Introduction of Spectrally and Spatially Flexible Optical Networks

Tiejun J. Xia, Herve Fevrier, Ting Wang, and Toshio Morioka

Abstract

Given the introduction of coherent 100G systems has provided enough fiber capacity to meet data traffic growth in the near term, enhancing network efficiency will be service providers' high priority. Adding flexibility at the optical layer is a key step to increasing network efficiency, and both spectral and spatial functionality will be considered in next generation optical networks along with advanced network management to effectively harness the new capabilities.

Introduction

Network traffic will undoubtedly continue to grow in the foreseeable future due to the ever increasing demands of emerging applications, such as peer-to-peer video sharing, machine-to-machine communications, ultra-high definition video, gaming, mobile data, and Internet of Things (IoT). The overall global end-user IP traffic annual growth rate has been reported as 21 percent from 2013 through 2018 on average [1]. To handle this continuous growth in traffic demand, telecom carriers must increase capacity in their networks to support the demands from end users, devices, and applications in a scalable and cost-effective manner.

Fortunately, since commercial 100G systems with polarization multiplexed quadrature phase shift keying (PM-QPSK) modulation format and coherent detection was introduced into carriers' networks, the urgency to provide enough network capacity abated. It is estimated that the existing fiber infrastructure is able to support traffic demand growth for at least another 10 years without costly larger-scale fiber infrastructure upgrades [2]. Carriers now face a more serious challenge in how to make their networks more efficient to lower the overall cost of transporting bits. Next generation networks are expected to have better equipment utilization, customer service, and application performance. To reach this goal, adding more flexibility is a key step. Networks have had a lot of flexibility in the upper layers because they are not sensitive to physical distance and fiber impairments; however, the optical layers (layers 0 and 1) are. Here both spectral flexibility and spatial flexibility need to be considered. Consequently, network control platforms need to be improved to harness this flexibility if we are to realize highly efficient networks.

In this article we review aspects of spectral and spatial flexibility studied in recent years and show benefits of network flexibility to telecom carriers. Expected benefits include less capital expenditures (CAPEX), higher equipment utilization, faster service provision, better traffic protection, and easier network management. This article also shows several experiments supporting network flexibility. Finally, space-division multiplexing (SDM), as an additional way to provide spatial flexibility, is discussed from the angle of its potential benefit to optical networking in the future.

Spectral Flexibility and Spatial Flexibility

When we consider flexibility in networks, there are many flavors. In this article we focus on spectral flexibility and spatial flexibility in optical transport networks. Figure 1 shows some examples of network flexibility in the spectral and spatial domains, where the double arrow represents that one scenario can be adjusted into another scenario, controlled by network management systems.

The concept of flexible grid was introduced several years ago such that the optical bandwidth, and the central wavelength of a channel can vary depending on its data rate, symbol rate, channel arrangement in spectrum, and overhead of the channel (Fig 1a1). The modulation level of a channel can be controlled according to a balance between signal-to-noise ratio at the receiver and maximized spectral efficiency, as shown in Fig 1a2. Historically, most commercial optical channels have only had one optical carrier. However, commercial channels with data rates beyond 200 Gb/s, such as 400G or 1T channels as proposed in the industry, will likely be super-channels, which contain multiple optical carriers. Single-carrier solutions for the high-data-rate channels are still being investigated in research laboratories with challenges in data processing speeds and signal-to-noise ratio. Flex-

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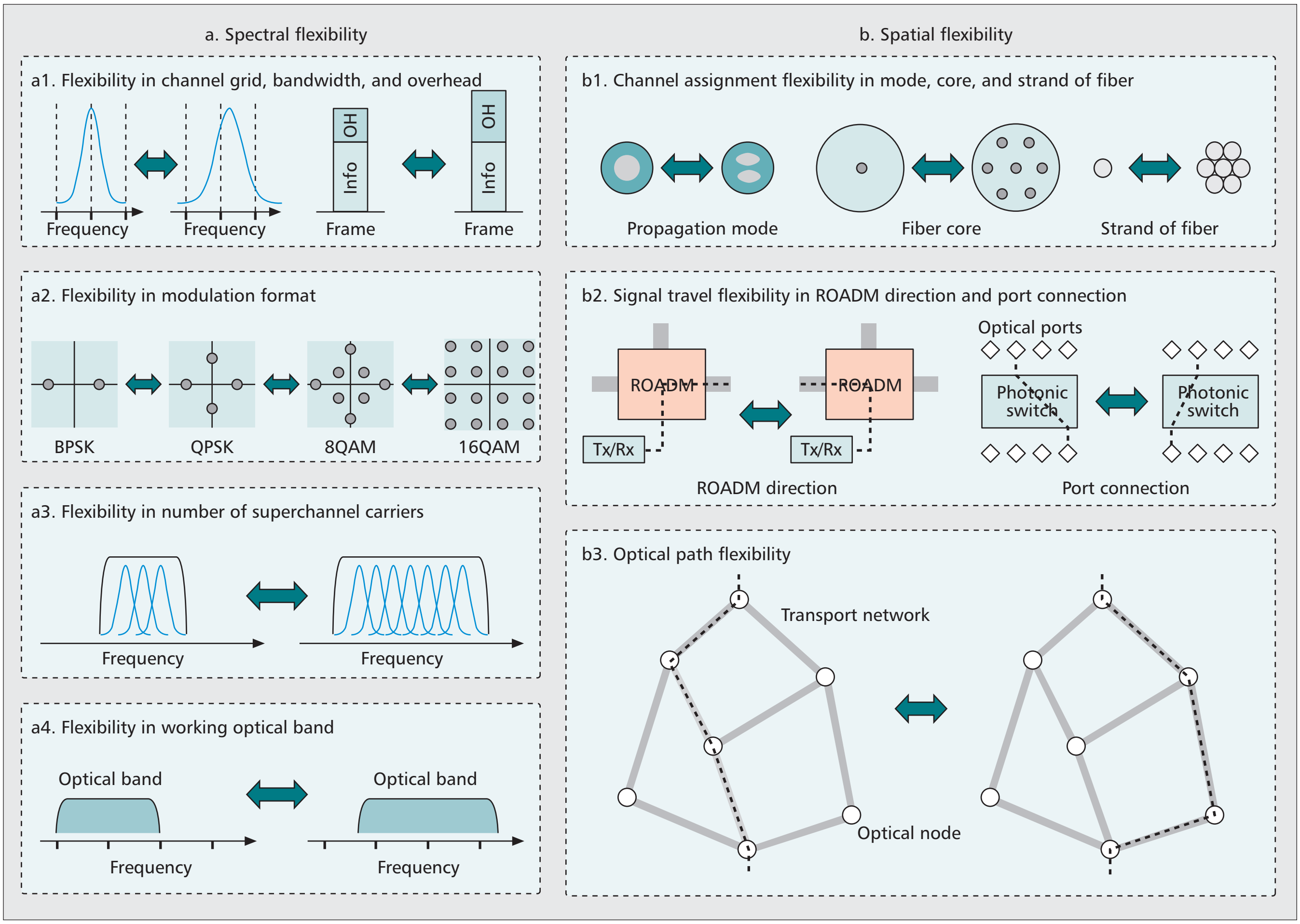

