Addressing Unrelenting Growth In Backbone Fiber Systems Using Next Generation Photonics And Automation

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

There is a limit to how many bits can be sent down an optical fiber. This limit, known as the 'Shannon Limit' is defined as the maximum rate at which data can be sent over a medium with zero errors. Technologies such as coherent optics allow operators to get closer to this theoretical limit. However, moving forward, the gains in spectral efficiency that will be achieved with future generations of coherent technology are diminishing. This will require alternative approaches and ideas to deal with network scalability challenges. Using updated designs, next generation hardware, and software tools, network operators will be able to extend the life of their networks as well as deploy new networks more quickly, efficiently, and accurately. Using these ideas, operators can start reducing the slope of their spectral usage curve while at the same time, deploying new photonic networks with higher efficiency.

2. Preface

It is estimated that global internet traffic will grow 3.7-fold from 2017 to 2022. Globally, IP traffic (alone) has also grown three-fold in the same period. This reflects a compound annual growth rate (CAGR) of 30% and 26% respectively[1]. Drivers for this tremendous growth include Video (IP, Internet, VoD), gaming, mobile devices, social media, and the Internet of things. Additionally, the average residential bandwidth speed has more than doubled from 24 Mbps to almost 50 Mbps. Consumers now regularly achieve 100+ Mbps download speeds with "standard" cable internet service.

Looking into the future, will these tremendous growth rates continue? And what are the drivers? The answer to the continued growth question is "yes". The drivers will be new and expanded offerings that will continue to drive the need for bandwidth such as medical imaging, tele-medicine, virtual reality and gaming, cloud storage, and of course this new necessity of "working from home". These new drivers, as well as the old ones, will continue to drive demand for the internet and fuel the growth of optical networks.

How much bandwidth will be needed? While this is certainly a "loaded" question, let us consider some simple math that could provide some direction for thought. The C-band, or conventional band, covers the fiber spectrum from 1530 nm to 1565 nm and is approximately 4800 Ghz wide. That might be forty-eight 100 Ghz spaced channels or that might be ninety-six, 50 Ghz spaced channels. If we consider ninety-six 50 Ghz spaced, 35 GBaud, 100 Gbps channels as a "full spectrum system", how many of these "full spectrum systems" are required if we project a 25% CAGR into the future for the next 11 years?

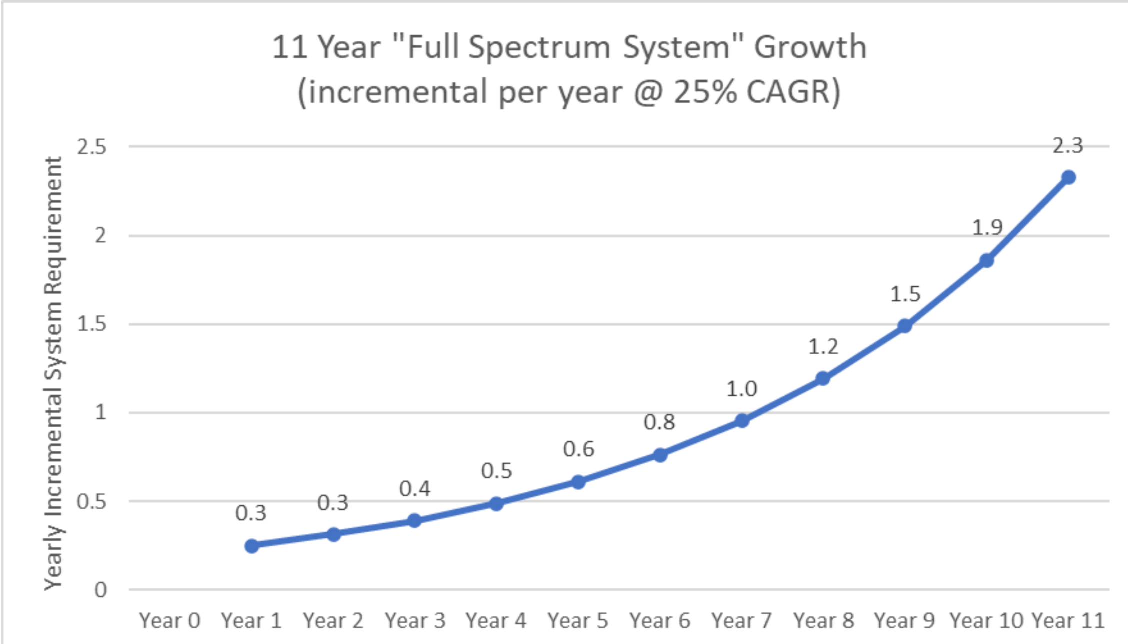

Figure 1: 11 Year 'Full Spectrum System" Growth

This graph shows that using a compound annual growth rate of 25% per year, an operator using a photonic layer capable of ninety-six 100 Gbps channels will, by year 7 have to deploy and enable a new, full spectrum, photonic system with EVERY subsequent year. When the provider hits year 11, the growth rate exceeds TWO new, full spectrum systems every year.

