optical level

At its heart, SilkRoad SRSC™ is a *broadcast* technology. That is, every channel transmitted from a node goes to every other node on the ring. SilkRoad SRSC™ does not demultiplex and remultiplex the optical signal that travels around the ring. The ring is a continuous loop of fiber, which includes:

- Optical Signal Conditioners (SilkRoad OSC™) that maintain a clear signal over long distances.
- Optical splitters that bring the signals from the ring down to a node, while also allowing signals to continue around the ring (Figure 4.2).

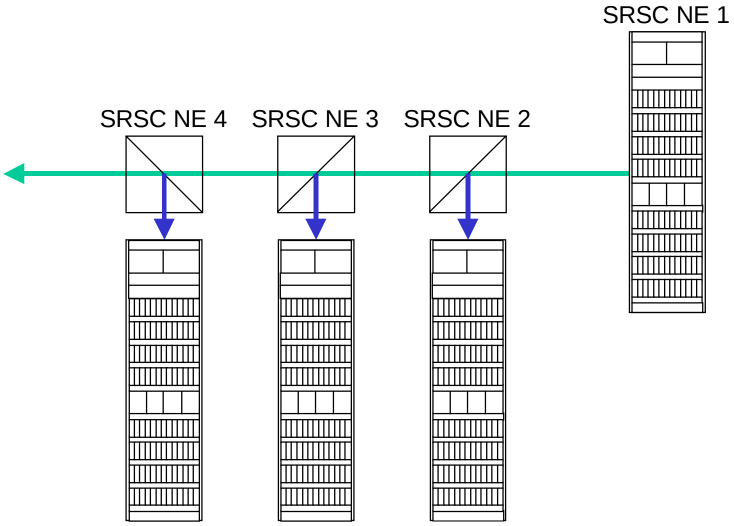


Figure 4.2 Signal Drop at SilkRoad SRSC™ Node

Since every node receives *all* of the signals, every node can access any channel on the system. In this basic configuration the SilkRoad SRSC™ node is in a drop-and-continue mode. *All channels are dropped at the node, and all channels continue*.

Add/drop filtering that does not subject the transport signal to electronic processing.

To move from a drop-and-continue configuration to a full add/drop system, any SilkRoad SRSC™ node can add its own channels to the ring and make them available to other nodes, combining its own beam with the existing beam on the fiber ring (Figure 4.3).

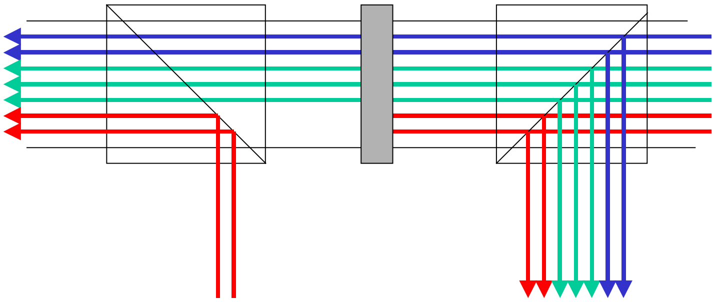


Figure 4.3 Add/Drop at SilkRoad SRSC™ Node

Since a SilkRoad SRSC™ ring is an uninterrupted fiber conduit, every channel signal will eventually return to its original node. When a signal arrives at the receiving side of the SilkRoad SRSC™ node, the channels that originated at that node are filtered from the signal (Figure 4.4).

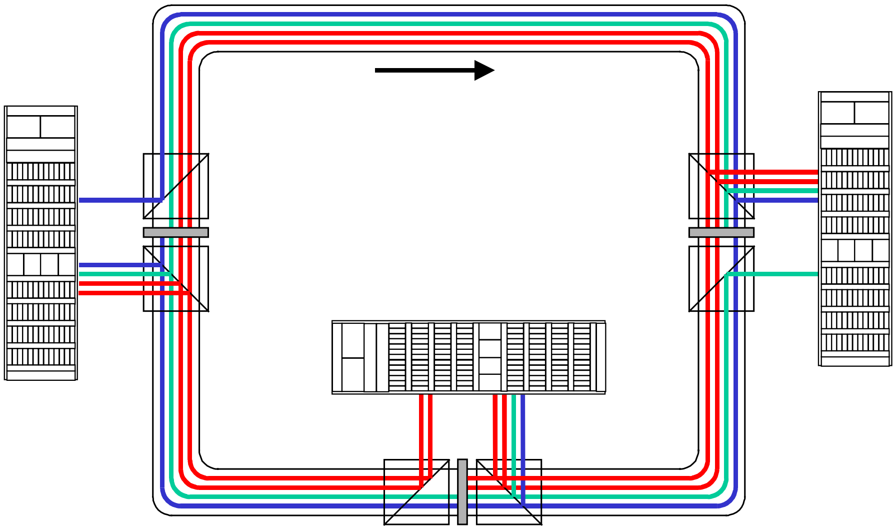


Figure 4.4 SilkRoad SRSC™ Add/Drop in a Ring

This filtering ensures that the allocated channels for that node are cleared so the arriving signal does not interfere with the newly generated signal from that node. The newly generated signal is then combined with existing channels on the ring, filling in the empty frequency space

In contrast, DWDM/SONET solutions require the entire signal to be brought off the fiber through the DWDM equipment. The SONET equipment processes the adds and drops electronically (Figure 4.5), and the optical signal is then reconstructed and placed back on the network.

