QoT-Aware Adaptive Multi-Band Networking over Hybrid Fibers Enabled by Wavelength-Selective Band Switching

Masahiro Nakagawa, Takafumi Fukatani, Takeshi Seki, Rie Hayashi, Takeshi Kuwahara
NTT Network Service Systems Laboratories, NTT Corporation, 3-9-11 Midori-cho, Musashino, Tokyo, 180-8585, Japan
mshr.nakagawa@ntt.com

Abstract: We investigate highly adaptive multi-band networking for diverse physical-layer conditions. Using our wavelength-selective band-switchable OXC prototype, we demonstrate adaptive C+L-band spectrum utilization over hybrid SMF/DSF links as link-by-link band selection can suppress nonlinear interference accumulation.

1. Introduction

Ever-growing data traffic has motivated the continuous evolution of optical networks in terms of capacity. With the advent of digital coherent transmission and advanced modulation schemes, per-wavelength capacity of 100 Gb/s and beyond has been popularized. This has enabled high traffic volume over long distances without any 3R regenerators. Since the elimination of costly and power-hungry regenerators has obvious benefits for network operators, expanding transparent reach is also of great importance [1,2]. Therefore, capacity and maximum reach of each wavelength channel need to be well considered for evolving optical networks in a cost-effective manner.

Recently, multi-band (MB) networking has been actively studied as a promising approach for near- to mid-term evolution [3,4]. C+L-band transmission technologies are being deployed, and operations beyond the C+L-band are now attracting much attention. However, most conventional studies are based on standard single-mode fibers (SMFs). While the recent work in [5] has investigated MB transmission over cut-off shifted fibers (CSFs), there has been no significant study that focuses on other fiber types or hybrid fiber scenarios. In fact, there are several types of deployed fibers including dispersion-shifted fibers (DSFs) and non-zero DSFs (NZ-DSFs), which must be well considered for applying/upgrading MB operations. Specifically, C- and S-band signals can be severely affected by four-wave mixing (FWM) on DSFs and NZ-DSFs, respectively. Such nonlinear interferences (NLIs) strictly limit not only MB network performance but also the degree of freedom in network evolution strategies. Moreover, MB operation in a hybrid fiber scenario where different types coexist (such as SMF and DSF in [6]), raises the challenge of how to provide transparent paths while ensuring quality of transmission (QoT) in a spectrum-efficient manner.

In this paper, we present a concept of highly adaptive MB networking that leverages the wavelength-selective band switching that we recently introduced [7]. In particular, the transmission band can be selected link-by-link considering QoT for a transparent path, which can boost MB network performance even where multiple fiber types coexist. We also experimentally demonstrate its feasibility by emulating a C+L-band network over hybrid SMF and DSF links, where all-optical wavelength converters (AO-WCs) are used for band switching operations in our prototype node.

2. QoT-Aware Adaptive Multi-Band Networking

The aim of QoT-aware adaptive MB networking is to efficiently utilize MB spectrum resources while preventing the occurrence of a channel unusable for a transparent path on a network. In conventional MB networks, a particular wavelength channel on a particular band is allocated to each path demand, i.e., each path must use a single band end-to-end. This results in remarkable NLI accumulations in several specific combinations of bands and fiber types, such as “C-band and DSF” and “S-band and NZ-DSF”. The S-band signals can also be affected by multipath interference (MPI) on CSFs, as analyzed in [5]. Accumulated NLIs can be limiting factors not only of the QoT of each path but also of the total MB network performance. To address this issue and gain the potential benefit from MB operations regardless of fiber types, we leverage the wavelength-selective band switching [7], which greatly enhances the band-usage adaptivity during path provisioning. More specifically, for each path demand, according to physical conditions (e.g., fiber types) on the route, the transmission band is selected in a link-by-link manner for maintaining transparent reach and efficient spectrum utilization. Please note that several QoT estimation methods have been studied in MB scenarios (such as [8]), which can be applied to calculate transparent reach.

