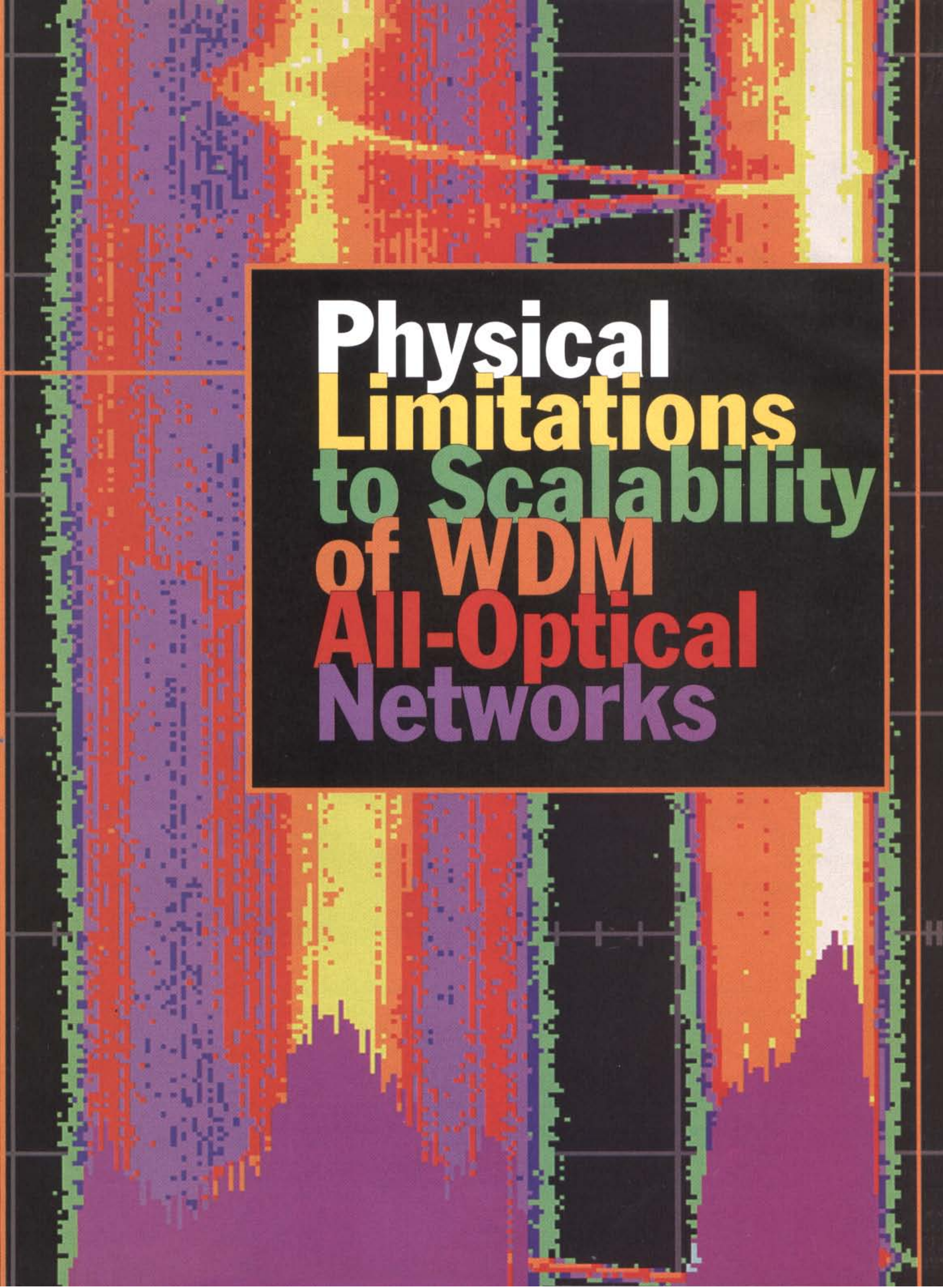
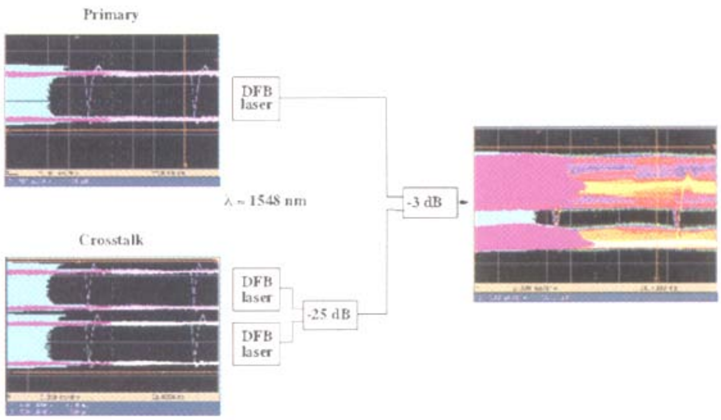
Physical Limitations to Scalability of WDM All-Optical Networks