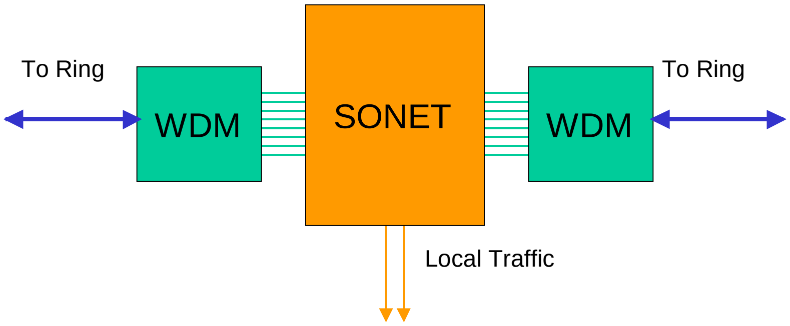


Figure 4.5 Traditional DWDM/SONET Ring Solution

This configuration requires DWDM termination equipment on the end of every fiber and a SONET box that processes the entire system throughput. Facility, support, and maintenance costs make this system expensive, and when those costs are added to the cost of the systems themselves, the DWDM/SONET combination becomes a costly lifecycle solution for networking needs.

Because SilkRoad SRSC™ adds, drops, or continues channel signals at the optical level, we eliminate both the DWDM and SONET add/drop multiplexing equipment from the loop (Figure 4.6). In place of racks of equipment, SilkRoad offers a simpler system that requires less maintenance, support, and floor-space in the POP.

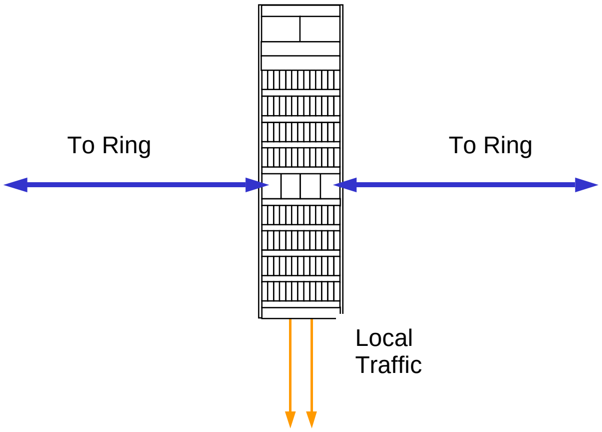


Figure 4.6 SilkRoad SRSC™ Replaces both DWDM and SONET

The SilkRoad method of adding and dropping channels gives SRSC™ a significant advantage over competing technologies:

- Channels are not separate wavelengths of light. Each channel can be selectively add/dropped at the optical level independent of the bandwidth that channel is carrying.
- Traffic is add/dropped at the optical level, so there is no delay for demultiplexing or regeneration as the signal passes around the ring. Gateway switching is the only delay in signal propagation over the entire network.
- SilkRoad SRSC™ provides point-to-point circuits over a ring. Each channel will represent an OC-XX signal that can pass between any two nodes on the ring.

SilkRoad SRSC™ Ring Redundancy

Four usable signals provide TRIPLE redundancy

As shown in Figure 4.7, the nodes on a SilkRoad SRSC™ ring may have unidirectional two-fiber or four-fiber connections.

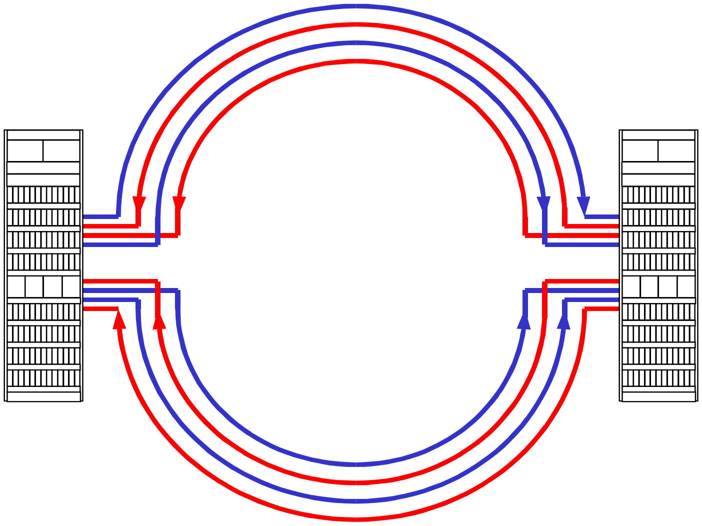


Figure 4.7 Four Signal Paths between Nodes on a Ring

- In the two-fiber topology, the signal has two distinct paths.
- In the four-fiber topology, the channels have an extra level of redundancy due to the extra pair of paths for the signal.

In the four-fiber configuration shown above, the system safeguards against failure in up to three of the fibers and handles multiple failures in the terminating equipment. Since the signal comes in on four fibers, each node has four replications available for every channel. When not in a backup processing mode, the SilkRoad SRSC™ switch chooses channels based on the path distance between the channel endpoints.