Figure 1. a) Scenarios showing spectral flexibility; b) spatial flexibility.

ibility in super-channel designs is reflected in the number of optical carriers and spacing between the carriers for a super-channel (Fig 1a3). Next generation optical transponders will have some or all of the attributes mentioned above. Using Raman amplification can increase network flexibility even further by allowing new optical channels to be assigned over wavelengths outside optical bands currently supported by Erbium-doped fiber amplifiers (EDFA). Raman amplification can allow new transmission bands to be created as required by traffic demand, as shown in Fig 1a4.

Spatial flexibility is referred to as the controllable arrangement of optical signals in the spatial domain. The introduction of SDM provides flexibility in the assignment of an optical channel to have spatial attributes, for example, different propagation modes, different fiber cores, or different strands of fiber in a fiber bundle, as shown in Fig 1b1. Next generation reconfigurable optical add/drop multiplexers (ROADMs) provide increased flexibility in optical path arrangement. A channel can be switched to different directions out of an optical node, controlled remotely by the network operation center (NOC) (Fig. 1b2). Spatial flexibility has also been introduced into port connections. Traditionally, port-to-port connections have been locked with fiber jumpers. Any change of port connections requires manual intervention. Adding photonic switches, which are wavelength- and data-rate-independent, will allow the NOC to be able to change equipment port connections remotely, as shown in Fig 1b2. At the network level, fast optical path reconfiguration is an ambitious but reachable target in the near future (Fig 1b3).

ROADM is a key element for optical networking. Colorless, directionless, contentionless, and flexible-grid ROADM (CDC-F ROADM) will play an important role in next generation flexible optical networks. ROADMs have been used in networks for more than a decade. However, only the CDC-F ROADM is a true flexible network enabler. Figure 2 shows a comparison of a basic ROADM design and a CDC-F ROADM design in a four-degree node as an example. A ROADM has an express core and add/drop modules for different degrees (directions). Bypassing traffic is switched to different directions in the express core, while added and dropped channels are switched to add/drop modules. In a basic ROADM each degree has its own add/drop modules, and each add/drop port has been assigned with a fixed wavelength. When a transponder (TRx) needs to change its wavelength or direction, it has to be physically moved to another port or another add/drop module, as shown in Fig. 2a. In a CDC-F ROADM, as shown in Fig 2b, a transponder does not need to move again once it is plugged into the node. The wavelength of the optical signal from the

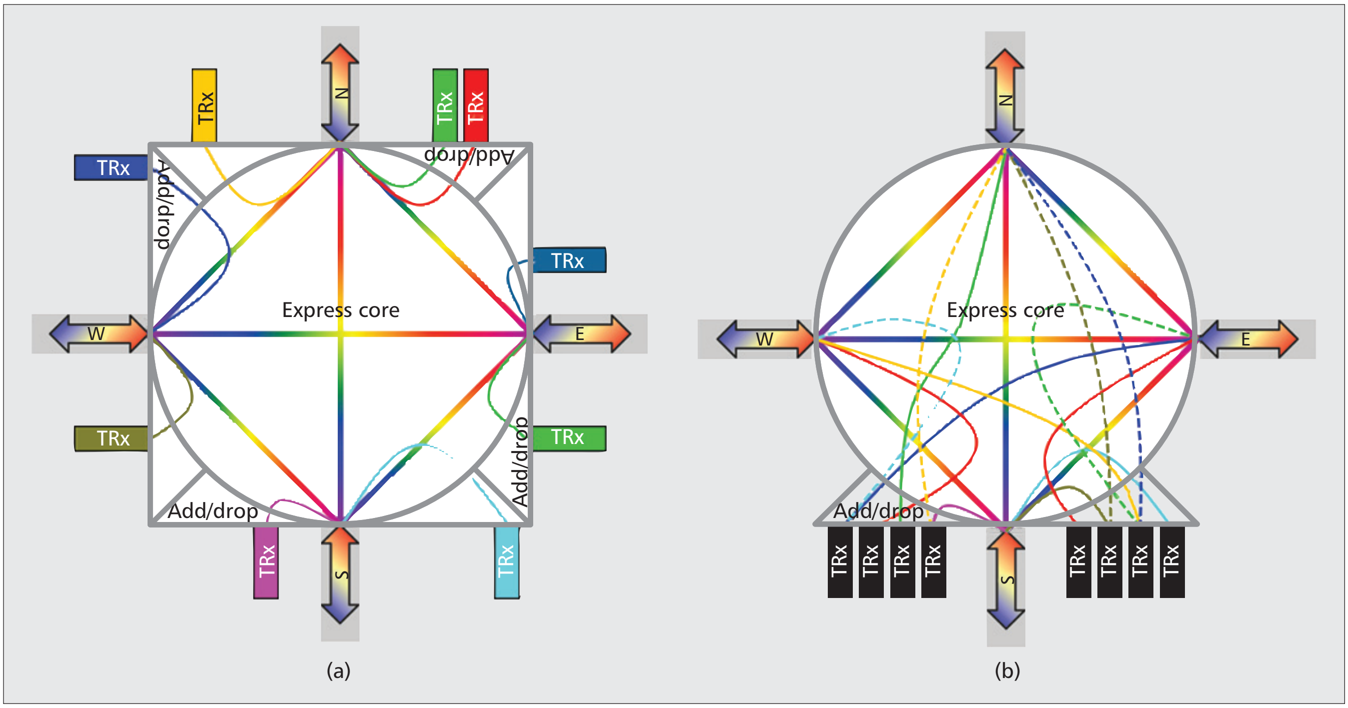

Figure 2. Schematic ROADM designs: a) basic design; b) colorless/directionless/contentionless and flexible grid (CDC-F) design for flexible optical networks (dashed lines represent potential connections).