So, how are operators to keep up with this growth? This paper has been written to suggest strategies that might be used by multiple-system operators (MSOs) to efficiently scale their networks and support more capacity with fewer incremental systems/fiber pairs (and network resources), and improve efficiencies for their customer as well as for their shareholders.

3. Network Design

3.1. Migration from Older Technologies

Older generation photonic networks are typically based on 100 Ghz or 50 Ghz ITU grid and use passive, fixed grid filters to provide optical channel access. These older systems are reaching capacity based on the limited spectral efficiency of this generation of photonics and transponders. The first opportunity that operators could use to slow their system deployment curve is to upgrade an older, fixed grid network to a newer, flexible grid photonic system.

Much of today's newer photonic equipment is still backward compatible with the older, fixed grid standards. This would allow, for example, flexible grid WSS hardware to provide a direct replacement for older fixed grid WSS hardware in the existing fixed grid network. This equipment compatibility would permit network operators to upgrade high use portions of their existing fixed grid system, using the current fiber pair, to newer, flex grid capable wavelength selectable switch (WSS) hardware. Additionally, flex grid capable colorless channel mux/demuxes would also be installed with the new flex grid WSS modules. Once the flex grid capable photonics are in place, flex grid functionality could be "enabled". Operators could then utilize the full functionality of flex grid. This fixed to flex upgrade does come with challenges such as migration maintenance windows, specific channel pass-through rules, and operational differences between the fixed and flex grid portions of the network. However, if specific portions of the fixed grid network are bandwidth limited, this type of flexible grid upgrade is an option available that could increase the spectral efficiency by as much as 350% on the new flex grid portion of the network.

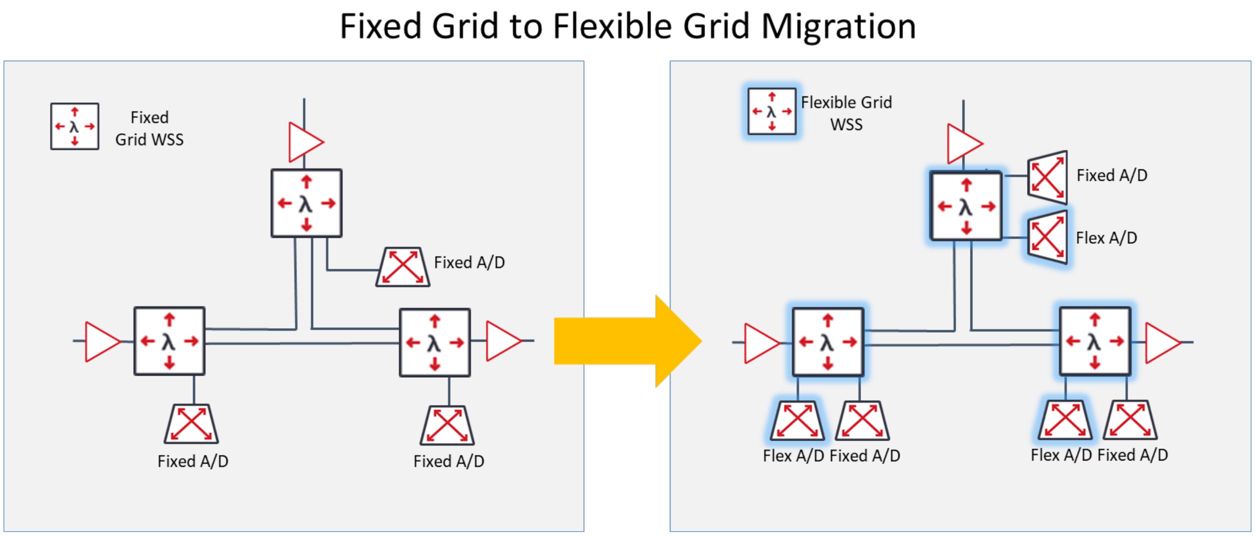

Figure 2: Fixed Grid to Flexible Grid Migration

With proper network planning during the fixed to flex migration, the spectrum can also be "de-fragged". The de-frag would allow for the efficient continued use of the operator's current transponders while also allocating space for the use of next generation, larger bandwidth transponders. This upgrade enhancement will delay network exhaust because of the higher spectral capacity of the next generation hardware while continuing to utilize existing transponder assets that the operator has already purchased.

3.2. Express Overlay Networks

Many current MSO networks were built as "one size fits all" networks. The one size fits all network must provide all transport functions including Core-to-Core, Core-to-Region, and Region-to-Region connectivity. These different functional traffic flows cause the network to grow at different rates. When highly used portions of the network grow faster than other portions, bandwidth bottlenecks can occur.

Single use, express overlay networks is another strategy available to MSOs that could provide targeted relief and extend the life of the original network. In the portions of the network where bandwidth bottlenecks are starting to occur, an express overlay photonic network could be added that would address the highest functional contributor to the bandwidth. As an example, if there is a bandwidth bottleneck in a Core-to-Core corridor, a new, purpose-built Core-to-Core express overlay network could be added. This does two things. First, the original Core-to-Core traffic would be migrated to this new network path. This migration of bandwidth from the original to the new express overlay system would free up spectrum on the original network for additional Region-to-Core and Region-to-Region traffic. This extends the original network's "time until full". Second, the new path could be built using new technologies (flexible grid, next generation transponders) that would then increase the spectral efficiency of the new path helping to slow even further the need for additional photonic systems.