At any time, the SilkRoad SRSC™ system can select from any of *four identical sources*, providing triple redundancy in the ring. Each node has dual transmitter/receiver pairs, with each transceiver working one direction of the ring (Figure 4.8).

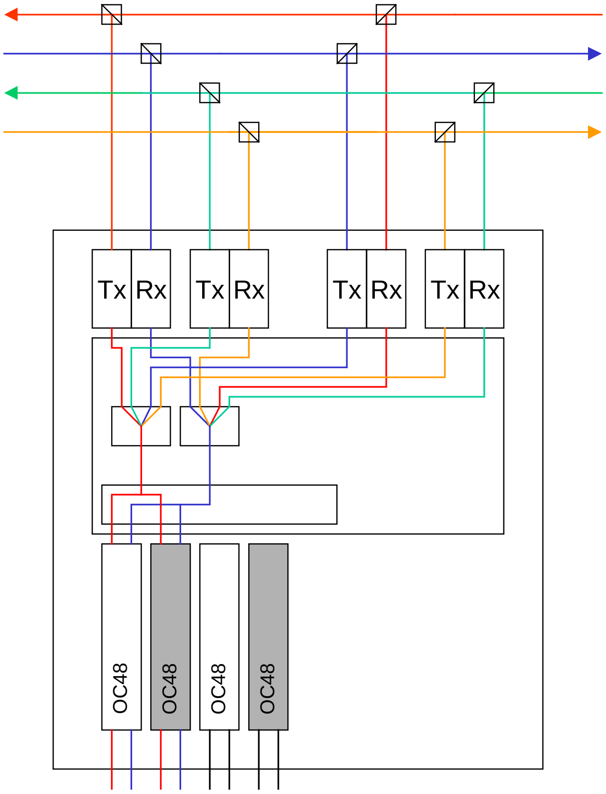


Figure 4.8 Four Fiber Redundancy

Since each SilkRoad SRSC™ node receives all four signals all the time, the system can constantly check for the availability of redundancy on the line. If a secondary redundant signal fails (a failure that may not immediately engage the redundancy features of the system) SilkRoad SRSC™ can instigate an alarm to the GNE/EMS/NMS system, providing network administrators with advance notice of potentially serious problems on the ring. This is a feature where the underlying SRSC™ broadcast technology allows SilkRoad SRSC™ to maintain availability and ring integrity on a proactive basis.

SilkRoad SRSC™ also provides superior fault tolerance against inter-ring gateway failures. Since all nodes receive all signals, secondary inter-ring gateways detect a loss of signal on inter-ring traffic from the primary gateway. The secondary inter-ring gateway can then engage the secondary inter-ring channels.

Figure 4.9 shows the primary path for a point-to-point OC-48-provisioned channel.

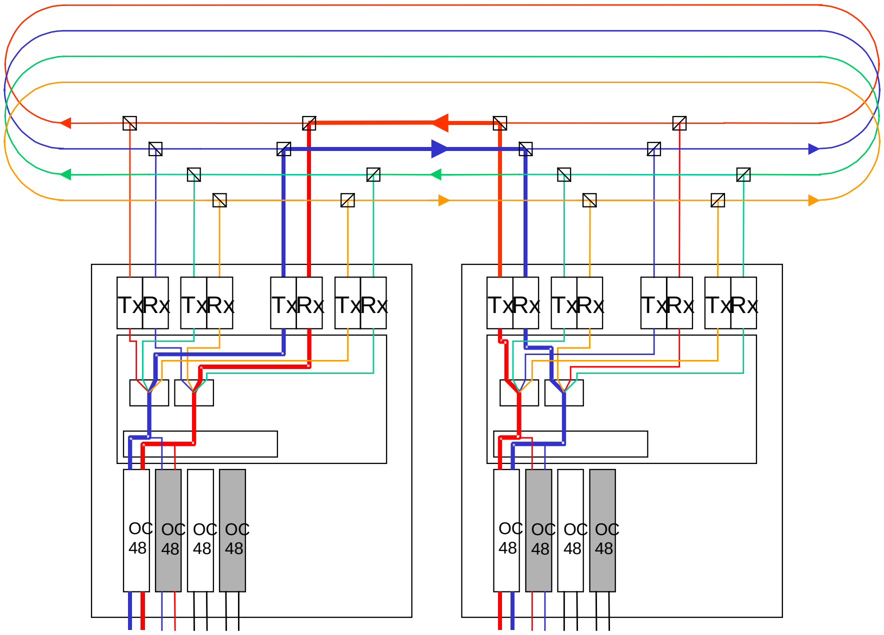


Figure 4.9 Primary Path Example

With signals coming in from four directions, the SilkRoad SRSC™ system must be configured to differentiate between the following available signals:

- At the top hierarchical level, the SilkRoad SRSC™ system is set to recognize a primary and secondary fiber pair. These pairs equate to the working and protect lines in SONET terms.
- At the interface module switch level, each interface card has a primary and secondary transceiver pair.

