Demonstration of Single-mode Multicore Fiber Transport Network with Crosstalk-aware Optical Path Configuration

Takafumi Tanaka, Takayuki Mizuno, Akira Isoda, Kohki Shibahara, Tetsuro Inui, and Yutaka Miyamoto

Abstract

Space-division multiplexing using multicore fiber (MCF) is considered to be one of the most promising technologies for breaking the capacity limit of traditional single-mode fibers and advancing fiber optic communication systems. For transport networks to utilize the capacity of MCF efficiently, it is essential to consider inter-core crosstalk (XT) in provisioning optical paths. We developed an MCF transport network testbed and used it to demonstrate our optical path configuration scheme, in which a software-defined networking controller configures programmable transponders that include a beyond-100G digital signal processor that factors in XT.

Keywords: space-division multiplexing, inter-core crosstalk, software-defined networking

1. Introduction

The maximum capacity of practical single-mode fiber (SMF)-based transmission systems is thought to be around 100 Tbit/s per fiber due to the fiber fuse phenomenon [1]. Efforts are underway to break the capacity limit of SMF, and space-division multiplexing (SDM) is one of the most active areas of research intended to achieve this [1, 2]. The European Union (EU)-Japan coordinated research and development (R&D) project named Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI) was launched in 2014 and has achieved many of the world's most significant advances in realizing Pbit/s/fiber-class and over 1000-km-distance programmable optical networks. For example, high-core-count single-mode multicore fiber (MCF) with spatial multiplicity of over 30 was demonstrated in the project [3], and it was used to achieve dense-SDM (DSDM) transmission with Pbit/s/fiber-class capacity [4].

If MCF-based transmission is to become feasible for wide-area transport networks, the effect of inter-core crosstalk (XT) must be considered. It is an important factor that occurs only in MCF and that limits the transmission distance and the modulation formats that can be used. A core in an MCF is affected by the XT generated in its adjacent cores, and the XT impairment accumulates as the transmission distance increases. In addition, the XT in a core will change over time in response to changes in optical path assignments to its adjacent cores. Therefore, careful consideration of XT is essential, especially for long-distance and dynamic MCF transport networks.

In this article, we report the recent achievement of the SAFARI project, a single-mode MCF transport network that offers XT-aware and programmable optical paths with XT monitoring [5]. We used the testbed to demonstrate an XT-aware traffic engineering

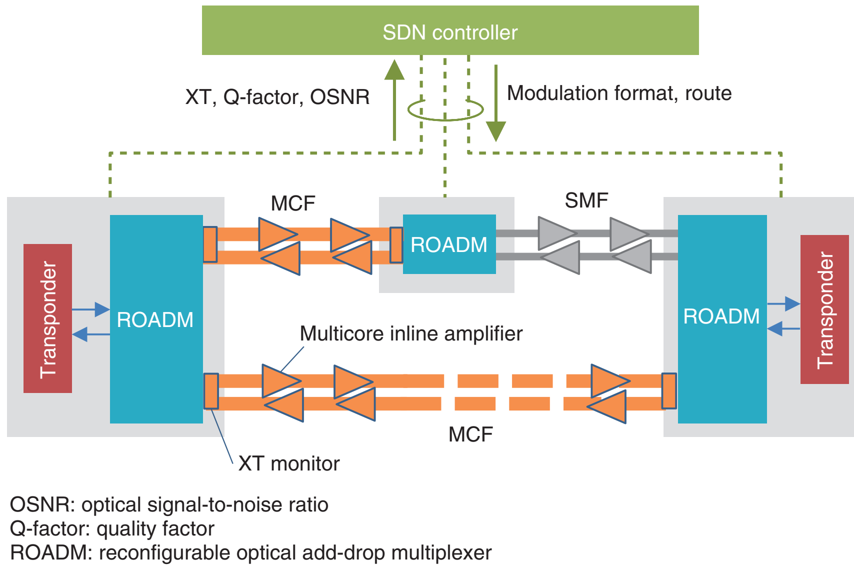


Fig. 1. XT-aware MCF transport network architecture with SDN controller.

use case, in which optical paths were adaptively (re)configured subject to consideration of inter-core XT with the help of a software-defined networking (SDN) controller.