An illustrative example highlighting the benefit of our concept is shown in Fig. 1, where SMF and DSF links coexist, each link can support C- and L-bands, and each band supports 2 wavelength channels. Suppose that an optical path request between nodes I and IV newly arrives at the initial state shown in Fig. 1(a), and an optical signal on λ_{C2} (around zero dispersion wavelength) is assumed to be unable to traverse 2 DSF links due to FWM effects. In

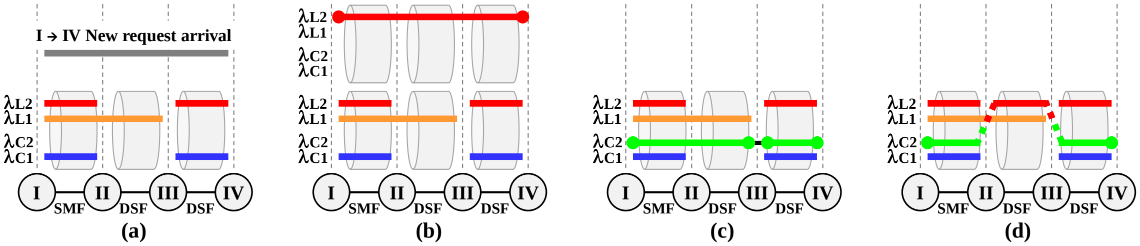

Fig. 1. Impact of adaptive MB networking; (a) initial state, (b) conventional operation, (c) using 3R regenerators, (d) adaptive networking.

this case, conventional operations where the use of λ_{C2} is avoided (as described in [9]), requires an additional fiber to accommodate the new request, as shown in Fig.1 (b). Although 3R regenerators can be used as shown in Fig. 1(c), the number of regenerators depends on the unusable channels, which is a costly solution. However, by switching the transmission band at nodes II and III, the new request can be accommodated utilizing residual resources without the need for 3R regenerators, as shown in Fig. 1(d). This example indicates the practical benefits of our concept.

3. Experimental Demonstration

To show the feasibility of our concept, we report on the experimental demonstration by emulating a C+L-band network over hybrid SMF and DSF links with our prototype node. Due to the limited availability of devices, a 3-degree C+L-band OXC node is configured, and three unidirectional rings (one 60-km SMF and two 60-km DSF rings) are connected, as shown in Fig. 2. In the node configuration, C- and L-band erbium-doped fiber amplifiers (EDFAs) are deployed just inside band de-/multiplexers (DEMUXs/MUXs) at ingress and egress ports. AO-WCs based on degenerate FWM in a highly nonlinear fiber (HNLF) are implemented, just as in [7]. Such AO-WCs can convert the wavelengths from/to C-band to/from L-band without the need for electronic processing. Egress wavelength selective switches (WSSs) equalize the wavelength-dependent gain/loss of optical components. On the transmitter side, 72-channel 100-Gb/s dual-polarization quadrature phase shift keying (DP-QPSK) signals with 50-GHz spacing ranged from 1529.55 to 1556. 96 nm are generated. One channel of them is replaced with the DP-QPSK signal output from a commercially available white-box transponder (WB-TR). In addition, C-band WDM signals are replicated by a splitter (SPL) and added to the node. The replicated signals are converted to L-band signals to generate dummy channels, and C+L-band DWM signals are launched into the ring 1 (SMF). After the first span transmission, our wavelength-selective band-switchable node delivers individual signals to ring 2 or 3 (DSF) and to C- or L-band. The path setting patterns are shown in Table 1. Please note that patterns #1~#8 are assigned to every 8 channels of 72-channel WDM signal. According to the work in [10], the channel launch power is set +1, +2, or +3 dBm/ch at all the rings. On the receiver side, through a WSS for drop, EDFA, and tunable filter (TF), an individual channel within C-band WDM signal is detected at the receiver of a WB-TR, and the bit error rate (BER) is measured in real-time. Note that optical signal-to-noise ratio (OSNR) is also measured using an optical spectrum analyzer (not explicitly shown in Fig. 2).

To show the basic characteristics of adaptive band usage, overall and expanded spectra at the input of each fiber

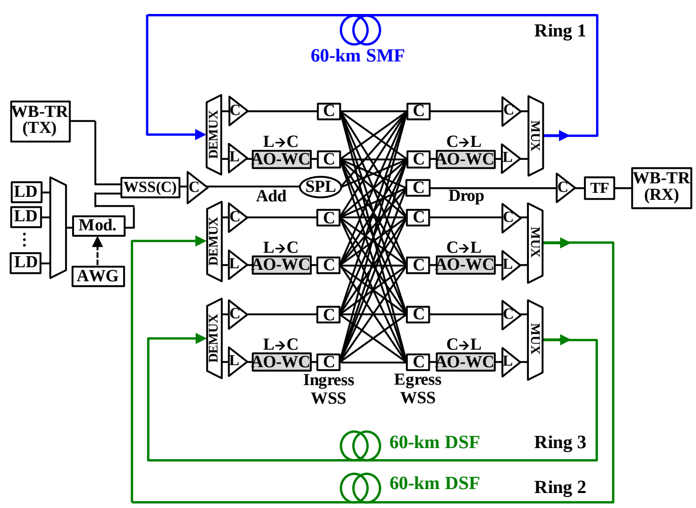

Fig. 2. Experimental setup.