Since each transceiver pair transmits in only one direction (i.e. to the left or right of the ring) for each interface module, one transceiver services the shortest path signal and the other the longest path signal. The interface module I/O matrix must be set to use the shortest path signal as the primary and the longest path signal as the secondary. Either the SilkRoad SRSC™ internal processor automatically sets the IMSM, or an operator can set it.

Single failure on the primary cable

If the SilkRoad SRSC™ receiver detects a single failure on the primary fiber or a component failure on the shortest route, it will automatically switch to the secondary fiber pair.

Switch times vary depending upon the type of failure. If the detector module loses a signal, it automatically switches over within 2 milliseconds. If an interface module detects an increase in the BER, it will engage the switch-over through the NE processor within 10 milliseconds. The SilkRoad SRSC™ system handles these failures quickly because a loss or degradation of the signal triggers a fail-over without engaging the EMS. Figure 4.10 shows the new signal path after a primary, shortest-path failure.

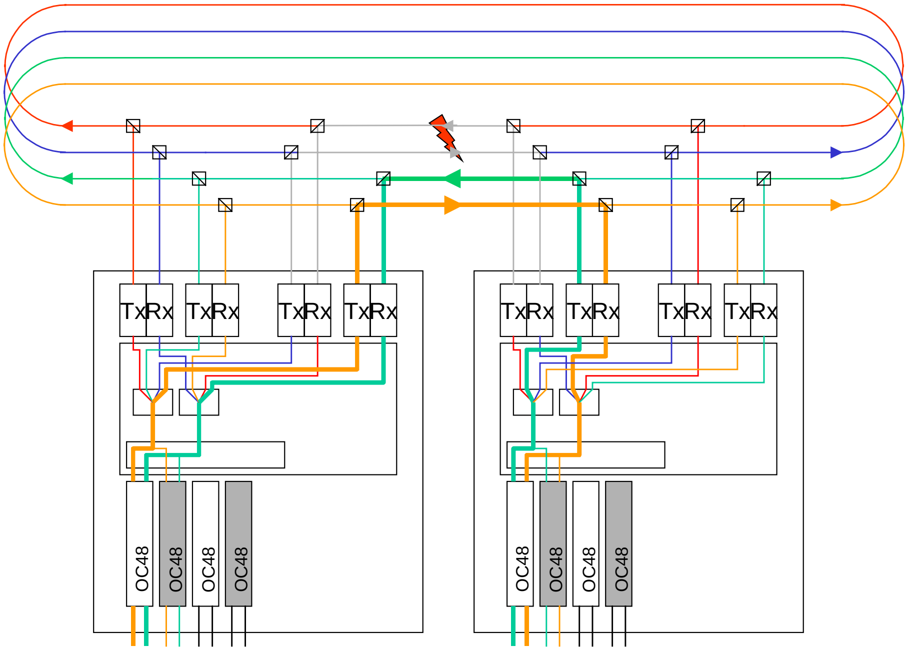


Figure 4.10 Primary, Shortest-Path Failure

Failures on both the primary and secondary cables

Figure 4.11 shows failures on both the primary and secondary fiber pairs along the shortest path of a provisioned channel.

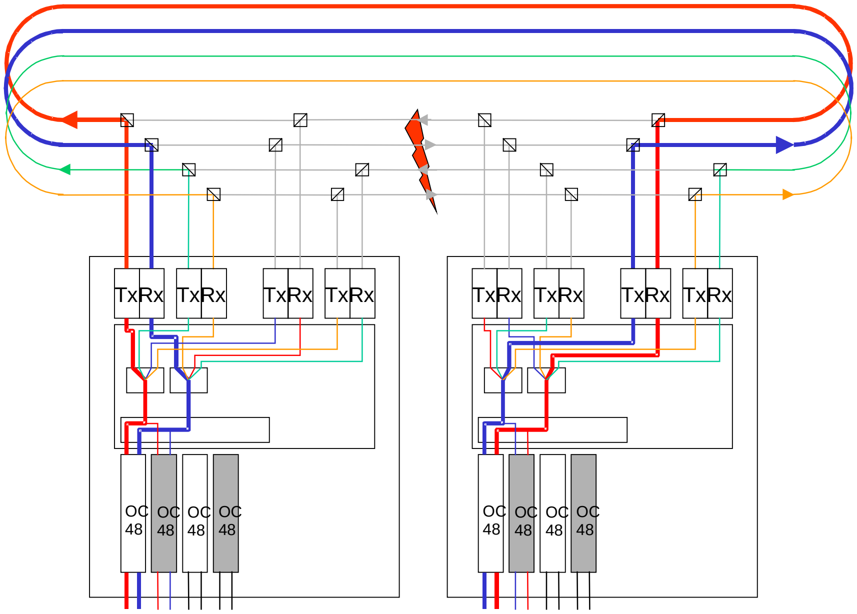


Figure 4.11 Failure in Primary and Secondary Fibers, Shortest Path

The following circumstances trigger the switch matrix to transfer to the signal from the transceiver for the opposite direction, or longest path:

- The switch matrix monitoring the transceiver which services the interface module detects a loss of signal.
- The interface module detects degradation.

Note that this is not a *working* and *protect* transceiver in the traditional sense. Both modules are working, and the switch matrix is programmed to use either signal on an individual interface/module basis.