transponder can be tuned and the direction of the signal can be changed without physically moving the hardware. In addition, the property of contentionless allows transponders sitting in the add/drop module to even have the same wavelength. Therefore, only one unified add/drop module is needed for a CDC-F ROADM. Using one unified add/drop module is particularly important since in this way the optical layer can be fully automatic and remotely managed by the NOC. Given that the flexible grid concept has been introduced into ROADM designs, it is also expected that the future CDC-F ROADM will be able to switch channels with variable optical bandwidths.

Equipped with flexible transponders and CDC-F ROADMs, a flexible optical transport node can also be constructed with electrical switch fabrics, as shown in Fig. 3. For global telecom carriers, the transport network must carry packet traffic from IP routers or multiprotocol label switched (MPLS) switches, time-division multiplexing (TDM) traffic from synchronous optical network/digital hierarchy (SONET/SDH) or optical transport network (OTN) switches, and packet or TDM traffic from customer routers or switches. Usually an optical node accepts the traffic via "grey optics," which are short-reach pluggable devices. The traffic will be groomed and switched according to its destination and loaded into optical channels generated in transponders via switch fabrics. The switch fabrics are able to switch both packet and TDM traffic. As mentioned above, an optical channel may contain one optical carrier (single-carrier channel) or multiple optical carriers (super-channel). The channels leave the optical node in different directions via the CDC-F add/drop module and the express core. Ideally, any channel can be controlled by the NOC to adjust its traffic load, wavelength assignment, modulation format, number of optical carriers, overhead, direction, and optical path in the network. The flexibility opens up a whole new world of capabilities that promises to significantly improve network efficiency if managed properly.

With spectral and spatial flexibility it is critical to develop flexible and agile network control/management schemes to harness time-varying traffic flows in optical networks. In existing carriers' networks, control systems are usually divided into domains, in which the equipment is usually supplied by different vendors and divided into layers. Network management across domains and layers often requires human intervention. The introduction of software-defined networking (SDN) into telecom networks is an effort to realize automation of network management and control. SDN has attracted a lot of attention recently in data center networks, enterprise networks, and academic networks. By decoupling the control plane from physical data forwarding devices, SDN is able to achieve simpler network management, faster traffic forwarding, and open development capability. The decoupling of the application layer, control layer, and infrastructure layer (Open Networking Foundation, ONF, terminology) is enabled by the northbound/southbound application programming interfaces (APIs) being standardized between different layers. There is growing interest in extending SDN to include optical transport layers [3]. Unified network controller software will control all network elements, including elements in the optical layer. Different from the upper layer control, the network controller software may not control optical elements directly, since physical layer perfor-

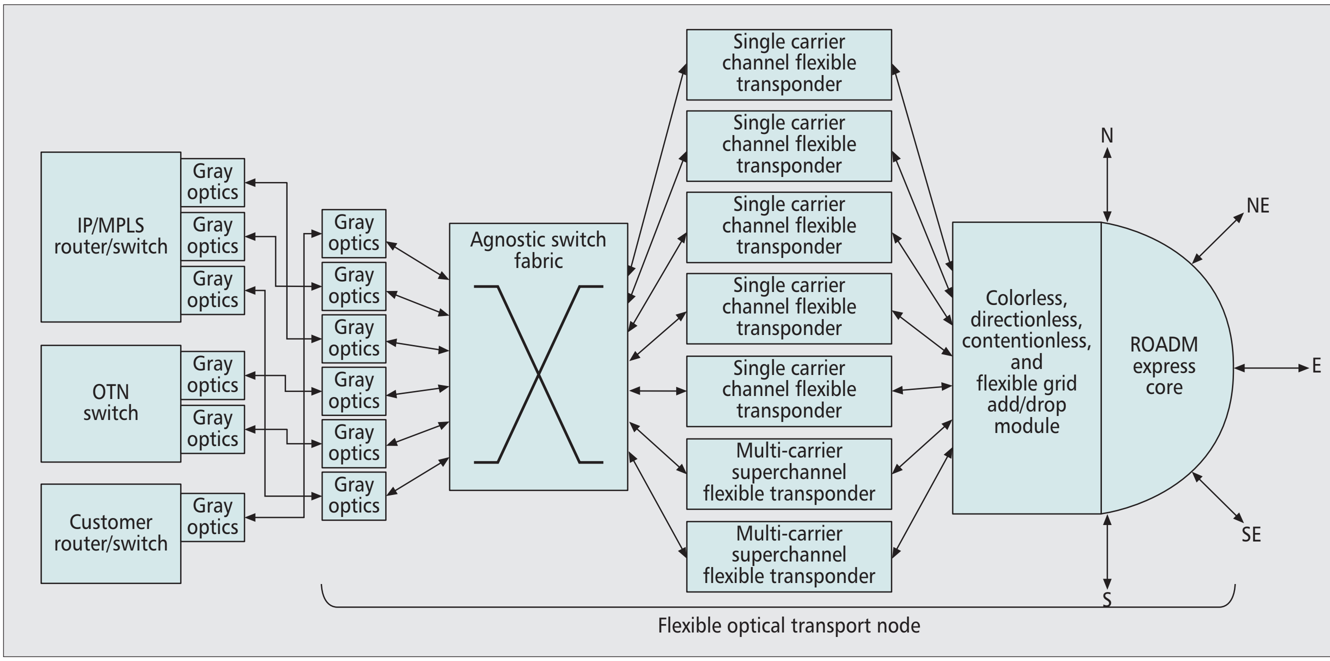

Figure 3. An example of a flexible optical transport node with agnostic switch fabrics, coherent channels, and CDC-F ROADM.

mance of optical signals is technology-dependent, and no standard in optical channel designs can be expected in the foreseeable future. A practical way to have unified control over optical elements is via control planes of optical domains. The control plane in each optical domain communicates with the unified controller software with a set of standard parameters and hides other attributes within the domain. With an SDN control/management platform, flexibilities in the optical layer are able to work with other layers in a coordinated manner.