2. MCF transport network architecture

The proposed XT-aware MCF transport network architecture is shown in **Fig. 1**. This network contains a mixture of MCFs and SMFs, as the former will incrementally replace the latter. The network connects three reconfigurable optical add-drop multiplexers (ROADMs) using three SMF/MCF links that include inline amplifiers. Of particular note is the fact that the MCF links contain FI/FO (fan-in/fan-out) devices and XT monitors to estimate the inter-core XT values of each link. The transponders have the ability to adaptively select the modulation formats from among quadrature phase-shift keying (QPSK), 8 quadrature amplitude modulation (8QAM), and 16QAM.

The SDN controller collects transmission performance data such as inter-core XT, Q-factor (quality factor), and optical signal-to-noise ratio (OSNR) values at regular intervals from each node. The SDN controller uses the monitored values to set the transponders to an appropriate modulation format and/or configure the ROADMs to change optical path routes.

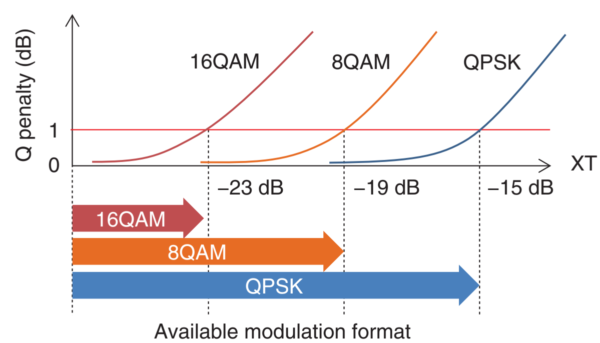


Fig. 2. Available modulation formats with respect to XT.

3. XT-aware optical path configuration scheme

This section describes how XT is taken into consideration in optical path configuration. The initial step prior to optical path configuration is to associate XT values with suitable modulation formats, as shown in **Fig. 2**. In long-distance MCF transmission, transmission quality (e.g., Q penalty) mainly depends on the XT induced in the MCF link. If a certain level of allowable Q penalty due to XT is set (typically < 1 dB as shown in Fig. 2), the XT threshold for each modulation format is automatically determined.

In the second step, the XT values are monitored continuously or periodically during operation of the transport network because it will change dynamically