Like the single failure, a loss of signal from the transceiver triggers the switch in a double failure. The fail-over occurs automatically without the need to either engage the software management system or re-route traffic onto a secondary fiber pair. The signal is already being transmitted through the secondary fiber, so the switchover is less than 2 milliseconds.

Failure on three cables

Figure 4.12 shows how SilkRoad SRSC™ recovers from failures on three cables. Using four simultaneous signals SilkRoad SRSC™ allows the system to continue even with a third cable break. In this case, a failure occurs on both primary rings and on the secondary ring in one direction, but the signal still gets through via the one remaining fiber of the secondary ring.

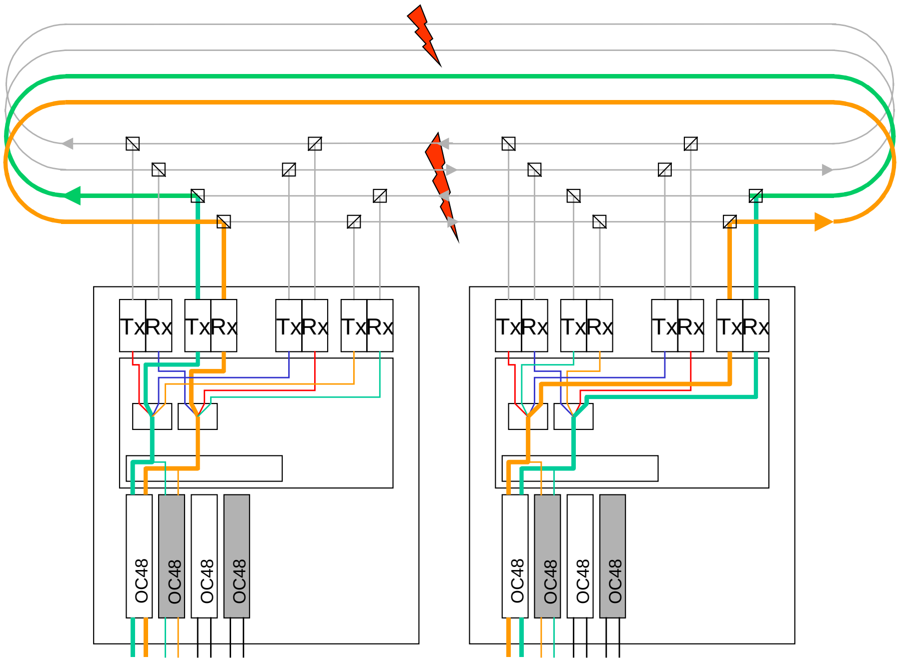


Figure 4.12 Triple Failure

Contrast this with a SONET BLSR ring, which needs both the *working* and *protect* fiber pairs to handle a multiple failure that involves traffic travelling the long way around the ring. *SilkRoad SRSC™ can move 100% of the data with only a single fiber between its nodes*.

Redundancy at the inter-ring gateway

When SilkRoad SRSC™ is deployed in an inter-ring gateway configuration, both the primary and secondary gateways are provisioned to carry 100% of the necessary inter-ring traffic. One site is configured as the primary gateway and is normally transmitting the traffic between the rings. Upon failure of the primary gateway, the secondary gateway will detect a loss of the inter-ring traffic, as shown in Figure 4.13.