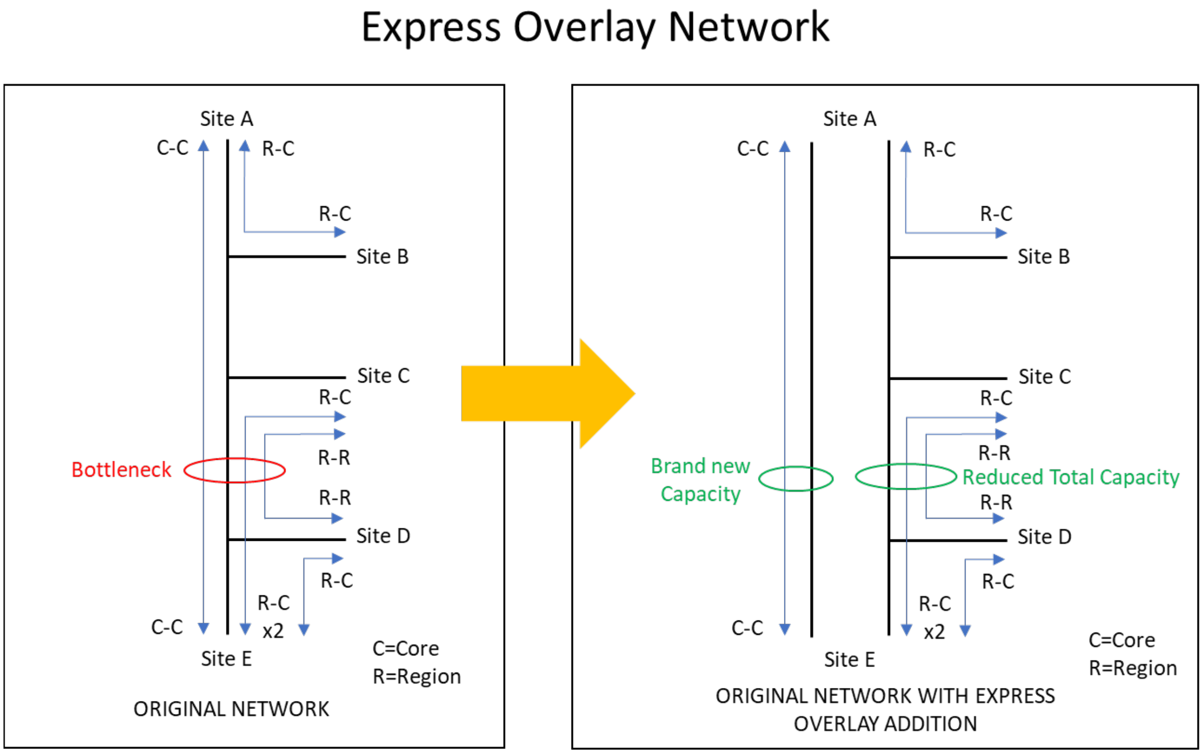

Figure 3: Express Overlay Network

4. New Hardware

In addition to network design strategies, there is a new generation of photonic equipment that can dramatically increase spectral efficiency and thus increase the time required between network builds. This new hardware includes higher baud, coherent modem technology that creates higher bandwidth channels to optimize reach and eliminate regeneration. Flexible grid photonics facilitate the efficient transport of higher baud transponders and ultimately increase the spectral density of the fiber and lower the cost per bit. L-Band photonics that enable the L-Band spectrum adjacent to the C-band allow for doubling the capacity of the fiber, increasing the return on investment of fiber assets and delaying new fiber builds.

4.1. Higher Baud, Higher Bandwidth Transponders

Using today's newest optical transponders, operators can make transponder selections that exactly fit their network transport needs. "I have a short link, and I need maximum fiber capacity." Or, "I have a long link and I don't want any regeneration." And, "I want to optimize my spectral efficiency." Today's newest generation optical transponders can provide a solution for all of these needs.

With the ability to select coherent optic technology with baud ranging from 35 GBaud up to 95 GBaud, spectral efficiency can be optimized for the given photonic layer topology. Today's transponders use probabilistic constellation shaping which creates the ability to select optical transponder line rates from 100 Gbps to 800 Gbps to optimize the capacity relative to available margin. The new transponders also use enhanced forward error correction (FEC) and other sophisticated algorithms that ultimately permit longer reach of the photonic signal.

These next generation transponder features allow network operators the ability to independently select the baud and line rate to maximize the spectral usage across a desired path. As an example, for shorter reach paths an operator would be able to create an 800 Gbps link while using a symbol rate of approximately 90 Gbaud. Then, provision a second transponder pair to create a non-regenerated 400 Gbps line using 95 GBaud on a path that goes from Miami to Seattle. Finally, a third transponder pair could be used to "dial in" the optimal bit rate to satisfy any specific route in-between. This degree of transponder flexibility is creating a new paradigm in how photonic networks can optimize their spectral use.