By Daniel J. Blumenthal, Michael Shell, and Mark D. Vaughn

Wavelength division multiplexing (WDM) takes advantage of optical fiber's tremendous bandwidth. To get the most from an all-optical network, researchers must understand the physical limitations of WDM networks and how to overcome them. Signal degradation, attenuation, distortion, and crosstalk all influence the ability to expand WDM, all-optical networks.

The explosive growth of telecommunications and computer communications has placed increasing demand on the national and global communications infrastructure. There is a worldwide effort to find new technologies that will support our future networking needs. A global research effort is currently underway to determine if Wavelength Division Multiplexed All-Optical Fiber Optic Networks (WDM-AONs) can meet these needs.



Eye Diagram. Upper left: Oscilloscope output of a typical eye diagram of a high SNR transmitter. Lower left: Oscilloscope output of two optical data streams that simulate interfering channels. Right: Oscilloscope output illustrating combined three data streams incident on a photodetector. The detrimental effect of coherent crosstalk causes the prominant closure of the upper eye level with respect to the lower eye level.

Wavelength division multiplexing (WDM) allows multiple users to share a fiber optic link or network in a manner similar to radio communications except that the carrier frequencies are at 10^{14} Hz! WDM takes advantage of the tremendous bandwidth of optical fibers, which is on the order of 25,000 GHz (25 THz). Approximately 1% of the electromagnetic carrier bandwidth can be modulated with information, meaning that a single optical carrier (wavelength) can ideally carry over 1 THz of information. Today, WDM links are designed so that several optical wavelengths are used to transmit moderate data rates in parallel. This is motivated by the cost of the transmitting and receiving electronics and the evolution of the existing fiber plant.

An analogy can be drawn between WDM and radio communications where 30 GHz of radio frequency (RF) bandwidth is available around the planet, yet we are able to select the desired 10 KHz using a $5 radio. A radio that could process ALL of the 30 GHz spectrum prior to delivering a single radio program would be prohibitively expensive. While the fastest research grade digital electronics operate up to 40 GHz, affordable, reliable electronics operate in the 100 MHz to a few gigahertz range. Therefore, WDM can play a key role in utilizing the fiber-optic bandwidth using current electronics. Point-to-point WDM fiber links are currently being deployed worldwide and provide a cost effective means to upgrade the capacity of existing fiber by adding additional wavelengths. While WDM has been studied in research laboratories for over 20 years, the field is finally coming to commercial realization due to advances in component technology and the maturation of field deployed systems.[1]

In practice, the usable bandwidth in a fiber link or network is lower than the 25 THz stated above and is determined by a complex interplay between the components and devices and the link or network architecture. Before discussing WDM-AONs, it is useful to look at a simple WDM transmission link where different wavelengths or "colors" of light

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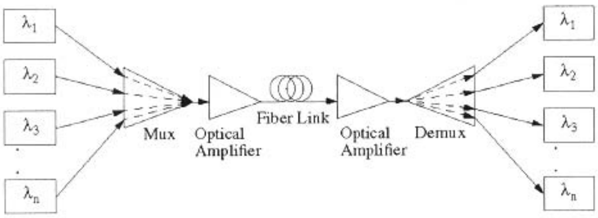

Figure 1a (above). A simple WDM transmission link: Different wavelengths of light, each carrying information, are combined at the input of an optical fiber and separated at the fiber output.