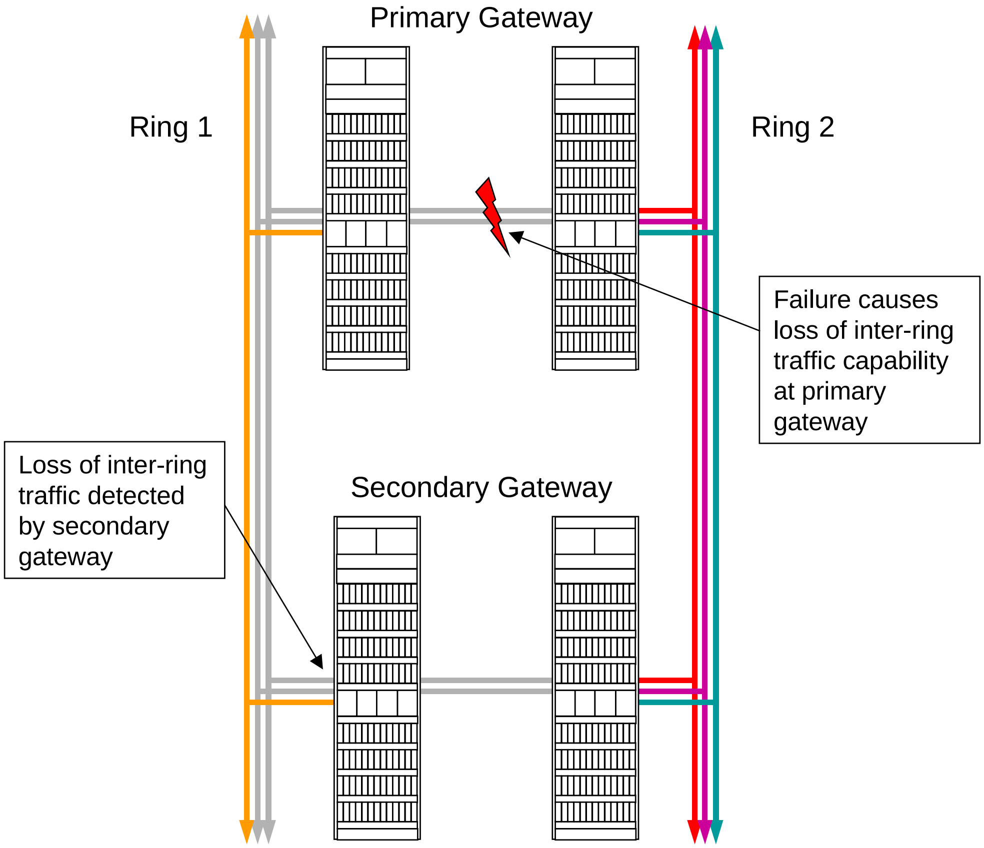


Figure 4.13 Inter-Ring Configuration

Once the secondary gateway detects a signal loss or degradation, it instantly starts moving traffic between the rings via its pre-provisioned interface modules, as shown in Figure 4.14.

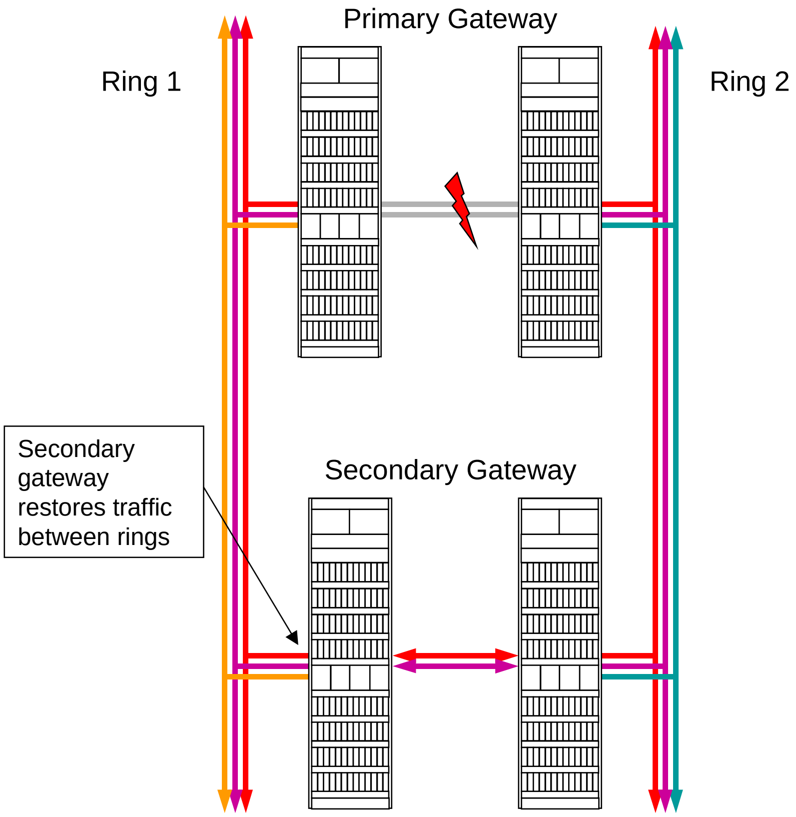


Figure 4.14 After Problem is Detected

Network Span Design

SilkRoad OSC™ does not amplify noise

SilkRoad's long-haul network solution places SilkRoad OSC™ signal conditioners every 200 kilometers on the SRSC™ ring. Traditional SONET EDFA optical amplifiers must be installed at more frequent intervals.

Each time a signal passes through an EDFA amplifier, system noise is amplified with the signal. Figure 4.15 shows how amplified noise eventually saturates an EDFA system and makes a signal unusable to the point where it requires full regeneration.

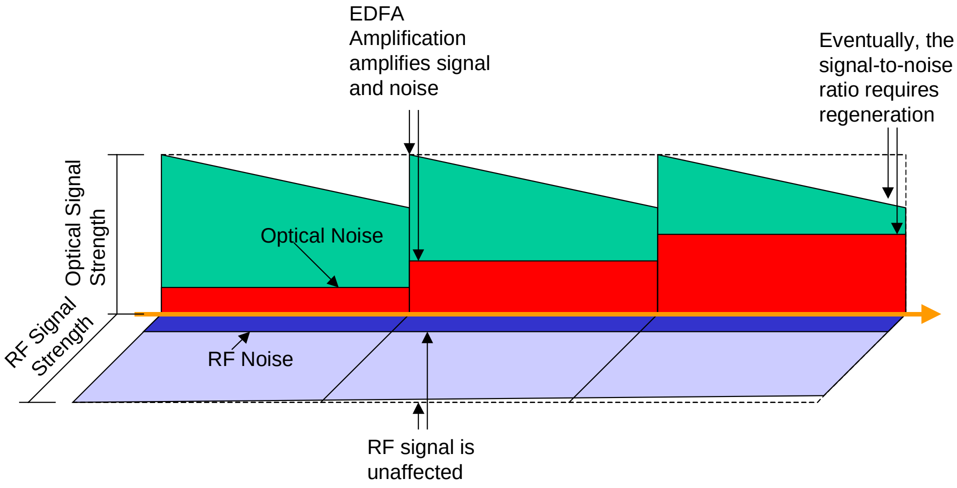


Figure 4.15 The Consequence of SONET/EDFA Noise Amplification

Another major problem with SONET amplification/regeneration systems is that they can only process the signal at the digital (electronic) level. This slows the signal processing and makes it more complex.