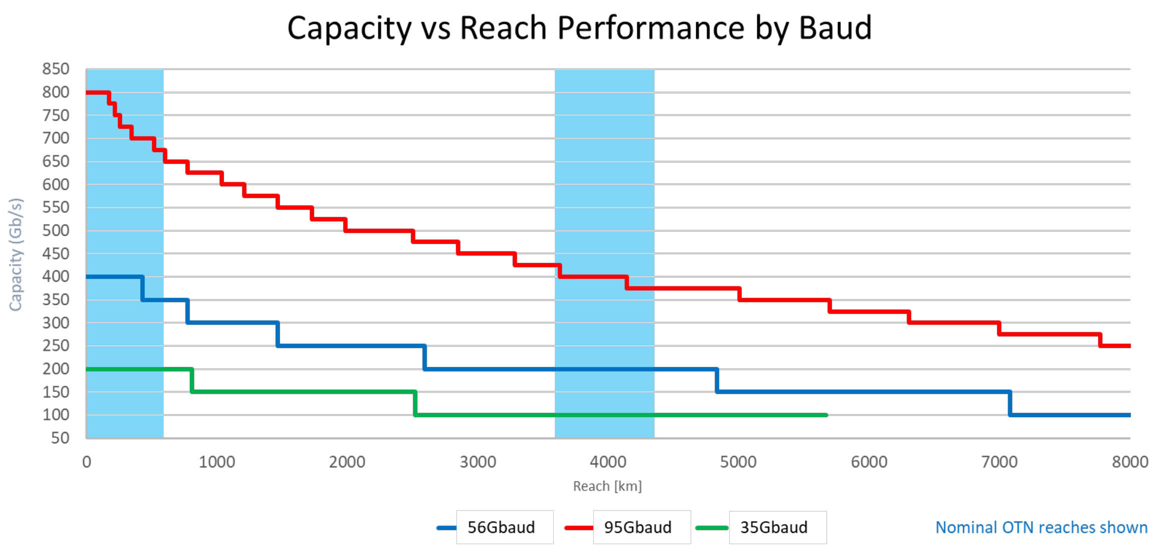

Figure 4: Capacity vs. Reach Performance by Baud

4.2. Flexible Grid Photonics

Older generation optical networks are based on 100 Ghz or 50 Ghz spaced photonic systems. These older, gridded networks can offer forty-eight or ninety-six fixed grid optical channels within the total 4800 Ghz C-Band spectrum. This fixed grid spacing is based on the ITU standard and has been the norm for most photonic systems for over 20 years. These older systems use passive, ITU grid filters to provide wavelength ingress/egress. Second and third generation optical transponders running at 35 GBaud typically require 37.5 Ghz of optical spectrum which fit perfectly into these ITU gridded filters. This version of the network has served the industry well for years.

As next generation transponders become available, they bring with them the need for larger per channel spectrum. This larger channel spectrum requirement exceeds that which is available on these ITU gridded filters. Flexible grid photonics offer bandwidth "chunks" as small as 6.25 Ghz. The flexible use of these 6.25 Ghz chunks as well as a WSS based mux/demux for wavelength ingress/egress, permits more granular utilization of spectrum needed for the desired network transmission characteristics.

With flexible grid photonics and the ability to change the baud and bit rate of each specific transmitter, network operators can optimize the use of the spectrum. In the situation where the operator provisioned an 800 Gbps channel using a symbol rate of 90 GBaud, this configuration would provide as many as 48 (x800 Gbps) channels which is a total bandwidth of 38.4 Tbps on the fiber pair for a short reach path in the C-Band. If the L-Band is in place, that number is doubled. In the example of a path that crosses the United States running at 400 Gbps and 95 GBaud, this configuration would provide as much as 33.6 Tbps (42x400 Gbps channels) transported coast to coast without any O-E-O regeneration.

Flexible grid photonics add another level of adjustability to the new optical network. With the ability to specify the guard band appropriate for the link design, operators can engineer their photonic deployments with the highest spectral efficiency available for their specific network. For example, on shorter photonic paths, packing multiple network media channels into a single media channel allows for a reduced guard band size which permits the channels within the media channel to occupy less spectrum. This ultimately allows more channels to be placed in the total spectrum. This guard band reduction is another way that flex grid photonics improve spectral efficiency.