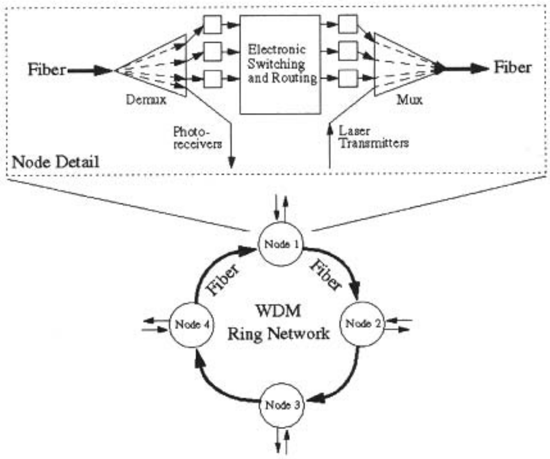

Figure 1b (right). A WDM ring network with optoelectronic regeneration: An extension of WDM point-to-point transmission links where electronic switches are used to add, drop, and pass through channels. Node detail illustrates optoelectronic conversion at the node inputs and outputs.

(λ_1, λ_2, . . . λ_N) are combined at the input of an optical fiber and separated at the fiber output, with each wavelength carrying different information (see Fig. 1a). Wavelengths are combined and separated using wavelength division multiplexers/demultiplexers.[2] WDM links may also contain optical amplifiers to periodically boost the optical signal levels of all WDM channels.[3] The important quality of a WDM link is that multiple optical channels are transmitted together and amplified simultaneously and are then converted to electronic signals only at the link output.

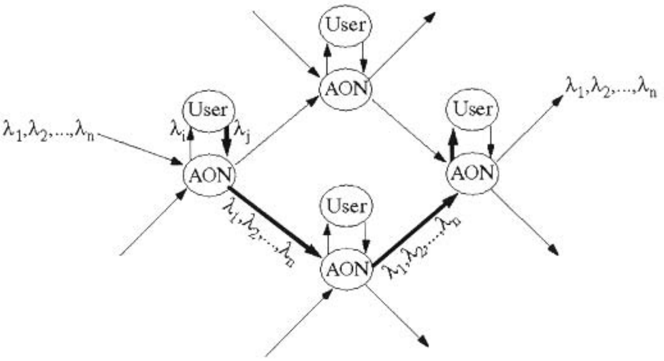

Figure 2. Generalized WDM-AON: Fiber-optic links connected by all-optical network nodes. Access to the network and connections within the network are achieved by "adding," "dropping," and"routing" wavelengths at each node.

WDM transmission links can be used to construct WDM networks. Networks are more complex than transmission links since they connect a large number of users in a flexible, efficient manner, using less links than it would take to connect each user to all other users. This requires that users have "shared access" to the network, where time on the link and/or bandwidth is shared over multiple wavelengths. Networks are characterized by a number of factors, including connectivity, flexibility, reliability, scalability, manageability, robustness, level of performance, and fault-tolerance.[4] Scalability is a measure of how well a network can support the addition and removal of users as needed, the maximum number of users supported, the geographical area that can be covered, how the performance degrades with increasing traffic, the required number of wavelengths needed for a given number of users, and the maximum bit rate per wavelength. In this article, we discuss scalability as it relates to the physical aspects of the network and not the architecture or protocols.

As an example, consider the straightforward extension of WDM point-to-point transmission links to a "ring" network as illustrated in Figure 1b. Each fiber link begins and ends at a network node. At each link output, individual wavelengths are separated using demultiplexers in a manner similar to the way prisms or gratings separate the colors of white light into a rainbow spectrum, and are then converted to electronic signals using photoreceivers. An electronic switch inside the node "drops" a channel off the ring or "bypasses" it back onto the ring. The switch can also "add" new signals from the user onto the ring. Each output of the switch is retransmitted on a different wavelength and re-

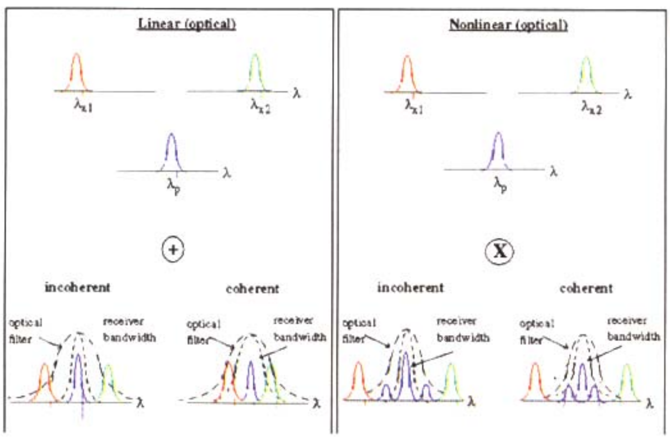

Figure 3. Left: Linear optical crosstalk does not generate new optical frequencies. Right: Nonlinear optical crosstalk results in generation of new optical frequencies. In both cases, the optical and electrical filter bandwidths are illustrated by dashed and dotted curves. Channels can interfere incoherently or coherently at the photodetector.

combined using a wavelength multiplexer. This implementation is called a regenerative optoelectronic WDM network[5] where optical signals are converted to electronic signals at each node.