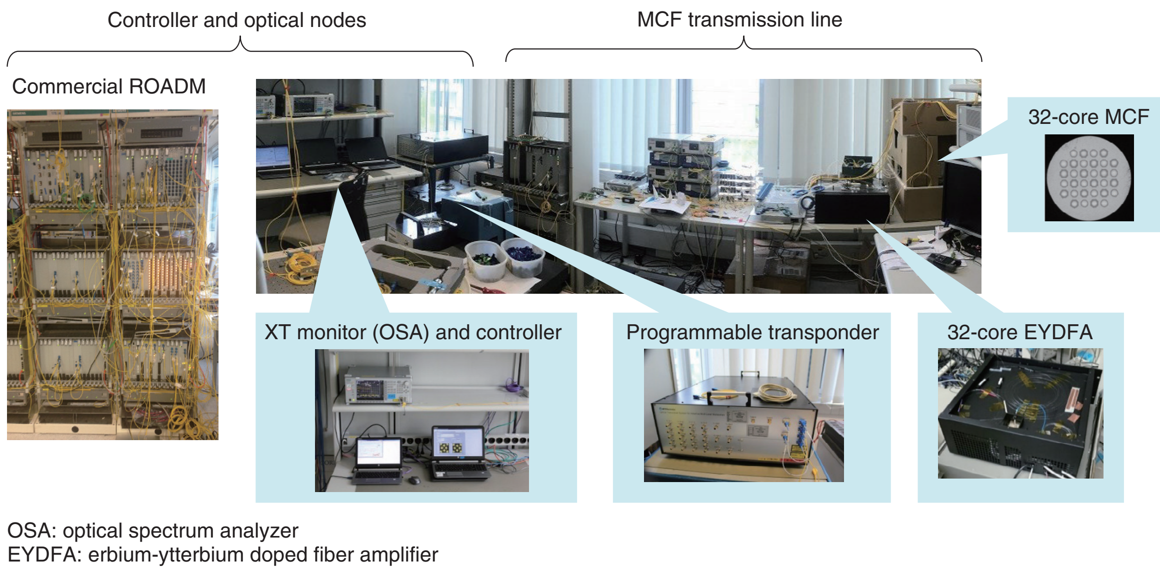


Fig. 3. Constructed testbed.

over time as optical path assignment conditions in adjacent cores change. In addition, to ensure high-quality network services, in-service XT measurement is necessary, which means that the XT monitoring method should not affect or interrupt the wavelength-division multiplexing (WDM) signals. Our in-service XT measurement scheme has been adopted in the network [6].

In the final step, the SDN controller commands the transponders and ROADMs to (re)configure the modulation format and the optical path route. The modulation format is determined by plotting the measured XT value, as in Fig. 2, and selecting the format with the highest modulation level.

4. Testbed setup and evaluation results

We constructed a testbed in order to evaluate the system. The testbed setup and the results of our experiments are described in this section.

4.1 Use case

The constructed testbed is shown in **Fig. 3**. The testbed is designed to demonstrate XT-aware traffic engineering, shown in **Fig. 4(a)**, as a representative use case where XT-awareness is a key attribute. First, for this use case, we assume a low priority optical path established on a low-XT MCF span (Link A in Fig. 4(a)). Since the XT is low, the span supports 16QAM. Next, we assume that a request for a high priority optical path arrives that needs to be served using Link A. This forces the route of the low priority path to be changed to a less favorable route (Link B-C) to make room for the newly arrived high priority path. Since the XT level of the new route (Link B-C) is higher than that acceptable for 16QAM, a lower-order modulation format is selected, that is, QPSK or 8QAM.

4.2 Testbed setup - transmission line

The right side of **Fig. 4(c)** represents the DSDM transmission line. It consists of a 51.4-km 32-core single-mode MCF [3], a 32-core erbium-ytterbium doped fiber amplifier (EYDFA) [7], and in-service inter-core XT monitors [6].

To model different levels of XT and their effects on an MCF network, sets of cores were connected in series in various combinations. As shown in **Fig. 4(b)** and Fig. 4(c), a set of eight concatenated cores (blue-colored cores in Fig. 4(b)) surrounding several high input power cores was used to represent a 411.2-km high-XT line. Another set of eight concatenated cores around the outer perimeter of the fiber (orange-colored cores in Fig. 4(b)) yielded a 411.2-km low-XT line. Further, a set of two cores (red-colored cores in Fig. 4(b)) represented a 102.8-km line with minimum XT. This arrangement shows how different deployment and operation scenarios can be tested.

For XT monitoring, two pilot tones are combined with the input WDM signal by a 2 x 2 coupler for