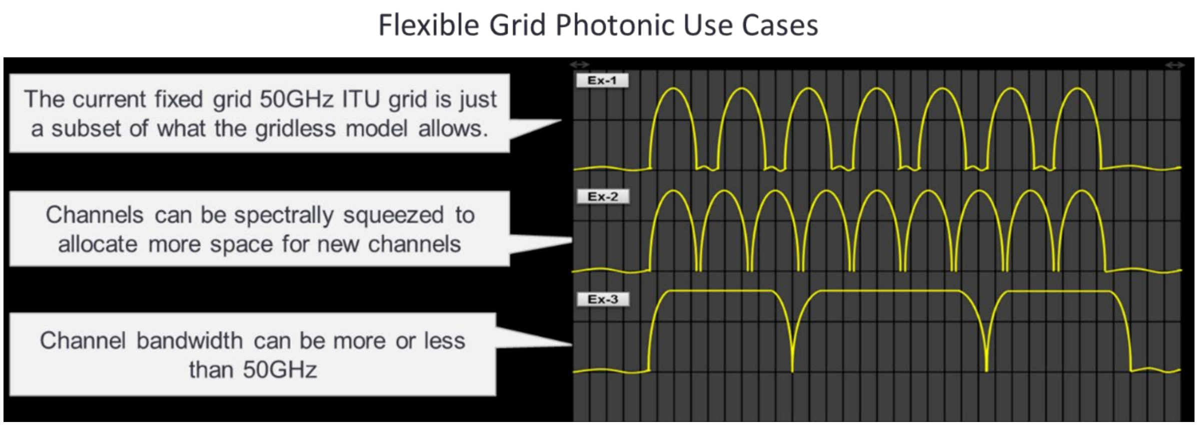

Figure 5: Flexible Grid Photonic Use Cases

4.3. L-Band Capability

As the incremental gains in spectral efficiency progressively diminish with each new generation of coherent technology, expanding the photonic layer into the L-band is becoming an increasingly popular option for scaling networks. The L-Band, long band, or extended band is the wavelength band immediately next to the C-Band. The L-Band covers the spectrum from 1565 nm to 1625 nm. For years, the L-Band has held the promise of extending the usable spectrum for operators. Unfortunately, first generation L-Band hardware never commercially delivered the additional L-Band capacity due to usability issues and deployment/upgrade complexities.

First generation L-Band deployments required splitter/couplers to provide fiber access to the L-Band equipment that was to be added later. These splitter/couplers used valuable span margin ultimately reducing much needed receiver optical signal to noise ratio (OSNR) on early generation transponders.

Additionally, when the L-Band is added to the C-Band in an active network, the L-Band can experience optical amplification at the expense of the C-Band due to stimulated raman scattering (SRS). So, when the L-Band is finally added to the C-Band fiber, the C-Band could experience a reduction in optical power. This reduction in C-Band total power has a potential impact to the OSNR of those in-service C-Band channels, especially when the C-Band spectrum is full. This link performance challenge is made harder by different fiber types, span losses, raman configurations, and channel powers in the network. As a result, the link engineering for the L-Band addition can be quite complicated.

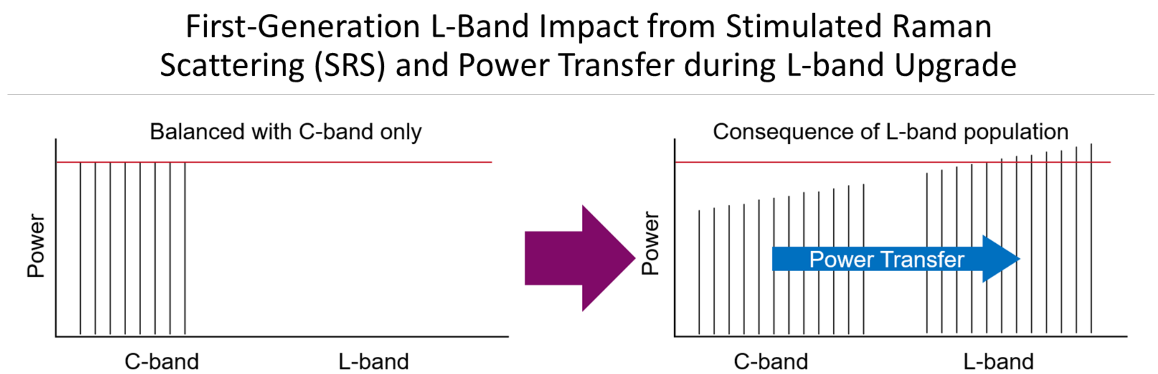

Figure 6: First Generation L-Band Impact from Stimulated Raman Scattering (SRS) and Power Transfer during L-Band Upgrade

Finally, the first-generation L-Band upgrade challenge was further complicated by the fact that none of the L-band hardware had been added day one. This meant that every site in the network had to be visited to add the needed L-Band equipment. On larger networks, a visit to every site could be very costly and time consuming.

Next generation C&L band equipment includes the day one deployment of both C&L band optimized/ready hardware. These new photonic systems include C&L band amplified spontaneous emission (ASE) that provides "full power" to the entire C&L band spectrum from day one. As working channels are added to the C&L system, the ASE for that spectrum is replaced by the new channel, keeping the total power constant. This means that once the new C&L photonic system has been engineered and turned up, no additional link engineering or optimization is required. The operator can count on stable, predictable performance across the lifetime of the system, regardless of the channel count.