Benefits of Network Flexibilities

Flexible optical networks can provide a lot of benefits to telecom carriers. Here we use a hypothetic optical network to show several such benefits. This hypothetic network has seven nodes, each equipped with a multi-degree CDC-F ROADM, transponders, switch fabrics, and grey optics, as shown in Fig. 4. An end-to-end data traffic connection is shown in the figure, from a router/switch in node A, via CDC-F ROADM A, D, F, and G, to another router/switch in node G. In the following several scenarios, we show how flexibility in the optical layer can help network operators.

Application Driving Network Reconfiguration

If a 400G super-channel going to node G originally via path A-D-F-G needs to be redirected to node B via path A-B according to the application riding on the channel, controller software can send commands to involved ROADMs to reconfigure the optical path of the channel. Assuming the 400G super-channel has four optical carriers, each of which has a PM-QPSK modulation format, to reach a long distance from node A to node G, after the path reconfiguration, the shorter distance between node A and node B allow the controller software to change the number of optical carriers to two and the modulation format to PM-16-quadrature amplitude modulation (QAM). The channel now still carries 400G data but uses only half the optical bandwidth. With unified controller software, optical path and channel bandwidth can be adjusted based on application needs.

Software Controllable Fast Network Restoration

Assuming there is a fiber cable cut between node A and node D, network controller software can immediately find an alternative optical path for the affected transponder pair. Since the optical signal of the channel is fully reconfigurable in wavelength and direction, the path of the channel can be configured to A-B-E-G. During path reconfiguration, the wavelength of the channel may be adjusted with a command from the controller software to fit into the spectral arrangement of the new path. If the path reconfiguration were fast enough, the router or switch would not even feel the cut. That is an important feature in an optical network to prevent unnecessary data rerouting or switching at higher layers. After the fiber cut is repaired, the controller software can shift the optical path of the channel back to the original one with minimal data traffic interruption.

Flexible Spare Cards Reduce Protection Costs

Since there is only one unified add/drop module in a CDC-F ROADM (logically), and all transponders are wavelength tunable, in principle, only one spare transponder card is needed to protect a failure in any transponder card of

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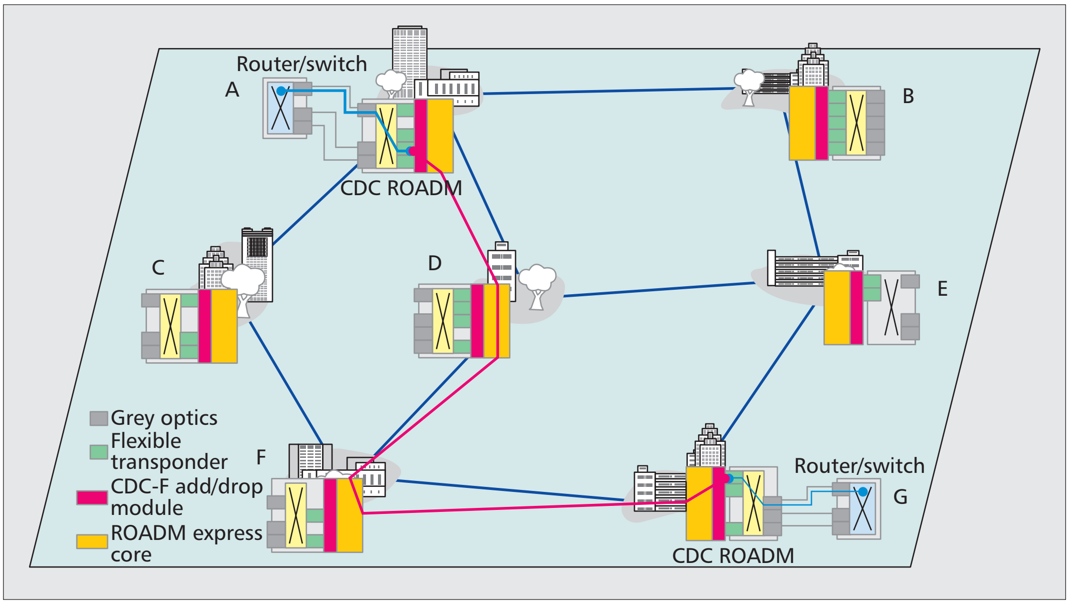

Figure 4. Hypothetic transport mesh network showing benefits of flexibility in the optical layer.

the same type in a CDC-F ROADM. For example, as shown in Fig. 4, assuming one of the transponder cards in node A is assigned as a floating card, if the network management system detects a failing working card in the ROADM, it can quickly issue commands to the node to shift the traffic flow from the failing card to the floating card via the switch fabrics, adjust the wavelength of the floating card to be the same as the failing card, and direct the signal from the floating card to the same destination as the failing card. Using floating cards to protect traffic is much more cost effective than traditional ways of traffic protection, but that can be realized only when the optical node has full flexibility.

Flexibility Helps Continuous Spectrum Arrangement Optimization

During installation of an optical channel it is very difficult, if not impossible, to assign the "right" wavelength to this channel by predicting what wavelengths other channels may take in future. After channels gradually populate a fiber network, it is almost inevitable that spectral fragmentation happens just like data fragmentation happens in hard disk drivers. With the freedom to tune wavelengths and optical paths, controller software in next generation networks will be able to defragment spectrum arrangement and free up spectrum for future use. Furthermore, controller software is able to perform such defragmentation periodically to continuously optimize the path and wavelength of optical channels.