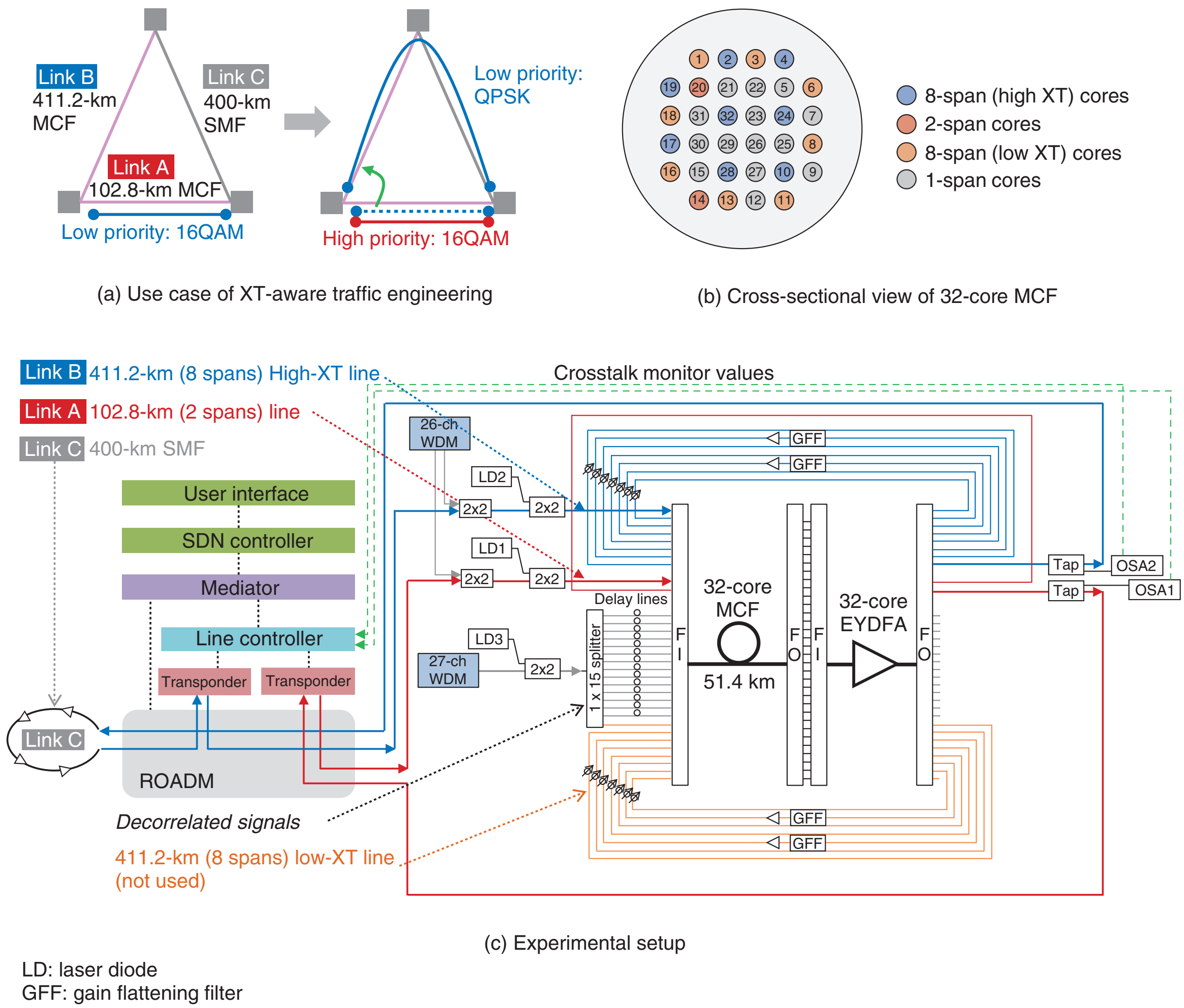


Fig. 4. Use case and experimental setup.

each transmission line, and the output signal is tapped and its spectrum is measured using an optical spectrum analyzer (OSA).

