Distance-Adaptive Spectrum Allocation in Elastic Optical Path Network (SLICE) with Bit per Symbol Adjustment

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Abstract: We present a concept of spectrally-efficient optical networking with distance-adaptive spectral allocation by adjusting the number of modulation levels. We demonstrate it by routing 40 Gb/s optical paths using short-reach, narrow-spectrum 16APSK and long-reach QPSK.

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1. Introduction

In the current wavelength-routed optical networks, optical channels are aligned to the ITU-T frequency grid. The rigid, large granularity presents a drawback in the form of bandwidth stranding when the volume of end-to-end traffic is not sufficient to fill the entire capacity of a λ. If the request is higher than the capacity of a λ, several λs are grouped and allocated according to the request. However, in the case of such grouped λ, adjacent λs must be separated by a spectral buffer to aid demultiplexing, which leads to inefficient spectral resource utilization.

The efficient use of network resources is always one of the main concerns of the telecommunication carrier. Recently, it has received a lot of attention as the standard optical fibers are beginning to approach the physical limit of capacity. Moreover, the carriers are facing a strong pressure to reduce network energy consumption as well as the per unit-bandwidth cost. The ongoing advances in photonic technologies, such as the optical multilevel modulation [1] or seamlessly bandwidth-variable wavelength-selective switches (WSSs) enable sharing the optical fiber resource of the optical network as a flexible, continuous resource pool. We have recently proposed a spectrum efficient and scalable optical transport network architecture called spectrum-sliced elastic optical path network (SLICE). In SLICE the necessary spectral resources on a given route are "sliced off" and allocated to the end-to-end optical path adapting to the traffic volume and user request in a highly spectrum-efficient manner [2-5].

In this paper, we present a novel concept of spectrally-efficient optical networking with distance-adaptive spectrum allocation through adjustment of the number of bits per symbol. We also report the experimental results of spectrum-efficient transmission of 40 Gb/s optical paths of shorter-reach, narrower spectrum 16APSK (amplitude-phase-shift keying) and longer-reach, wider spectrum QPSK (quadrature phase-shift keying).

2. Distance-adaptive spectrum allocation

In the current optical networks, a single given modulation format, such as ASK (amplitude-shift keying), QPSK, and most recently n-QAM (quadrature amplitude modulation) is employed. The design of the system ensures that the worst case optical path in the network, usually the longest path with multiple optical linear repeaters, ROADMs (reconfigurable optical add/drop multiplexers), and WXCs (wavelength cross-connects), can be transmitted with a sufficient quality of signal. Therefore, at the transmitter all paths have the same robustness to transmission impairments and occupy the same spectral width regardless of the optical path length. The paths shorter than the worst case have excess transmission performance at the receiver which results in overspending of network resources.

The concept of distance-adaptive spectral allocation in SLICE is based on saving the assigned spectral resources for shorter paths by varying the number of modulated bits per symbol. This is achieved by increasing the degree of modulation, for example from QPSK (2 bits per symbol) to 16QAM (4 bit per symbol), while reducing the spectral occupancy to 1/2, or from QPSK to 64QAM (6 bits per symbol), while reducing the spectral occupancy to 1/3. The increase in the number of modulation levels is accompanied by the reduction of the symbol rate while maintaining a fixed bit rate. This enables narrowing the allocated signal spectrum. The principle is illustrated in Fig. 1. The trade-off in increasing the number of modulation levels lies in the narrower spacing of symbols of signal constellation, resulting in receiver sensitivity deterioration. The deterioration of signal performance in terms of SNR penalty increases with modulation depth for both square n-QAM and ring n-PSK modulation formats [6].

The reduction in performance limits the reach of the optical signal, which nevertheless remains sufficient for most optical paths in the network. It should be emphasized that in the distance-adaptive SLICE transmission data bit rates remain unchanged even for the longer optical paths, yet wider spectra are allocated in order to guarantee the