SilkRoad OSC™ does not require digital regeneration. Instead, it reconditions the optical RF signal, creating a new optical signal without amplifying the noise. Using SilkRoad OSC™ in place of SONET removes the problems of amplification and regeneration and allows for more flexible span designs.

SilkRoad OSC™ and SilkRoad SRSC™ can be used in any combination at varying span distances. Because the SilkRoad OSC™ system provides a new optical signal, the signals can travel much farther than those in SONET-based systems. Figure 4.16 shows SilkRoad OSC™ signal conditioning.

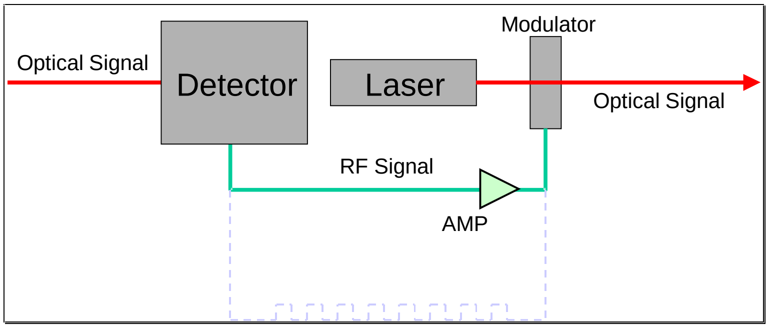


Figure 4.16 SilkRoad OSC™'s SRSC™ Signal Reconditioning

Figure 4.17 shows that SilkRoad OSC™ signal conditioning does not increase the level of optical noise over distance.

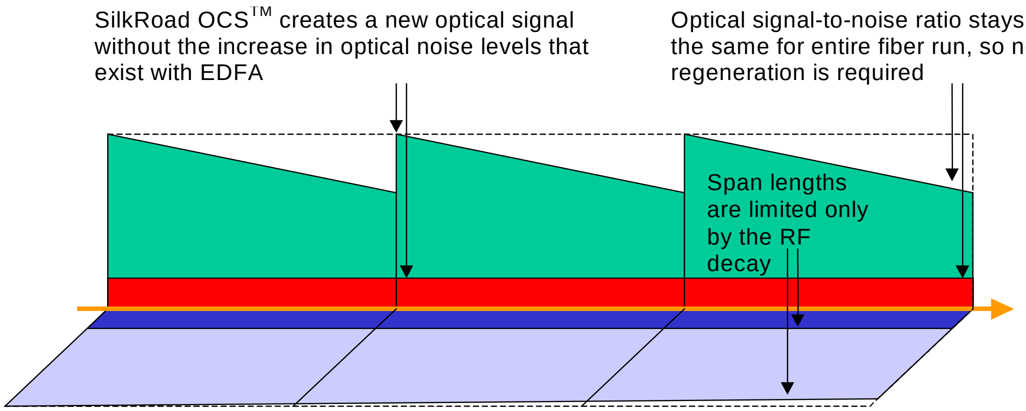


Figure 4.17 SilkRoad OSC™ Optical Noise Levels vs. EDFA

Signal-to-Noise Ratios

The SilkRoad SRSC™ system has the following power output and input specifications:

- Output signal: 15 dBm
- Input signal: 4 dBm to -40dBm

The SRSC™ signal at 1550nm conforms to the specification of 0.25 dB/km. This allows our signal to propagate 200 kilometers before the need to recondition the signal. The Optical Signal-to-Noise ratio (OSNR) of SilkRoad SRSC™ is approximately 15.3. Figure 4.18 compares OSNR to BER ratings.

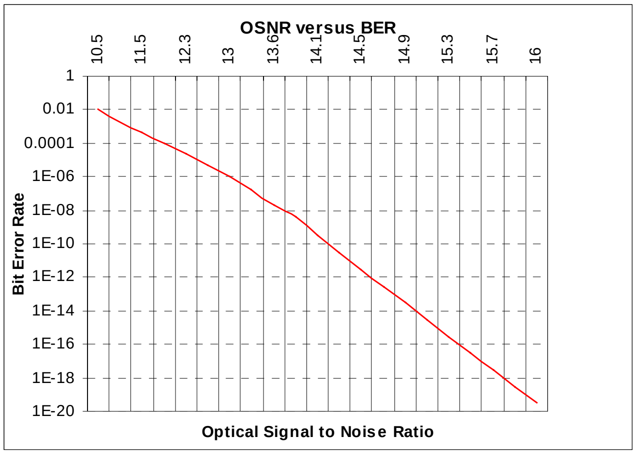


Figure 4.18 OSNR Compared to BER

Current OSNR numbers and experimental results show the SRSC™ BER to be less than the maximum allowed 10^{-15} *without* Forward Error Correction (FEC). On the electrical side, our ESNR is approximately 30.6, which also correlates with a BER of less than 10^{-15}. Figure 4.19 compares ESNR with BER.