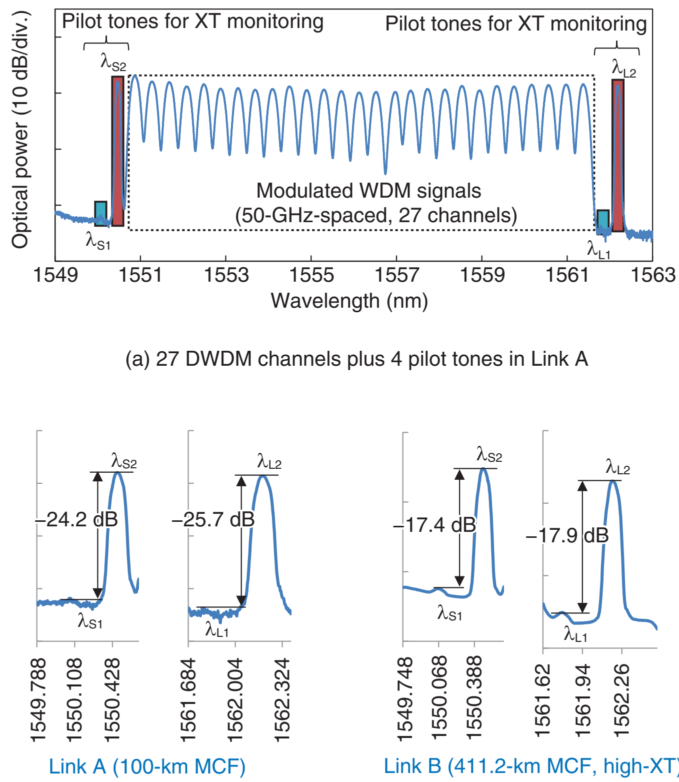
4.3 Testbed setup - SDN controller

The SDN controller in the testbed adopts the hierarchical layer model as shown on the left side of Fig. 4(c). The MCF transmission line is controlled using the SDN controller via its user interface. We assume the adoption of OpenDaylight [8], a widely used open-source SDN controller. However, it lacks several specific functions required for the use case, for example, identifying the MCF core number, collecting XT values, and setting the modulation format, so we added an intermediate function named Mediator that can issue commands to implement these functions to the ROADM and transponders.

The line controller controls and manages the programmable transponders and the MCF transmission line. This implementation enables (re)configuration of the modulation format, wavelength, laser on/off, and performance monitoring. The controller also collects the monitored XT values from the OSAs and forwards them to the SDN controller to determine the modulation format.

4.4 Results

The DWDM (dense-WDM) spectrum in Link A measured using the OSA after transmission is shown in **Fig. 5(a)**. The inter-core XT outside both ends of the WDM signal bandwidth were estimated by comparing the optical power differences between the



(a) 27 DWDM channels plus 4 pilot tones in Link A

(b) Excerpt of pilot tone channels in Link A (c) Excerpt of pilot tone channels in Link B

Fig. 5. Measured XT monitoring performance in the testbed.

corresponding reference and XT pilot tones. The XT at the signal wavelength was estimated by linear interpolation of the estimated XT values at the WDM spectral edges. For example, we can see that the XT range of Link A is estimated to be between –25.7 dB and –24.2 dB by taking the differences between reference and XT pilot tones at the respective WDM spectral edges (the difference between λ_{S2} and λ_{S1} at a short wavelength, and the difference between λ_{L2} and λ_{L1} at a long wavelength) (**Fig. 5(b)**). By linearly interpolating these values, we can estimate that the XT at the wavelength used by the test signal in Link A is about –24.9 dB. Similarly, XT at the same wavelength in Link B is estimated to be about –17.7 dB (**Fig. 5(c)**). By comparing these estimated XT values with those in Fig. 2, which represent the relationship between Q penalty and XT, we can see that QPSK, 8QAM, and 16QAM formats are available for Link A, while QPSK is the only available modulation format for Link B.