WDM-AONs

Here we review the physical limitations in WDM-AONs and how these limitations influence network scalability. In contrast to optoelectronic WDM networks, WDM-AONs extend the WDM transmission concept to the network level. Communications "paths" are established between different users and each path appears as a point-to-point WDM link without optoelectronic regeneration at the nodes. The transmitted data remains as an optical signal throughout the network—hence the term "all-optical." While the user data is "all-optical," certain signals used to control the network functions may be extracted and converted to electronic signals at each node.[6] A primary motivation for studying AONs is the potential "transparency" to bit-rate and signal format that results from the large transmission and switching/routing bandwidth and the absence of digitally clocked buffers within the nodes. Transparency describes a network that allows a continuous range of bit-rates, different types of traffic, and possibly supports both digital and analog signals. However, it is precisely these desired characteristics that make WDM-AONs analog by nature, giving rise to issues that can adversely affect scalability.

Figure 2 illustrates a generic WDM-AON with fiber-optic links connected by "all-optical" network nodes. The nodes allow users to add and drop data from the network in addition to determining how signals are connected from the node inputs to its outputs. For two users to communicate over the network, a "path" is set up over a series of links and nodes. Access to the network and connections within the network are achieved by "adding," "dropping," and "routing" wavelengths at each node. Therefore, a distinguishing feature of WDM-AONs is that while each fiber link carries optical wavelengths $(\lambda_1, \lambda_2, \ldots \lambda_N)$, the origination of these wavelengths varies from link to link. This feature, known as "wavelength reuse," allows the number of users in a network to be larger than the number of wavelengths.[7] Another important characteristic of WDM-AONs is that each path is essentially a point-to-point WDM link with two important modifications: 1) Signals travel through a variety of optical and photonic devices and components necessary for network functions, and 2) the actual data and number of wavelengths that coexist in the fibers can change from link to link. An example of an all-optical path is illustrated in Figure 2. Optical preamplifiers and booster amplifiers are used at node inputs and outputs to compensate for link and node losses. An internal optical switch or router connects each wavelength independently between input ports, output ports, and the user. An electronic node computer mediates how the inputs, users ports, and output ports are connected so that identical wavelengths from multiple inputs are not sent to the same output.

Type of Degradation	Sub-type	Source
Crosstalk	Linear (optical)	WDM mix/demixes
		Optical filters
		WDM add/drop
		Photonic switches
	Nonlinear (optical)	Fiber nonlinearities
		Optical amplifier nonlinearities
Signal Attenuation	Linear (optical)	Fiber loss
		Fiber dispersion
		Optical filter cascading
	Nonlinear (optical)	Fiber nonlinearities
		Optical amplifier gain saturation
Signal Distortion	Linear (optical)	Optical frequency passband misalignment
		Fiber dispersion
	Nonlinear (optical)	Fiber nonlinearities
		Optical amplifier gain saturation
Noise Accumulation	Nonlinear (optical)	Fiber nonlinearities
	Linear (electrical)	Additive receiver noise
		Additive ASE
	Nonlinear (electrical)	ASE-signal beating
		ASE-ASE beating

Table 1. The four major degradation mechanisms can be classified as linear or nonlinear and can be attributed to various physical effects in the network as shown in the right hand column.

Signal degradation mechanisms

The scalability of a WDM-AON is intimately linked to the way optical signals interact with the physical network and the overall network architecture and protocols. The physical interaction can lead to degradation of signal quality. There are multiple causes of signal degradation that occur as optical signals propagate between two users in an WDM-AON including: signal attenuation, crosstalk, signal distortion, and noise accumulation as shown in Table 1. These effects reduce the signal-to-noise ratio (SNR) at a photoreceiver, resulting in bit errors in digital systems or distortion in analog systems.