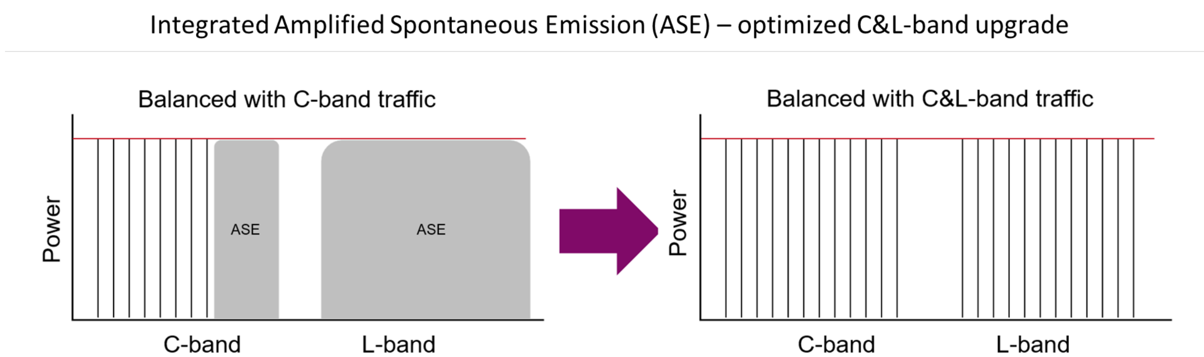

Figure 7: Integrated Amplified Spontaneous Emission (ASE) – Optimized C&L-Band Upgrade

From a deployment perspective, all intermediate sites (line amplifier and dynamic gain equipment (DGE)) would include full C&L band capable equipment day one. The "terminals" would include the C-Band WSS and C-Band amplifiers as well as both C&L band ASE hardware. Using this configuration, the C-Band can be fully populated with transponders from day one while the L-Band (with ASE) is idle. Then, when capacity demands require upgrade to L-Band, only the terminal sites are visited where the L-Band WSS and amplifier hardware is added. Since the intermediate line amplifier and DGE sites are deployed full C&L band day one, these sites do not require any additional visits or work. All the limitations of the first-generation L-Band have been addressed and corrected with these new C&L band photonic systems.

An additional benefit of having all the C&L line amplifiers and DGEs already deployed is L-Band upgrade velocity. Since the L-Band upgrades only require a visit to the terminal sites, these upgrades can happen in a very rapid manner.

4.4. Additional Fiber Diagnostics

Today's new photonic systems also include "onboard" fiber diagnostic equipment. Every new photonic element (terminals, line amps, and DGEs) now includes an integrated optical time domain reflectometer (OTDR) that can measure fiber length, fiber loss, reflective events, and chromatic dispersion. Additionally, with the support of the built in ASE, the non-linear properties of the fiber can also be evaluated in real time. These enhanced fiber characterization capabilities will make photonic layer turn ups more accurate and provide the NMS with in-service, real time fiber information permitting a host of improvements in network operations and maximizing network capacity.

5. Software and Automation

Software and automation continue to increase its role in our lives, from an alarm clock on our smart phones to automated control of our home thermostat. Likewise, software and automation are becoming more critical to the efficient operations of network operators as well. The following are next generation uses of software and automation that will become essential to operators' ability to work efficiently.

5.1. Software – From Planning to Operating

Telecom operators have always struggled with software. There were different software platforms for every vendors' equipment. There was an Element Management System (EMS) for each different network element. There were Network Management Systems (NMS) for every platform. These different systems typically did not communicate with each other and as a result, interoperability between different vendors' EMS/NMS systems and the equipment under those systems was difficult to affect. These systems were basically good at one thing . . . managing their specific equipment and the signals going through them.

Today's next generation NMS systems take a much more holistic approach. These new NMSs are designed with "open" in mind. North and sound bound interfaces allow operators to utilize single system orchestration across multi-vendor domains. Additionally, these systems are no longer just for operations, alarms, management, and provisioning. Next generation network management systems have been architected to additionally provide support for the entire network life cycle from planning to deployment to operations to optimization.

5.2. Planning Equals Deployment

In the past, planning was considered a necessary evil. There were never any good planning tools. So, everyone "had a spreadsheet". When design and planning are completed offline, the probability of the plan and the network becoming out of sync is very high.

The next generation NMS has integrated the planning function into the NMS. Now, design and planning can be done on the NMS itself. Those designs and plans are stored on the NMS which assures that there is complete agreement between the designs and the network. When new planning is needed, the network is the starting point for the new plan and all previously created designs are considered in the new plan. As plans are implemented and become deployed in the network, the NMS is aware of these adds. The ability of the NMS to be the gatekeeper is especially helpful in companies with large planning groups. The synchronization between planned and deployed keeps everyone on the same page thus reducing waste from duplicate, overlapping, or incompatible designs.

5.3. Zero Touch Provisioning

Once a new design has been created, how is that design processed into deployed and operational equipment? In the past, the design was probably transferred to a spreadsheet and a drawing was made which was then handed off to the deployment team who re-typed the provisioning data from the spreadsheet into the new equipment. This method was inefficient and potentially inaccurate with many manual operations required.