The real-time measurement data for a low priority, 16QAM path initially routed across the two-core 102.8-km MCF link (Link A) having low XT is shown in **Fig. 6**. Since the SDN controller continuously collects inter-core XT of the low priority path from the OSA, we can see that the inter-core XT of the low priority path is initially kept low. When the request for a high priority 16QAM path arrives, the low priority path is pre-empted by the high priority path and rerouted to the eight-core high-XT MCF link and 400-km SMF (Link B-C). Accordingly, the modulation format of the low priority path was changed to QPSK. After waiting a few minutes for the change in modulation format to be completed, the low priority channel was successfully switched to the new route, and all established paths showed stable error-free operation after forward error correction (FEC) decoding.

5. Conclusion

We presented the concept of the single-mode MCF transport network orchestrated by an SDN controller. To suppress the effect of inter-core XT impairment,

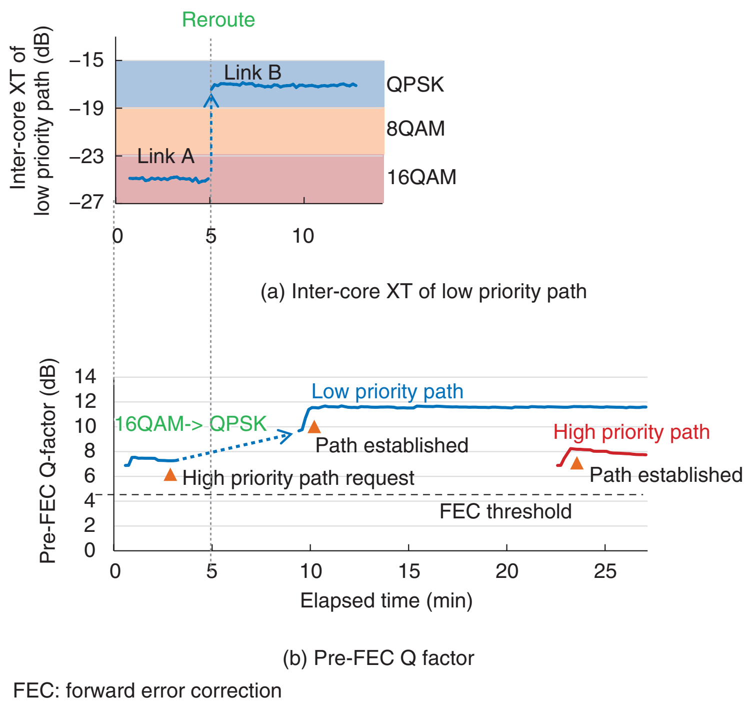


Fig. 6. Transition of inter-core XT and pre-FEC Q factor.

which is the main factor limiting the transmission distance and which modulation formats can be used, we applied our SDN-supported XT-aware optical path control scheme with in-service XT monitoring. We constructed an MCF transport network testbed around a 32-core MCF and EYDFA, programmable transponders, 3-degree ROADM, and an SDN controller. An XT-aware traffic engineering scenario was examined as a use case, and the results confirmed that the SDN controller was able to dynamically change both the modulation format and the optical path route.

Some technological advances are required in order to further improve the feasibility of the MCF transport network. These include an MCF-compatible optical node that can connect to multiple MCFs and switch optical paths at multi-granular levels (e.g., fiber, core, wavelength), and an efficient optical path assignment algorithm that calculates optimal parameters such as route, core, wavelength, and modulation format.

Acknowledgments

This work was supported by the EU-Japan coordinated R&D project on "Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI)" commissioned by the Ministry of Internal Affairs and Communications (MIC) of Japan and EC Horizon 2020.

Moreover, the authors would like to thank K. Pulverer, U. Häbel, C. Castro, and M. Bohn from Coriant R&D GmbH; Y. Sasaki, Y. Amma, and K. Aikawa from Fujikura Ltd.; S. Jain, Y. Jung, S. Alam, and D. J. Richardson from the University of Southampton; and M. Nooruzzaman and T. Morioka from the Technical University of Denmark for contributing to the testbed demonstration.

References

[1] T. Morioka, "New Generation Optical Infrastructure Technologies: 'EXAT Initiative' Towards 2020 and Beyond," Proc. of the 14th OptoElectronics and Communications Conference (OECC 2009), FT4, Vienna, Austria, July 2009.