The four degradation effects can be further classified as linear (optical), linear (electrical), nonlinear (optical), and nonlinear (electrical). In the linear (optical) case, there is no coupling between the wavelengths and no new wavelengths are generated. Additionally, signal loss and fiber dispersion occur independently for each frequency in the fiber, amplifiers, and nodes. The linear (electrical) case refers to photodetection using a square-law detector followed by a filter that passes only the baseband signal and rejects higher order frequencies. The nonlinear (optical) case refers to coupling between wavelengths and possibly the generation of new optical frequencies (wavelengths) in optical components like fibers and amplifiers. Nonlinear (electrical) refers to the generation of new frequencies during square law detection at the photodetector with the photoreceiver bandwidth large enough to pass these new frequencies. The physical effects that contribute to each linear and nonlinear category are listed in the right hand column of Table 1.

The basic problem in designing the physical portion of a WDM-AON can be summarized as follows: The SNR will degrade due to optical amplifier noise as well as link and node losses. Therefore, the power of an individual wavelength as it is launched onto the network must be strong enough to provide an acceptable SNR at the receiving user. This might lead one to believe that increasing the input power will improve the SNR. However, increasing the signal power can lead to crosstalk, amplifier distortion, and power dependent signal attenuation. The result is that the transmitted power per wavelength must be strong enough to overcome noise and losses but not so strong as to induce crosstalk and distortion. Reasons to limit the input power per wavelength are that increasing optical power in one channel can introduce crosstalk into the other channels, and increasing optical power can distort the signal in the fiber and optical amplifiers.

Signal attenuation

Signal attenuation occurs when power in any wavelength is "removed," "blocked," or "misdirected" from its primary destination. Linear attenuation can occur in the optical fiber during multiplexing/demultiplexing and within wavelength selective node components. A not so obvious source of loss is optical nonlinearities in fibers and amplifiers that deplete the power in one wavelength to generate new wavelengths. Another not so obvious source of signal attenuation is propagation of a signal through cascaded optical filters. When optical filters are cascaded, the passband becomes narrower than that of any single filter—even if the passbands of the filters are in perfect alignment! This effect, coupled with the fact that, in practice, there will be misalignments between the filters and wavelength of the data source, will reduce the overall received optical power at the final destination.

Consider the effect of signal attenuation in a fiber-optic link that transmits binary bits (ones and zeros) in the presence of fiber and node losses with optical amplification. The quality of the received signal can be determined using an "eye diagram," which is defined as a composite picture of received random "zero" and "one" bits. Such a diagram is seen on page 17. The "opening" of the eye is a measure of the received SNR. An example eye diagram for a high SNR signal is shown in the upper left oscilloscope output of the image. Optical signal loss due to the fiber and nodes will reduce the "height" of the eye, where the height is measured as the distance between the average "low" level and average "high" level. Optical amplifiers are used at the node inputs and outputs to cancel out losses and restore the eye height. However, the use of optical amplifiers introduces noise in the form of amplified spontaneous emission (ASE) into the signal path.[8] In addition to converting the desired signal, the receiver will also convert noise due to ASE and the square law detection of ASE with the signal. The result will be to "smear" the low and high levels and essentially "close" the eye opening, which leads to decreased SNR and increased digital errors.

Crosstalk

Crosstalk is the leakage or transfer of information from one received wavelength channel to another received wavelength channel. It is a primary issue in WDM-AONs and can be classified as linear or nonlinear. Crosstalk is especially important in WDM-AONs due to the cascading of multiple fiber links, optical amplifiers, and network nodes over any given path. Since linear and nonlinear crosstalk occur simultaneously, it is important to understand how each is characterized. Linear crosstalk can be caused by leakage of unwanted optical power from adjacent wavelengths through an optical filter, multiplexer/demultiplexer, photonic switch, or an add/drop element.[9] Linear crosstalk can also occur between time slots in digital systems due to fiber dispersion, also referred to as intersymbol interference (ISI). Nonlinear crosstalk can occur between multiple wavelength channels through optical nonlinearities in the optical fiber[10] or in optical amplifiers[11] since new optical frequencies can be generated that coincide with the desired signal wavelength. Nonlinear optical crosstalk is much worse in cascaded fiber/amplifier chains. Linear (optical) crosstalk is illustrated in the upper left portion of Figure 3 (page 18). In this case, the signal propagating in the network is the linear combination of individual wavelengths. The photoreceiver or wavelength selective elements will select one wavelength in the presence of other wavelengths that can interfere at the photoreceiver. This case is illustrated by the optical filter passband shown in the lower left hand portion of Figure 3. The portion of adjacent wavelengths that pass through the optical filter passband will be converted to an electronic signal by the photodetector. Nonlinear (optical) crosstalk is illustrated in the upper right portion of Figure 3. Here, new optical wavelengths can be generated by various effects in the optical fiber[10] and optical amplifiers[11] and include four-wave mixing (FWM), cross- and self-phase modulation (XPM, SPM) and stimulated Brillouin and Raman Scattering (SBS, SRS). The new optical frequencies can fall within the optical filter bandwidth at the photoreceiver.