Experiments Supporting Network Flexibility

Here we show a few examples of how spectral and spatial flexibility can be implemented in optical networks to help make optical networks more efficient.

Flexible Transponder Designs to Cope with Transmission Impairments

Of all elements able to present software controllable functions, transponders probably offer flexible functions the most since they serve as both source and destination of traffic flow. Therefore, technologies in transponder designs are key enablers for flexible optical networks. As mentioned above, by adjusting the modulation format, trade-offs can be achieved among system parameters such as spectral efficiency (SE), transmission distance, and system margin. Power consumption or capacity of transponders can also be adjusted through flexible forward error correction (FEC) designs with different coding gain options.

In an elastic WDM network, a flexible transponder can dynamically adjust signal characteristics, such as data rate, modulation format, and error correction coding scheme, for different channels in accordance with link conditions and quality of service requirements. This concept was first realized in a high-capacity field trial completed by Verizon and NEC that demonstrated 21.7 Tb/s fiber capacity over 1503 km [4]. Flexible modulation formats of 8QAM and QPSK were achieved by using a novel modulation unit. A total of 22 optical super-channels were transmitted over 19 dispersion-uncompensated field-installed fiber spans. A digital coherent receiver was used to receive the transmitted super-channels. For the first 18 super-channels the Q-factors of received signals (defined as digital SNR per symbol) are larger than 12.5 dB using PM-8QAM modulation. Their averaged spectral efficiency is 5.26 b/s/Hz. The last four super-channels on the short wavelength side have lower received optical signal-to-noise ratio (OSNR) due to lower gain and higher amplified spontaneous emission (ASE) noise and cannot support PM-8QAM transmission. With the flexible modulation unit, the transponder can still use the "inferior spectrum" by switching to

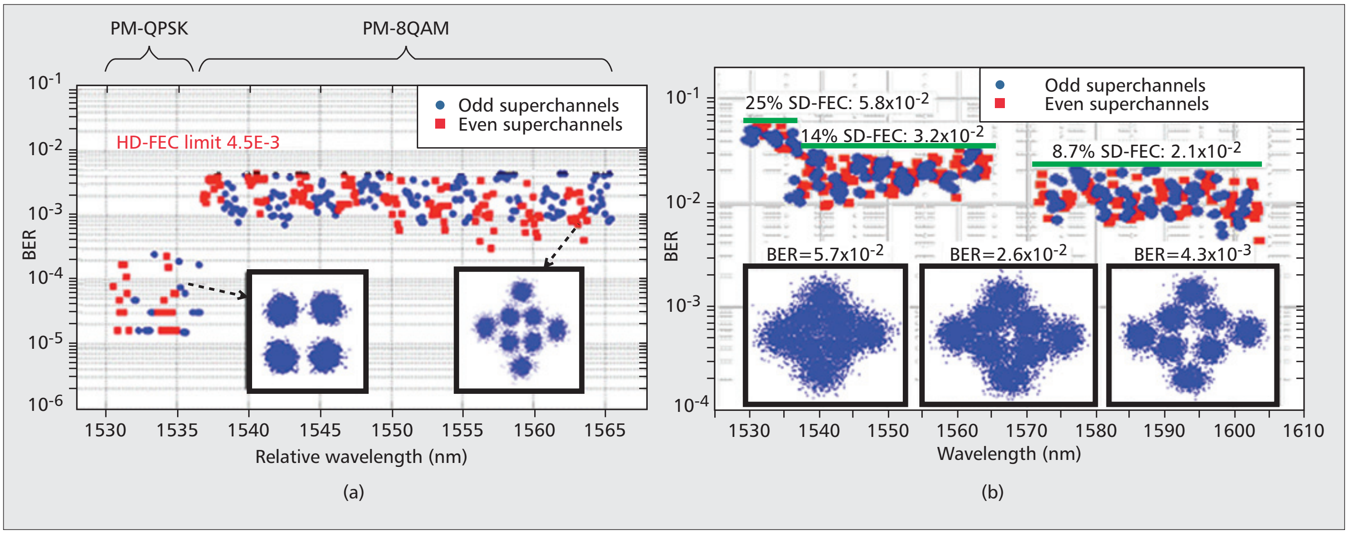

Figure 5. a) Field trial results of high capacity flexible transponders with adjustable modulation formats and b) adaptive FEC overheads.

QPSK and achieve error-free transmission with a reduced SE of 3.50 b/s/Hz. As a result, the total 4.4 THz WDM bandwidth was efficiently utilized with bit error ratio (BER) values of all optical subcarriers below the threshold of 4.5×10^{-3} using a product-ready CI-BCH FEC, as shown in Fig. 5a. Having the ability to administer different modulation formats, the transponders are able to use a larger portion of the spectrum with adjustable spectral efficiency, which is critical in > 20 Tb/s capacity at long-haul distances.

Other than changing modulation formats, adjustable FEC performance can also achieve trade-offs between spectral efficiency and transmission performance. In another record capacity field trial, an adaptive-rate low-density parity check (LDPC) code is employed to combat different received OSNR at different regions of C+L band WDM spectrum [5]. A total of 22 C-band super-channels and 19 L-band super-channels are combined to generate a total WDM bandwidth of ~9 THz. Each super-channel occupies 200 GHz and contains eight subcarriers with PM-8QAM modulation. The field trial uses 23 dispersion-uncompensated spans with a total distance of 1822 km and a hybrid amplification scheme including backward Raman pumping at 30 dBm averaged pump power with separate C- and L-band EDFAs. As a result of noise figure (NF) difference between C- and L-band EDFAs, unequal ASE noise distribution, and Raman energy shifting from C- to L-band, the 41 super-channels have as much as 2 dB difference in received OSNR. The adaptive LDPC coding with adaptive code rate and coding gain is designed to handle the non-uniform link condition. The pre-FEC BER results for all super-channel subcarriers are plotted in Fig. 5b, along with the BER threshold for the 25, 14, and 8.7 percent overhead used for the three spectral regions, respectively. In this trial, the adaptive FEC enables the transponder to maximize the data throughput based on the condition of its specific spectral region, as an example of many benefits in an elastic network. Using adaptive FEC, the field trial achieves highest long-haul field capacity of 40.5 Tb/s and field capacity-distance product of 73.7 Pb-km/s to date.