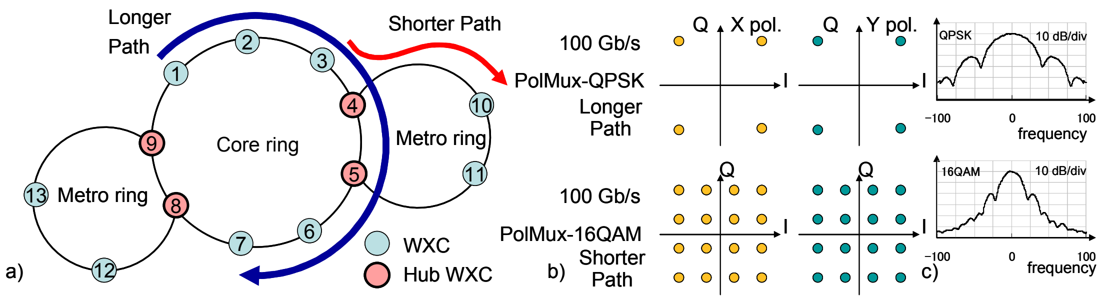

Fig. 1. Principle of distance-adaptive spectral allocation in SLICE: a) multi-ring network with optical paths of different lengths; b) constellation diagrams with PolMux-QPSK format for longer path and PolMux-16QAM format for shorter path; c) optical spectrum of the respective paths.

transmission quality. This is essentially different from the traditional rate adaptation in digital subscriber lines, fixed wireless access or other best effort services where the data bit rate is changed by adjusting the symbol rate or the number of subcarriers according to the connection quality when the transmission is affected by cross-talk from other users, noise, attenuation and other factors. The distance-adaptive spectral allocation enables spectrum efficiency (SE) improvement as shown in the simulation of a multi-ring network in Fig. 2, where a mixture of full mesh and protected ring traffic is assumed. The x-axis shows the number of nodes which can be reached using the advanced modulation format with the longer paths modulated by QPSK format. The baseline for comparison is an all-QPSK network. The three cases illustrate the results for 16QAM (squares), 64QAM (triangles) and a mix of 3 modulation formats (64QAM<=3 nodes<16QAM) (crosses). For example, a 50% improvement in SE can be achieved if the 16QAM modulation reaching 5 nodes is used. The analysis was performed basing on the required level of OSNR.

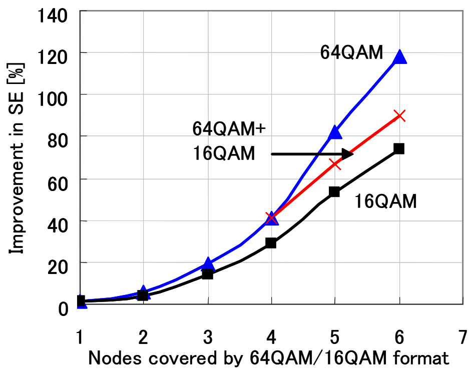

Fig. 2. Improvement of spectral efficiency as a function of the number of nodes in distance-adaptive SLICE.

3. Experimental demonstration

We experimentally demonstrate the concept of distance-adaptive spectrum allocation in SLICE by transmitting the DWDM optical paths over a WXC placed in a recirculating loop, mimicking the parameters of the ring network. The experimental setup is shown in Fig. 3. In this experiment, 16APSK format was used instead of 16QAM for simplicity [7]. We generate 40 Gb/s RZ-DQPSK (return-to zero DQPSK) signals for the long-reach paths and RZ-16APSK signals for the short reach paths. 50 GHz-spaced multi-carrier signal aligned to ITU-T frequency grid is generated by a pair modulators and an interleave filter [3]. The following WSS splits it into one of two modulator branches. One branch contains an RZ modulator and a DQPSK modulator driven by a pulse pattern generator (PPG). It produces 100 GHz-spaced 42.7 Gb/s RZ-DQPSK signals. The second branch contains an RZ modulator, a QPSK modulator and a Mach-Zehnder modulator driven by a 4-level signal, producing 10.7 Gbaud, 42.7 Gb/s 16APSK signals. A separate, single 16APSK signal is also generated to create a channel to test the performance of the multilevel format. All branches are multiplexed in a WSS. 6 DQPSK and 10 16APSK signals are transmitted in a recirculating loop containing 40 km of standard single-mode fiber (SMF), a dispersion compensating fiber (DCF), a WXC node and a gain equalizing filter. After transmission, both the DQPSK and the 16APSK signals are received and analyzed.