Once the signal is detected at the photoreceiver, crosstalk can be further classified as incoherent or coherent as shown in the lower portions of Figure 3. At the photoreceiver or within the node, the desired channel is isolated with a wavelength selective device like an optical filter. Power from wavelengths other than the desired channel that pass through the optical filter will be converted to an electrical "crosstalk" signal. If the photoreceiver electrical bandwidth, indicated by the narrower filter passband (dotted line), is much narrower than the spacing between interfering signals (*e.g.*, 10 times) then the output of the receiver will be a linear sum of the desired and crosstalk channels and this is referred to as incoherent crosstalk. However, if the electrical receiver bandwidth encompasses the desired channel and some portion of the interfering channels, then the crosstalk can be much more severe than the incoherent case. This can be thought of as nonlinear (electrical) crosstalk and is referred to as coherent crosstalk.

Coherent crosstalk is extremely detrimental to WDM-AONs and is illustrated experimentally in the diagram on page 17. The upper left trace is an input data stream that needs to be detected with very few bit errors. Due to any number of crosstalk mechanisms in the network, the two digitally modulated channels shown in the lower left of the diagram contribute power at the photoreceiver within the optical and electrical receiver bandwidths. This is the case of coherent crosstalk and results in a drastic closing of the eye and a sharp rise in the bit error rate. A "signature" of coherent crosstalk (see diagram, page 17) is that the upper level of the eye has been closed much more than the lower level of the eye.

Signal distortion

Signal distortion occurs from multiple sources as outlined in Table 1. Linear distortion mechanisms include fiber dispersion, which "spreads" bits and closes the received eye and the transmission of a chirped digital data stream through an optical wavelength selective device (*e.g.*, filters, demuxes, switches). Chirping refers to the wavelength actually changing during the rise and fall times of a bit at the transmitter. The wavelength selective device will cause portions of the signal to be attenuated as it moves in and out of the filter peak. Nonlinear distortion mechanisms include fiber and amplifier gain saturation effects as described below. Additionally, the wavelength of the signal can change during transit in the network due to self- and cross-phase modulation nonlinearities. The signal will then be distorted in the same manner as a chirped signal after passing through wavelength selective components.

Optical amplifier gain saturation is another very important effect that causes a digital signal to distort.[12] Gain saturation means the amplifier gain decreases with increasing input due to the total optical input signal level exceeding a specified input signal level. Depending on the amplifier type, gain saturation has different influences on a WDM transmission system. Erbium fiber amplifiers operated in gain saturation will exhibit an overall decrease in gain with little crosstalk induced between channels.[8] Semiconductor optical amplifiers will exhibit a decrease in gain when operated in saturation but will also introduce crosstalk in a WDM and digital transmission system.[13] In semiconductor optical amplifiers, a digital bit can cause the amplifier gain to saturate for a single bit period or for multiple bit periods. In either case, the digital eye closes due to amplifier gain saturation. In analog fiber networks, gain saturation in either type of amplifier leads to unwanted harmonic distortion.

Noise accumulation

At the output of an optical amplifier, noise (ASE) is added to the signal, degrading the overall SNR while amplifying the signal strength. When these amplifiers are cascaded, as is the case in WDM-AONs, each successive amplifier has to amplify the signal and noise from previous amplifiers. In a cascaded amplifier chain, if amplifier noise accumulates too rapidly, the amplifiers' gain saturates and less gain will be available for the signals. The photoreceiver detects the signal and noise as both a linear combination (additive noise) and as a nonlinear mixing of the signal and amplifier noise during square-law detection.[14]

Scalability

The scalability of a WDM-AON ultimately revolves around the overall network architecture and how the physical implementation limits the performance.[15] While the complete picture of scalability is complex and is a subject of current research, it can be summarized in terms of the limitations in Table 2. The maximum number of allowed wavelength channels is limited by frequency spacing, bit rate, and the optical bandwidth of network components, as well as the stability of frequency selective devices and the type of transmitter used. The minimum channel spacing is limited by crosstalk mechanisms like optical nonlinearities, which tend to become much worse as channel spacing narrows. Also, the performance of existing filter and demultiplexer technology plays a big role in determining how closely channels can be packed.