In today's environment where NMS planning has been completed, the NMS planned design is converted into a group of Zero Touch Provisioning (ZTP) files by that same NMS. The NMS sends the necessary ZTP files to a designated FTP server. After physical installation and power-up of the equipment is complete (including the connection of fiber), the installer provides the equipment with an IP address and the location of the FTP server. The new network element retrieves its boot file and commissioning file and then self-installs the commissioning information. Once the ZTP process is complete, the element reboots and is fully functional and ready for use.

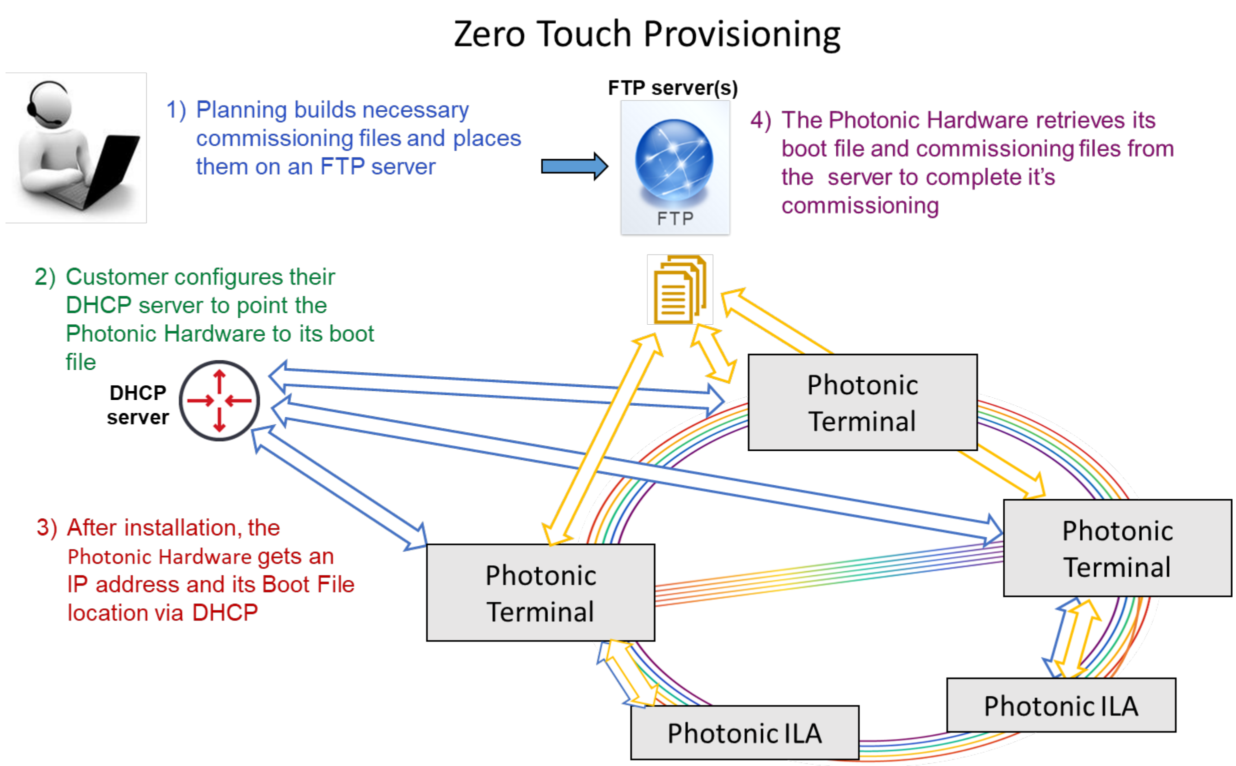

Figure 8: Zero Touch Provisioning

Another aspect of photonic ZTP is the ability of the amplifiers to self-characterize the fiber to which they are connected. The onboard OTDR provides advanced Fiber Characterization (FC) to thoroughly characterize the fiber plant connected to each amplifier. This FC information is provided back to the NMS. Using the configuration tools built into the NMS, optimized amplifier provisioning information can be calculated and provided back to the photonic hardware on a span-by-span basis to achieve the best possible performance. This software based, photonic optimization results in the highest possible spectral efficiency for that fiber path.

Finally, post turn up, these same fiber characterization tools allow operators to monitor their fiber plant to preemptively respond to issues and provide detailed information to isolate those issues when they arise.

Since the ZTP information delivered to each network element has been validated by the NMS, it is highly accurate. The accuracy of this information will reduce the overall time required to turn up new network elements. When bandwidth demands require operators to deploy a full photonic system every year, ZTP will be essential to accomplishing this deployment in an accurate, timely manner.

5.4. Margin Mining

On older fixed grid photonic systems, it was difficult to determine available transponder Rx OSNR margin. In some cases, error corrections could be counted and compared to pre-FEC numbers. Then, using complicated math, operators were able to confirm that their transponder channels were running within acceptable margins. However, even when these calculations were available, there was limited ability to change the characteristics or performance of those channels.

Today, advance software features coupled with next generation photonics and newer baud and bit-rate adjustable transponders provide many optimization options to network operators. One of these newer software implementations is margin mining.