[2] D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division Multiplexing in Optical Fibres," Nat. Photonics, Vol. 7, pp. 354–362, 2013.

[3] Y. Sasaki, R. Fukumoto, K. Takenaga, K. Aikawa, K. Saitoh, T. Morioka, and Y. Miyamoto, "Crosstalk-managed Heterogeneous Single-mode 32-core Fibre," Proc. of the 42nd European Conference on Optical Communication (ECOC 2016), W.2.B.2, Dusseldorf, Germany, Sept. 2016.

[4] T. Kobayashi, M. Nakamura, F. Hamaoka, K. Shibahara, T. Mizuno, A. Sano, H. Kawakami, A. Isoda, M. Nagatani, H. Yamazaki, Y. Miyamoto, Y. Amma, Y. Sasaki, K. Takenaga, K. Aikawa, K. Saitoh,

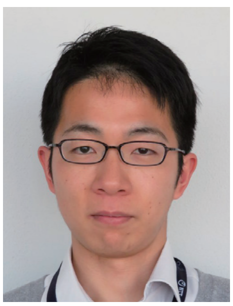
Y. Jung, D. J. Richardson, K. Pulverer, M. Bohn, M. Nooruzzaman, and T. Morioka, “1-Pb/s (32 SDM/46 WDM/768 Gb/s) C-band Dense SDM Transmission over 205.6-km of Single-mode Heterogeneous Multi-core Fiber Using 96-Gbaud PDM-16QAM Channels,” Proc. of the 40th Optical Fiber Communication Conference and Exhibition (OFC 2017), PDP Th5B.1, Los Angeles, CA, USA, Mar. 2017.

[5] K. Pulverer, T. Tanaka, U. Häbel, C. Castro, M. Bohn, T. Mizuno, A. Isoda, K. Shibahara, T. Inui, Y. Miyamoto, Y. Sasaki, Y. Amma, K. Aikawa, S. Jain, Y. Jung, S. Alam, D. J. Richardson, M. Nooruzzaman, and T. Morioka, “First Demonstration of Single-mode MCF Transport Network with Crosstalk-aware In-service Optical Channel Control,” Proc. of the 43rd European Conference on Optical Communication (ECOC 2017), Th.PDP.B.5, Gothenburg, Sweden, Sept. 2017.

[6] T. Mizuno, A. Isoda, K. Shibahara, Y. Miyamoto, S. Jain, S. U. Alam, D. J. Richardson, C. Castro, K. Pulverer, Y. Sasaki, Y. Amma, K. Takenaga, K. Aikawa, and T. Morioka, “In-service Crosstalk Monitoring for Dense Space Division Multiplexed Multi-core Fiber Transmission Systems,” Proc. of OFC 2017, M3J.2, Los Angeles, CA, USA, Mar. 2017.

[7] S. Jain, T. Mizuno, Y. Jung, A. Isoda, K. Shibahara, J. R. Hayes, Y. Sasaki, K. Takenaga, Y. Miyamoto, S. Alam, and D. J. Richardson, “Improved Cladding-pumped 32-core Multicore Fiber Amplifier,” Proc. of ECOC 2017, Th.2.D.2, Gothenburg, Sweden, Sept. 2017.

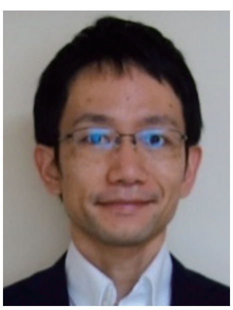
[8] Website of OpenDaylight community, http://www.opendaylight.org/



Takafumi Tanaka

Researcher, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

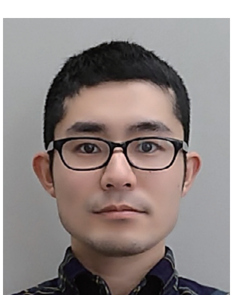
He received a B.E. in electrical engineering and an M.S. in informatics from the University of Tokyo in 2007 and 2009. Since joining NTT Network Innovation Laboratories in 2009, he has been engaged in R&D of next-generation photonic network architecture, planning, and control technologies. He received the IEEE JC Young Engineer Award from the Institute of Electrical and Electronics Engineers (IEEE) Japan Chapter in 2012.