Scalability Parameter	Limiting Physical Mechanisms	Related Network Issues
Internode Distance	Fiber loss Node design and implementation Fiber and amplifier nonlinearities Fiber dispersion	Network topology
Number of Wavelengths	Optical amplifier gain saturation Linear and nonlinear crosstalk Component and amplifier bandwidth Wavelength channel spacing Wavelength stability	Number of "Hops" Network load
Bit-Rate per Wavelength	Received signal-to-noise-ratio (SNR) Fiber dispersion Wavelength channel spacing Node design and implementation	Number of "Hops" Network load
Add/Drop Flexibility	Incoherent and coherent crosstalk Node design and implementation	Architecture (*e.g.*, Topology)
Total Number of Nodes	Total number of wavelengths Add/drop flexibility	Network access Network topology Number of "Hops" Protocols

Table 2. The scalability of a WDM-AON depends on both the limiting physical mechanisms as well as the overall network architecture and operating conditions.

The distance a signal travels will determine the amount of degradation due to time spent in the fiber with other wavelengths and the number of link/amplifier/node pairs it must traverse. A single link/amplifier/

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Glossary

Amplified Spontaneous Emission (ASE): The unwanted light generated by an optical amplifier that results when emitted photons from within the amplifier are also amplified.

Dispersion: A property of an optical device (usually a fiber) in which the propagation speed of optical carriers differs for differing wavelengths. Hence, with dispersion, the frequency components of an optical pulse will tend to separate temporally as the pulse propagates down a fiber.

Photonic Switch: A device that connects optical signals between one or more input ports to one or more output ports.

Saturation Power: The output optical power at which an amplifier's gain is reduced by 3 dB.

Square-Law Photodetection: Conversion of an optical signal to an electrical signal current where the output current is proportional to the square of the optical field amplitude.

node combination is referred to as a single "hop." Network topology, traffic load, and access protocols determine the number of node "hops" that are required for communication between two nodes. The node/link performance must be high enough to ensure that the network will preserve a signal's integrity through the required number of hops, which can vary depending on the network design, size, load, and other parameters. Since the path is all-optical, fiber dispersion will accumulate over multiple hops, limiting the channel bit rate. Dispersion compensation techniques exist to overcome this limitation. However, compensation for loss and dispersion are needed at each node since the number of hops can be an unknown quantity. To complicate the picture further, compensation of fiber dispersion can actually make fiber nonlinearities worse. Therefore, the distance between nodes is limited by the maximum number of hops, the number of wavelengths, and other network operating parameters. The bit rate per wavelength is ultimately limited by the amount of power that can be injected into the network and the amount of power that reaches the photoreceiver. In general, higher bit rates require more sensitive photoreceivers.

The ability to add and drop new nodes arbitrarily is largely a network architecture issue. However, this issue is strongly coupled to the function and performance of components used to build the nodes. Low crosstalk and low loss must be inherent in the technology used to implement add/drop functions or switching functions.[16] Acousto-optic tunable filters and fiber gratings are devices currently under investigation for this purpose. Another important issue not discussed in this paper involves the polarization independence of all fiber and components. Polarization independent components are critical to achieving scalable networks.

Future of WDM-AONs

The future of WDM-AONs most likely involves two parallel paths. The first path is evolutionary, where simple networks use fixed connections and a small number of wavelengths (*e.g.*, four to eight) to reduce cost, simplify management, and allow upgradability. These simple WDM-AONs will most likely use all-optical add/drop nodes to extend the connectivity of existing WDM transmission links.[7] Support of multiple services segmented by wavelength might be the first application of transparency. Routing in the first generation WDM-AONs will probably be performed by tuning wavelengths at the user end. Second generation WDM-AONs might include the capability to support switched services via WDM optical switches and active routers. These networks might also be able to support a higher level of transparency (*e.g.*, multiple transmission standards).

The second path involves addressing the physical limitations of WDM-AONs including the fact that these networks are analog by nature. In the near term, understanding the limitations and designing robust architectures will decrease the impact of these mechanisms on scalability. Ultimately, it is possible that optically transparent equivalents of signal level restoration, noise suppression, and timing restoration might make these networks more like their digital electronic counterparts with the added advantage of transparency.

Acknowledgments

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