Flexible Optical Band Supported by All-Raman Amplification

Spectral flexibility also plays a role in selecting an optical band and the bandwidth of the band, as shown in Fig 1. In this area, Raman amplification shows more flexibility than EDFA amplification, since the spectrum of Raman amplification is quite flexible. All-Raman amplification technology, including discrete and distributed configurations, can also provide much broader spectrum compared to traditional EDFA. All-Raman systems with 100 nm spectrum were shown as commercial deployments as early as 2004. Distributed Raman amplification has been widely used in transmission systems to achieve better noise performance and reduction in channel power for mitigating nonlinear effects. In this section a field trial with flexible optical band provided by an all-distributed Raman system [6] is reviewed.

The field trial was carried out in a Verizon fiber network. The fiber plant is standard single-mode fiber with multiple splice points, which present discrete loss points as a result of construction activities in the metropolitan area. Each span is 79.2 km, and the average span loss is 21.8 dB. In the trial the span losses were mainly compensated by backward Raman pumping and occasionally helped by forward Raman pumping. The backward Raman pump module consists of five pump wavelengths from 1420 to 1500 nm and can deliver up to 1.9 W of pump power. The forward pump module includes three pump wavelengths (in the 1430 to 1480 nm range) and can deliver up to 0.85 W. It is a 150-channel 100G system, taking advantage of a 7.5 THz optical band supported by the all-distributed Raman system. Figure 6a shows the calculated power profiles for 150 channels along the transmission distance. Figures 6b and 6c depict input and output spectra of the transmission, respectively. Input channels are pre-emphasized

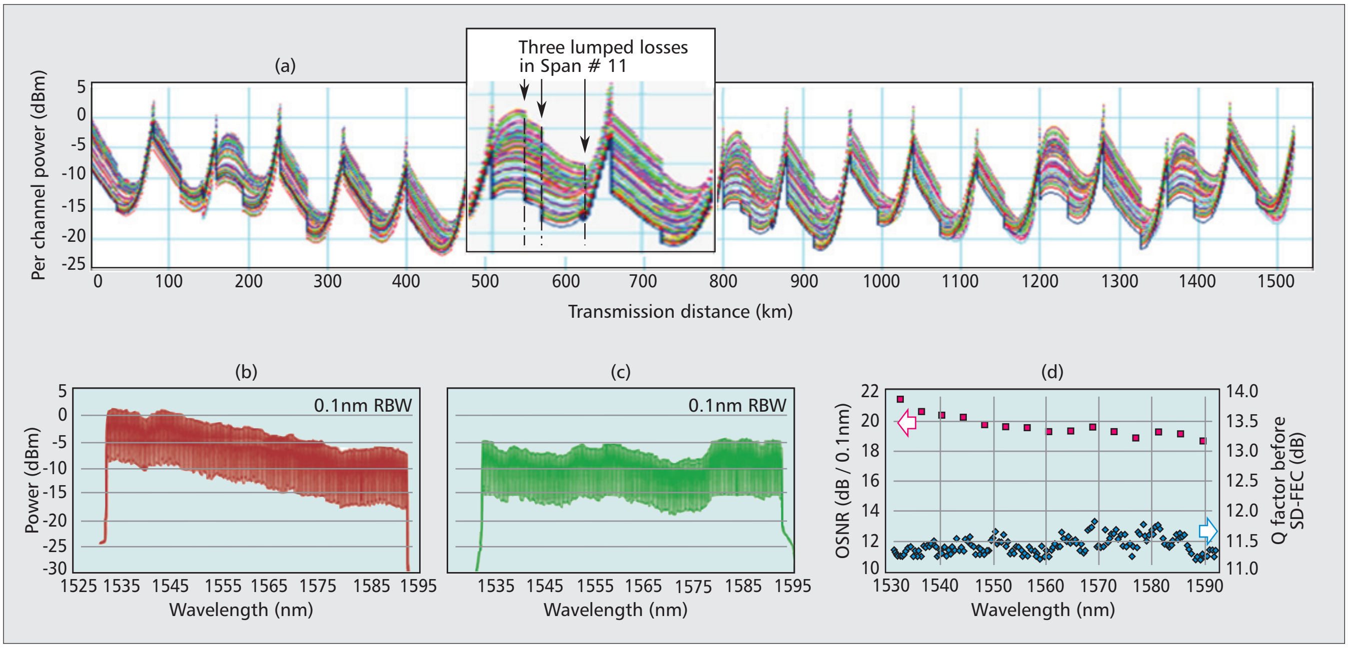

Figure 6. a) Results of the 150 × 100G all-Raman field trial, simulated per channel power profiles; b) spectrum at the booster output; c) spectrum after 1504 km transmission; d) measurements of OSNR and Q factor across the 150 × 100G channels spaced at 50 GHz.

to provide flat Q over spectrum at receive side. The gain ripple is smaller than 5 dB after the 19 spans across the 61 nm spectrum. Figure 6d represents the measurements of OSNR and Q factor performances across the 150 × 100G channels. The average OSNR is measured to be about 19.6 dB while Q factors of all channels are roughly uniform with an average value of 11.4 dB, which is 5 dB higher than the SD-FEC Q threshold of 6.4 dB.

The field trial demonstrated that properly designed Raman amplifiers can be deployed in fiber links with numerous optical connectors and discrete loss points. Given the nearly linear nature of the optical propagation (enabled by Raman distributed amplification), the high Q factor margin indicates that the 150 × 100G system is able to travel up to 4500 km in a real network environment. In the trial, channel spacing of 33.3 GHz was tested as well. Slight degradation in received signals due to the channel cross talk was observed, compared to 50 GHz channel spacing. However, the system still gives a 4 dBQ factor margin.