Takayuki Mizuno

Senior Research Engineer, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received a B.E. in applied physics, an M.E. in crystalline materials science, and a Dr.Eng. in quantum engineering from Nagoya University in 1998, 2000, and 2007. In 2000, he joined NTT Photonics Laboratories, where he was involved in R&D of silica planar lightwave circuit optical waveguide devices, including arrayed-waveguide gratings, Mach-Zehnder interferometer-based filters and switches, and digital coherent demodulators for advanced modulation formats. He has been with NTT Network Innovation Laboratories since 2013, where he is involved in innovative research on SDM transmission technology for ultrahigh-capacity optical transport systems. He was a co-chair of the 2016 IEEE Photonics Society Summer Topicals Meeting Series: Topicals on Space-Division Multiplexing and Multimode Photonics (SDMP), and he is currently a technical program committee member of the Optical Fiber Communication Conference and Exhibition (OFC) Digital Transmission Systems Subcommittee. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), the Optical Society (OSA), and IEEE Photonics Society. He was awarded the 68th Young Researcher’s Award in 2006 from IEICE.



Akira Isoda

Researcher, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received a B.S. in mechanics and an M.S. in biorobotics from Tohoku University, Miyagi, in 2012 and 2014. He has been with NTT Network Innovation Laboratories since 2014. His current research interests include SDM transmission systems. He is a member of IEICE and IEEE.

Kohki Shibahara

Researcher, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received a B.S. in physics and an M.S. in geophysics from Kyoto University in 2008 and 2010, and a Ph.D. in informatics from Kyoto University in 2017. He joined NTT Network Innovation Laboratories in 2010. His current research interests include SDM transmission systems and advanced multiple-input and multiple-output signal processing. He is a member of IEICE and the IEEE Photonics Society. He received the Tingye Li Innovation Prize from OSA in 2016 and the Young Researcher’s Award from IEICE in 2017.

Tetsuro Inui

Senior Research Engineer, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received a B.S. in electrical engineering from Waseda University, Tokyo, in 1995 and an M.S. in electronics engineering from the University of Tokyo in 1998. He joined NTT Optical Network Systems Laboratories in 1998, where he was engaged in R&D of high-speed optical transmission technologies and photonic node systems including ROADMs. His current research interests include next-generation photonic network architecture and design. He is a member of IEICE and IEEE. He received the Outstanding Contributor Award from the Open Networking Foundation (ONF) in 2016.

Yutaka Miyamoto

Senior Distinguished Researcher, Director, Innovative Photonic Network Research Center, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in electrical engineering from Waseda University, Tokyo, in 1986 and 1988. He later completed a Dr. Eng. in electrical engineering from the University of Tokyo. He joined NTT Transmission Systems Laboratories in 1988, where he engaged in R&D of high-speed optical communications systems including FA-10G (the first 10-Gbit/s terrestrial optical transmission system) using EDFA (erbium-doped optical fiber amplifier) inline repeaters. He was with NTT Electronics Technology Corporation between 1995 and 1997, where he was involved in the planning and product development of high-speed optical modules at data rates of 10 Gbit/s and beyond. Since 1997, he has been with NTT Network Innovation Labs, where he has been researching and developing optical transport technologies based on 40/100/400-Gbit/s channels and beyond. He currently serves as Chair of the IEICE technical committee of Extremely Advanced Optical Transmission (EXAT). He is a member of IEEE and a Fellow of IEICE.