Table 1. Path setting patterns

	Channel (ch1: 1529.55 nm ~ ch72: 1556.96 nm, 50-GHz spacing)	Transmission band / ring		
		1st hop	2nd hop	3rd hop
#1	ch1, ch9, …, ch65	C / 1	L / 3	L / 2
#2	ch2, ch10, …, ch66	C / 1	L / 3	C / 2
#3	ch3, ch11, …, ch67	C / 1	C / 3	L / 2
#4	ch4, ch12, …, ch68	C / 1	C / 3	C / 2
#5	ch5, ch13, …, ch69	C / 1	L / 2	L / 3
#6	ch6, ch14, …, ch70	C / 1	L / 2	C / 3
#7	ch7, ch15, …, ch71	C / 1	C / 2	L / 3
#8	ch8, ch16, …, ch72	C / 1	C / 2	C / 3

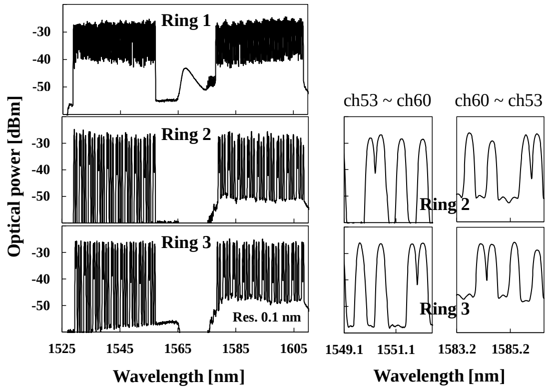

Fig. 3. Monitored optical signal spectra.

Table 2. Measured QoT results for each channel

	Wavelength in C-band	Transmission band / ring			OSNR margin for each launch power per channel [dB]		
		1st hop	2nd hop	3rd hop	+1 dBm	+2 dBm	+3 dBm
ch53	1549.32 nm	C / 1	L / 2	L / 3	~ 4	~ 4	~ 5
ch54	1549.72 nm	C / 1	L / 2	C / 3	~ 6	~ 6	~ 4
ch55	1550.12 nm	C / 1	C / 2	L / 3	~ 5	~ 6	~ 4
ch56	1550.52 nm	C / 1	C / 2	C / 3	~ 4	~ 4	N/A
ch57	1550.92 nm	C / 1	L / 3	L / 2	~ 6	~ 6	~ 6
ch58	1551.32 nm	C / 1	L / 3	C / 2	~ 5	~ 4	~ 4
ch59	1551.72 nm	C / 1	C / 3	L / 2	~ 7	~ 4	~ 3
ch60	1552.12 nm	C / 1	C / 3	C / 2	~ 5	~ 4	N/A

ring, when the channel launch power is set +2 dBm/ch, are shown in Fig. 3. This successfully confirms that the desired switching operation can be achieved. Moreover, in this experiment, we focus on QoT of channels around zero dispersion wavelength (~1.55 µm) in which FWM impacts must be considered. Table 2 shows the measured QoT results of such channels in the metric of OSNR margin, where “N/A” means that error-free operations cannot be achieved. This margin is defined as the difference between the observed OSNR and the minimum OSNR required for error-free operation when 20%-overhead soft-decision forward error correction (SD-FEC) is applied in this experiment. The results show that the accumulation of FWM effects significantly degrade QoT of ch56 and ch60 as launch power increases. On the other hand, L-band transmission over DSFs naturally avoid such effects and QoT of ch53 and ch57 exhibit good performance although they traverse four AO-WCs. This clarifies that the transmission penalty induced by AO-WCs is marginal compared to that induced by FWM. In addition, it should be emphasized that the other channels (ch54, ch55, ch58, ch59) actually use C-band resources on DSFs while maintaining acceptable QoT or transparent reach. This is mainly because link-by-link band switching operations can suppress the accumulation of FWM effects. These results successfully prove the physical-layer feasibility of our MB networking concept. Applying our concept to C+L-band networks including DSF links, C-band resources on DSFs can be efficiently utilized, which saves spare L-band resources for later or longer path requests and improves MB network performance. Furthermore, this experiment also investigates that C-band WB-TRs can be used for MB transmission applications. These insights should be useful for advancement of MB networking and further network evolution.

4. Conclusions

We presented and successfully demonstrated a concept of adaptive multi-band networking to efficiently utilize spectrum resources across multiple bands while ensuring transmission quality of each path. We believe that our concept can unlock the full potential of multi-band networking in diverse fiber infrastructures and enable network operators to maximize return on investment.

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