All-distributed Raman amplification also provides opportunity for PM-16QAM signals to be used for commercial long haul networks. PM-QPSK 100G channel is today's de facto standard long-haul transmission modulation format. PM-16QAM, on the other hand, thus far has been considered practical only for metro and regional networks due to higher OSNR requirements and sensitivities to nonlinearities along the line. The same setup as described above was used to demonstrate that PM-16QAM signals can be transmitted over long-haul distances in deployed networks with aged fibers [7]. In the trial, a total of eight dual-carrier 400G PM-16QAM channels, provided by NEC, were multiplexed in wavelengths with 134 100G PM-QPSK signals. All eight 400G PM-16QAM channels achieved transmission results above the SD-FEC Q-factor threshold of 4.95 dB, which corresponds to BER = 3.8×10^{-2}. With the above results we can estimate that 30 Tb/s capacity is feasible with 61 nm optical bandwidth for long-haul distances. Close to 50 Tb/s capacity is possible with usable optical band expanded to 100 nm with all-Raman amplification.

Unrepeatered subsea cable transmission represents another application of Raman amplification. Unrepeatered technology bridges long single-span submarine links connecting island to island or to mainland. Recent experiments show that Raman-powered remote optical amplifiers can support single span transmission with a full band of 100G channels up to 410 km with Corning's EX2000 ultra-low-loss fiber [8].

The optical band flexibility offered by Raman amplification provides a broader spectrum; therefore, larger transmission capacity and increased reach are possible. Components and subsystems for Raman systems, such as CDC ROADM, are available to provide optical networking functionality and wavelength tenability. The technical feasibility of similar flexibility for Raman systems with 100 nm gain spectrum has been demonstrated, and new deployments will happen again when they are required.

Software Defined Optics Experiments

As mentioned above, the emerging concept of SDN allows centralized control with a clear separation from the data plane. Several frameworks following this approach have been proposed, including, for example, the OpenFlow protocol developed by ONF and the Internet Engineering Task Force (IETF)-driven Network Configuration (NETCONF) protocol. Following the SDN paradigm, in principle all major hardware elements of an optical transport network can be controlled in a software-defined manner —

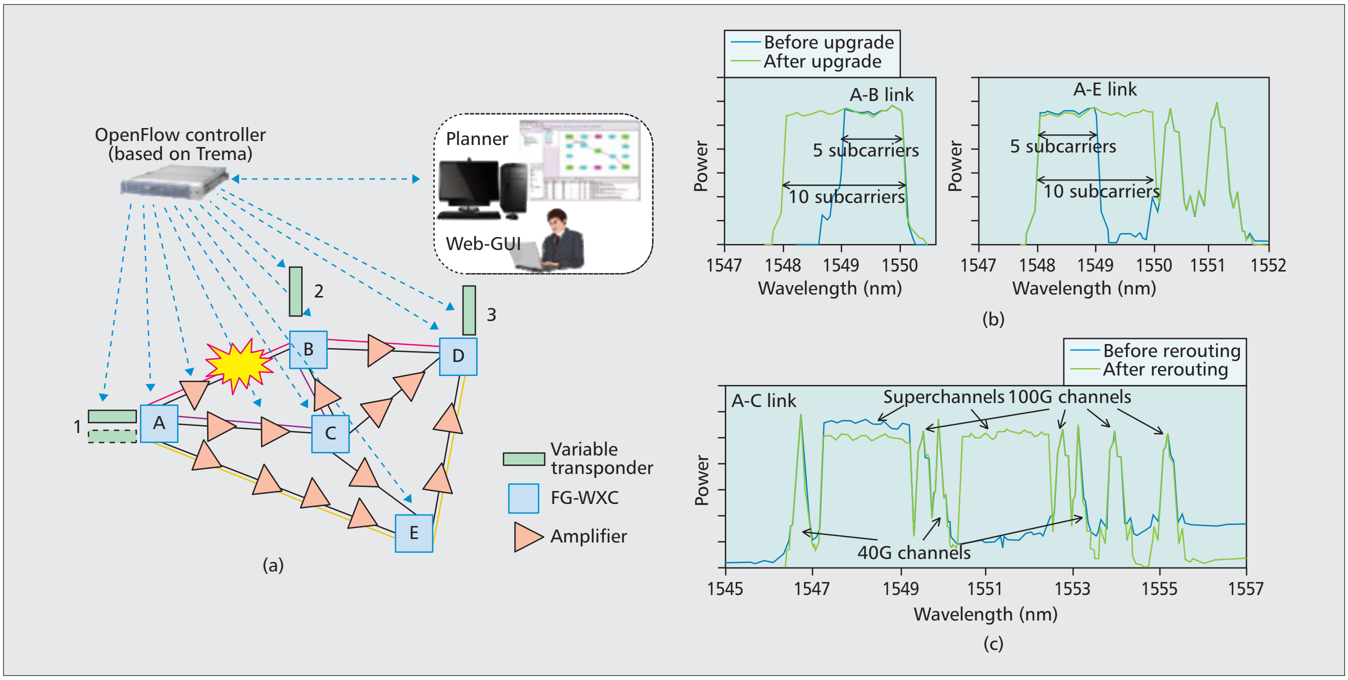

Figure 7. Demonstration of OpenFlow-enabled adaptive transport SDN.

including transponders, amplifiers, and switching nodes. Earlier, we presented how flexible tradeoffs can be achieved by adjusting the modulation format or FEC of a transponder. In some cases, a transponder's power consumption can also be adjusted by flexible FEC design with different coding gain options [9]. By maintaining a global view of the optical network status and being able to interact with the network elements through a centralized controller using a standardized network protocol, operators can orchestrate the network much more efficiently. Although there is currently ongoing effort to allow SDN control of optical equipment using the aforementioned frameworks, the debate is still open regarding the extent of such control (i.e., the exact definition of abstractions that would still allow different vendors to employ and take advantage of their proprietary PHY technologies).

Use cases for SDN-controlled optical transport networks would include fast and automated optical path restoration, rearrangement, and spectral defragmentation, taking physical layer limitations into account. Moreover, the use of common SDN APIs for controlling equipment across different layers (e.g,. L2/L3 electrical packet switches, L1/L0 OTN switches, optical transponders, and ROADMs) would make it significantly easier for network operators to come up with cross-layer schemes for increasing network utilization and to intelligently implement other beneficial features such as IP traffic offloading through optical paths.