The performance of the QASK and QPSK components of the 16APSK signal are shown in Fig. 4 a (diamond and square, respectively). Both components achieve bit-error rate (BER) performance above 10^{-3} corresponding to the Q-parameter of 9.8 dB after transmission over 5 nodes. The QASK components after the first node and after the 5th node are shown in Fig. 4 b. After the 5th node, there is a clear deterioration of each of the eyes due to the accumulation of the amplified spontaneous emission (ASE). Fig. 4 b also shows the waveform and the output of the clock

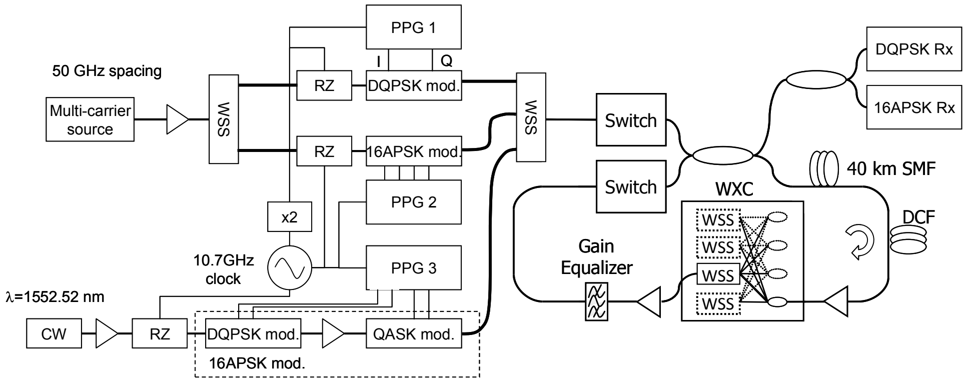

Fig. 3. Experimental setup for demonstration of the concept of distance-adaptive SLICE.

and data recovery (CDR) of the QPSK component after the 5th node. The eye closure and ASE noise lead to BER approaching 10^{-3}. It should be noted that the QASK modulation depth was adjusted to equalize the performance of the QASK and QPSK components. The 40 Gb/s DQPSK signals are influenced by four-wave mixing from the narrowly spaced 16APSK channels (approx. 0.1 dB penalty per loop) and the accumulation of ASE. The Q-factor performance of the DQPSK signal is also shown in Fig. 4 a with the reach of 37 nodes.

The distance-adaptive transmission enables allocating a larger amount of traffic using the same spectral resource when compared to the all-DQPSK transmission. In Fig. 4 c, 16 instead of 11 40 Gb/s channels can be transmitted when the distance-adaptive spectrum allocation is deployed, providing a 45% increase in SE.

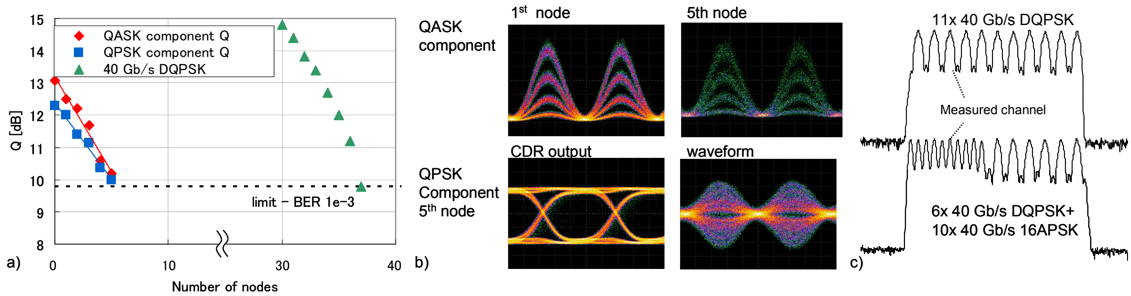

Fig.4 Experimental results: a) Q penalty in terms of the number of transmitted nodes; b) waveform of QASK and QPSK components after transmission over 5 nodes; c) spectra of all-QPSK transmission and distance-adaptive SLICE transmission.

5. Conclusions

We presented, for the first time, the spectrum-efficient optical networking using novel distance-adaptive spectral allocation. We realized the concept by adjusting the number of bits per symbol during modulation while trimming the symbol rate and channel spacing using the SLICE platform. We have successfully demonstrated the feasibility of the concept in the experiment. The presented distance-adaptive functionality completes the client bit-rate-adaptivity proposed in the previous papers for efficient spectrum allocation in SLICE architecture. It will substantially improve the optical network resource utilization in the 100 G Ethernet era and beyond.

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