Next generation photonics can provide enhanced operational information including fiber loss, dispersion, fiber types, span counts, BER, and SNR margin. Additionally, next generation transponders can change both the baud and bit rates to maximize performance. Using these parameters, the NMS can now identify available margin and quantify that margin for use in the network. Margin mining can be used to identify this available margin and increase a transponder's bit rate improving the throughput on the link. Margin mining could also be used to reduce the guard band between channels while using the current baud and bit rate. In both cases, there is an increase to spectral efficiency which will result in longer system longevity.

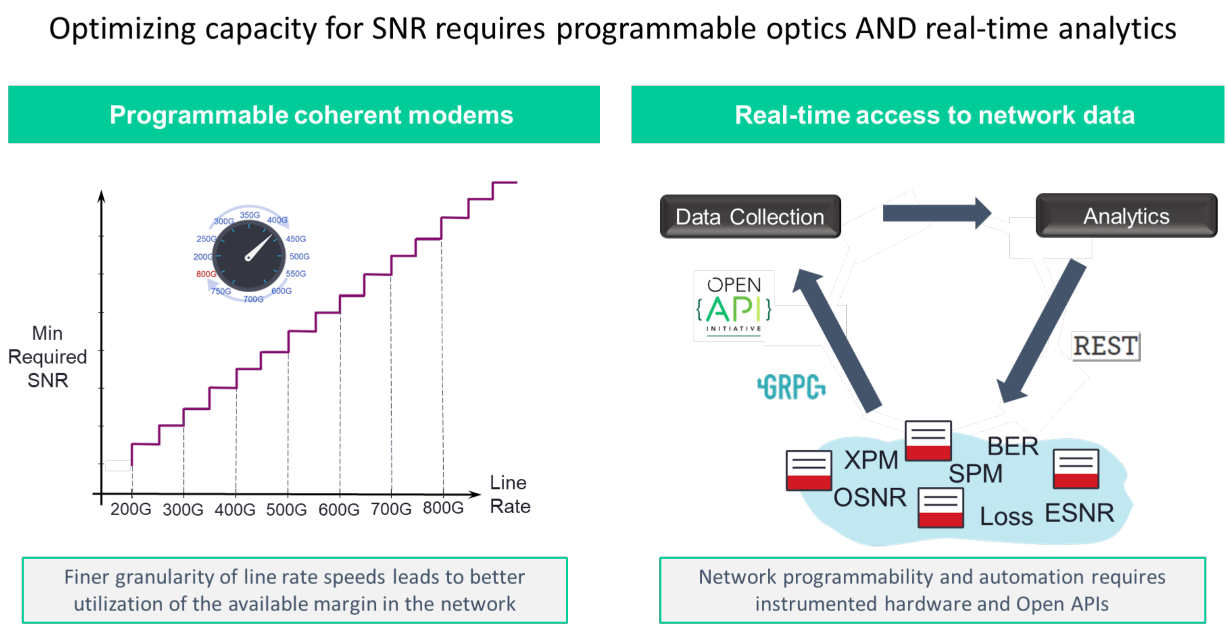

Figure 9: Optimizing capacity for SNR requires programmable optics AND real-time analytics

6. Conclusion

There is a limit to how many bits can be sent down an optical fiber. This limit, known as the 'Shannon Limit' is defined as the maximum rate at which data can be sent over a medium with zero errors. Technologies such as coherent optics allow operators to get closer to this theoretical limit. However, moving forward, the gains in spectral efficiency that will be achieved with future generations of coherent technology are diminishing. This will require alternative approaches and ideas to deal with network scalability challenges. Using updated designs, next generation hardware, and software tools, network operators will be able to extend the life of their networks as well as deploy new networks more quickly, efficiently, and accurately. Using these ideas, operators can start reducing the slope of their spectral usage curve while at the same time, deploying new photonic networks with higher efficiency.

Abbreviations

A/D	add/drop
BER	bit error rate
CAGR	compound annual growth rate
C-Band	conventional fiber optic band 1530 nm to 1565 nm
Demux	demultiplexing
DGE	dynamic gain (flattening) equipment
EMS	element management system
FC	fiber characterization
FEC	forward error correction
FTP	file transfer protocol
GBaud	gigabaud
Gbps	gigabits per second
Ghz	gigahertz
ITU	International Telecommunications Union
ILA	intermediate line amplifier
L-Band	long or extended fiber optic band 1565 nm to 1625 nm
MSO	multiple systems operator
Mux	multiplexing
O-E-O	optical-electrical-optical
NMS	network management system
OSNR	optical signal to noise ratio
Rx	receive
SNR	signal to noise ratio
SRS	stimulated raman scattering
Tbps	terabits per second
WSS	wavelength selectable switch
ZTP	zero touch provisioning

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[1] Cisco's VNI Complete Forecast Highlights: Global – 2022 Forecast Highlights; Cisco, 2018; https://www.cisco.com/c/dam/m/en_us/solutions/service-provider/vni-forecast-highlights/pdf/Global_2022_Forecast_Highlights.pdf