Recently, such synergy between diverse network elements of a flexible optical network under OpenFlow control was experimentally demonstrated [3] in order to showcase the benefits and feasibility of applying SDN to optical networking. As shown in Fig. 7a, the testbed consisted of five NEC SpectralWave DW7000 FlexGrid optical wavelength cross-connect (FG-WXC) nodes that use FlexGrid wavelength-selective switch (WSS) modules. Three bandwidth-variable transponders were employed at the optical network edges, each able to generate 10 optical subcarriers spaced at 25 GHz. Each subcarrier can be individually modulated with PM-QPSK or PM-16QAM signal with digital Nyquist shaping, delivering effective data rates of 180 and 90 Gb/s respectively. The adaptive optical amplifiers used were hybrid EDFA Raman amplifiers.

In this particular work all important network parameters like the number of subcarriers and modulation of bandwidth-variable super-channel transponders, the switching configuration of FG-WXC, as well as the gain of optical amplifiers were all controlled by a custom Trema-based OpenFlow controller through OpenFlow agents and extended OpenFlow messages. It was demonstrated that capacity upgrades via the use of an overlying network planner can easily be performed in a pay-as-you-grow fashion (Fig. 7b). It is noted that due to the software-defined nature of the system, bandwidth-on-demand services through automated processes could also be supported. In a second experiment (Fig. 7c), when link A—>B failed, the affected path was automatically rerouted through links A—>C and C—>B, while amplifiers' gain was remotely readjusted to account for the longer restoration path.

Discussion on Spatial Flexibility with SDM

For single-mode/single-core fiber, the total fiber capacity achievable has almost reached its limit. One approach to increase link capacity is to use spatially parallel transmission, or SDM. SDM provides a new approach to design channels and

Adding spectral and spatial flexibility has proven to be an important step toward improving network efficiency. Next generation optical network management platforms, such as extended SDN controller software, are a key element to harness the flexibility toward optimization of network resource utilization.

high-capacity links in a flexible way [10]. SDM can be broadly categorized into two categories:
- The parallel optical channels do not couple to each other; hence, existing transponders for single-mode fibers can be reused.
- The parallel channels couple to each other; thus, multiple-input multiple-output (MIMO) signal processing is required to untangle crosstalk.

SDM transmission using uncoupled multicore fibers (MCFs) has seen rapid progress since 2011. MCF can provide capacity more than 100 Tb/s relatively easily. So far the highest fiber capacity, 1 Pb/s, was reported with 12-core single-mode MCF [11] and 14-core hybrid-core MCF [12]. These experiments achieved spectral efficiencies of 91.4 and 109 b/s/Hz, respectively, in a single fiber. Multicore fiber design, fan-in fan-out devices, amplifier design, splicing techniques, mating sleeves, and cabling technologies are now sufficiently advanced. It is possible to combine few-mode-fiber (FMF) technology with uncoupled MCF to achieve even higher spatial multiplicity (SM). It has been reported that a 12-core MCF carrying three spatially non-degenerate modes per core (SM = 36) achieved a record spectral efficiency of 247.9 b/s/Hz [13]. If all the C- and L-band channels were fully utilized, capacity as high as 3 Pb/s may be achieved. Although the maximum number of cores achieved so far is 19, MCFs with > 30 cores can be well anticipated with the most advanced fiber designs. Since MCFs with uncoupled core behave like parallel fibers, they can enable the same networking functions performed on their spatial and wavelength channels as in current SMF-based systems.

The second type of SDM systems use coupled parallel channels, including coupled MCF and FMF. While these SDM fibers can achieve higher spectral efficiency per unit area than uncoupled MCF, they also face more engineering challenges. For example, mode coupling will generally require the use of MIMO processing at the receiver. To recover a particular spatial channel, the receiver must have access to the full field of all the parallel channels that couple into it. In terms of networking, we expect the use of spatial super-channels, with switching and networking functions restricted only to the wavelength dimension. Another challenge in strongly coupled parallel transmission is mode-dependent loss (MDL), which needs to be overcome to reach desired transmission performance. To support multi-mode transmission in FMF for long distance, few-mode EDFAs (FM-EDFAs) with low mode-dependent gain (MDG) are needed, along with a variety of spatial multiplexing solutions for FMF such as phase plates, spot couplers, or photonic lanterns. To date, long-haul transmission using FMF has reached 500 to 1500 km depending on the number of WDM channels.

In terms of network flexibility, the spatial dimension in SDM also allows flexible allocation of power and spectrum in the spatial domain. For example, channels with different spatial characteristics can support different constellation sizes. For single-mode cores, low core-to-core crosstalk (< –30 dB) may allow the use of high-level modulation formats for all cores. For few-mode fiber, mode-dependent loss may cause large variation in channel performance.

In addition to providing spatial flexibility, using SDM also achieves cost per bit reduction as total fiber capacity increases. It has been shown that cost reduction can be achieved in in-line components and at the transponders. Parallelization enables equipment overhead sharing, leading to better power efficiency, more efficient use of chip area, as well as reducing component counts and connector counts. For example, it is feasible to integrate parallel 100G transceivers in a single line card. Such a parallel transponder can be used to form spectral or spatial super-channels (i.e., parallel channels in frequency or space), leaving to higher-layer management how the super-channels may be transmitted flexibly. At this point, SDM fiber is likely to be deployed first in data centers with uncoupled MCF, where the benefit of increased spatial information density has already been demonstrated. There is still much debate on the optimal SDM solutions for access, metro, and long-haul networks.

Conclusions

While providing capacity in backbone and metro networks to meet end users' traffic demands seems not to be an issue to most telecom carriers, enhancing network efficiency is a very urgent task for the same carriers to ease cost reduction pressure and provide better services for new applications. Adding spectral and spatial flexibility has proven to be an important step toward improving network efficiency. Next generation optical network management platforms, such as extended SDN controller software, is a key element to harness the flexibility toward optimization of network resource utilization. Several experimental results, including SDO, are reviewed to show that an optical network is able to not only provide high capacity but also further increase network efficiency.

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