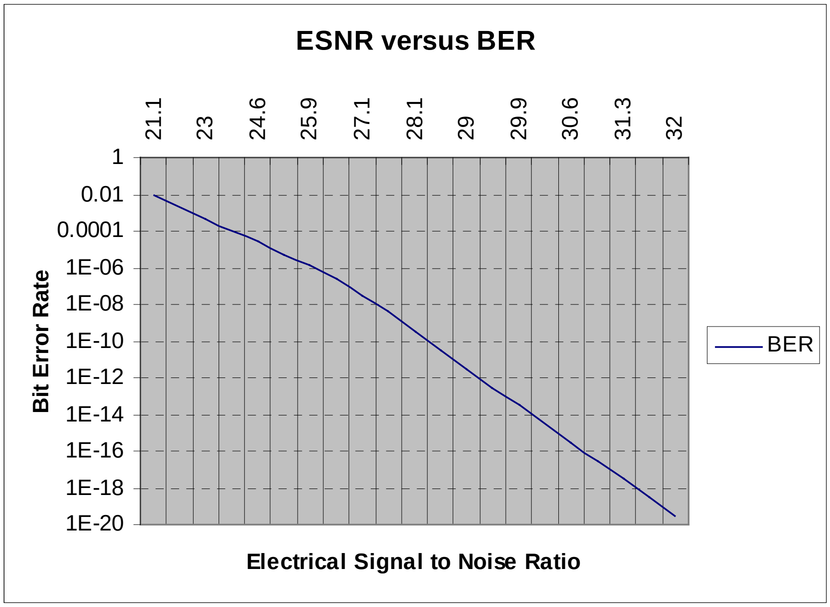


Figure 4.19 ESNR Compared to BER

SilkRoad SRSC™ design eliminates the need for separate BLSR and UPSR rings

Unlike a node using SONET Add/Drop Multiplexers (ADM), SilkRoad SRSC™ nodes do not interrupt the ring, so a signal placed on the ring is not converted from optical to electrical and then back to optical. Each SilkRoad SRSC™ ring is an uninterrupted optical path, with nodes adding and dropping channels as needed. This greatly improves transmission speeds. Propagation time through the SilkRoad SRSC™ system is less than 0.5 milliseconds.

Since the signal propagates around the ring uninterrupted, most of the delay occurs in the flight time around the ring. For a typical loop (Figure 4.20), total time for a complete traversal is less than 6.3 milliseconds from ingress to egress, so the signal will not spend more than 6.5 milliseconds on the ring.

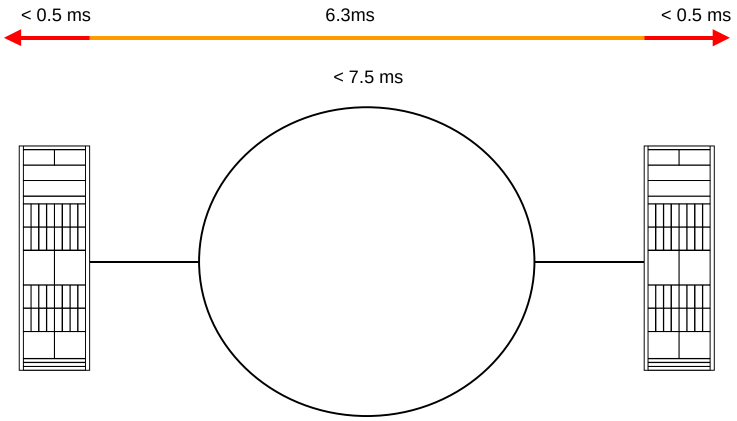


Figure 4.20 Propagation Delay Across a Typical Ring

As an even more vivid example of propagation delay, consider a seven ring interchange over a typical 10,000 kilometers of fiber linking New York to Los Angeles (Figure 4.21). Signal transmission requires more than 49.2 milliseconds. Of this amount, the flight time on the rings is approximately 43.5 milliseconds, and less than 6 milliseconds result from SilkRoad SRSC™ system delays.

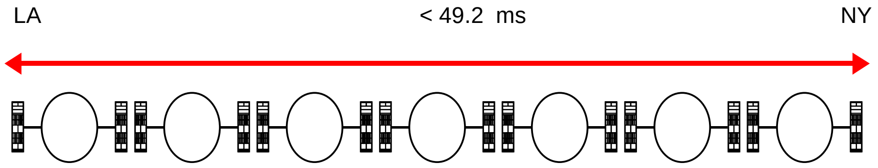


Figure 4.21 Propagation Delay from New York to Los Angeles

T*here is no need to provide separate BLSR and UPSR rings under the SilkRoad SRSC™ system*. Instead, all traffic can move on the same physical and logical ring system without the need to distinguish between *express* and *local* traffic. This allows a more flexible provisioning model, since many customers are not locked into fixed bandwidths for local or express traffic.

Because SilkRoad's propagation delays in the ring are low compared to SONET, we process both local and express traffic through the same systems by simply provisioning the number of cards based on the bandwidth assumptions supplied by our customer. This provides a much more flexible provisioning model that allows our customers to allocate more or less bandwidth to local versus express traffic as network demand dictates.