Recent Progress in Space-Division Multiplexing Optical Network Technology

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***Abstract*— Space-division multiplexing (SDM) technology is attracting attention as an upcoming technology for future ultra-large capacity optical networks. The SDM approach introduces an additional dimension (space) for optical signal multiplexing and switching, thus providing an increase in switching flexibility and transmission capacity. These advantages are seen as critical to ensuring network evolution in the long term. In this paper, we review recent technical progress in SDM ultra-large-capacity transmission and software-defined control for sliceable SDM optical networks. We also present a gap analysis toward standardization of SDM technology.**

Keywords—Space-division multiplexing (SDM), Ultra-large-capacity transmission, Network control, Standardization.

I. INTRODUCTION

Network traffic has been increasing every year and research and development efforts have focused on ultra-large-capacity transmission technology in future optical networks designed to support the increase in network traffic [1]. Current optical networks are based on wavelength-division multiplexing (WDM) over standard single-mode fiber (SMF) infrastructure. Since the maximum capacity of existing SMF has been predicted to be limited around 100 Tb/s [2], the capacity limitations of WDM networks make it difficult to cope with the future bandwidth-hungry demand. Current short-term solutions to capacity exhaustion include use of a flexible grid to utilize efficient modulation formats, complex power-hungry digital-signal processor (DSP)-based technology, and use of L band in conjunction with C band. One of the possible long-term solutions to increasing transmission capacity is deployment of parallel infrastructure (e.g. transmitters, amplifiers, fibers, reconfigurable optical add drop multiplexers (ROADMs)). However, this duplication is a non-optimal solution in terms of cost, power consumption and floor space. SDM technology can provide a long-term solution to the transmission capacity bottleneck in an efficient manner. Recently, SDM technology has been studied intensively as a candidate for future ultra-large-capacity transmission systems. To date, several research projects and industry initiatives have been conducting studies about SDM technology. These worldwide studies have developed attractive key technologies for SDM fibers, devices, subsystems, and transmission systems. In this paper, we review recent technical progress in SDM ultra-large-capacity transmission and software-defined control for sliceable SDM optical networks. We also present a gap analysis toward standardization of SDM technology. The remainder of this paper is organized as follows. Section II presents recent technical progress in SDM ultra-large-capacity transmission. Section III shows recent software-defined networking (SDN) control technology for SDM optical networks. Section IV introduces a gap analysis toward SDM standardization. Section V summarizes this paper.

II. SDM-BASED ULTRA-LARGE-CAPACITY TRANMISSION OVER 1 PB/S

In this section, we review recent technical progress in SDM ultra-large-capacity transmission. There are several performance indicators in transmission experiments. Examples of the performance indicators are transmission capacity, transmission distance, product of transmission capacity and distance, spectral efficiency, and spatial multiplicity. Here, we report historical demonstrations of ultra-large-capacity transmission using SDM technology from the viewpoint of spatial multiplicity and transmission capacity. Fig. 1 shows the relationship between ultra-large capacity SDM transmission experiments and spatial multiplicity reported in recent SDM transmission experiments with a fiber capacity over 1 Pb/s [3-10]. In the graph, the horizontal and vertical axes are special multiplicity and transmission capacity, respectively.

In 2012, 1-Pb/s transmission capacity has been achieved by using multi-core fiber (MCF) transmission technology [3, 4]. 1.01-Pb/s transmission over 52 km with an aggregate spectral efficiency of 91.4 b/s/Hz was demonstrated using a 12-core

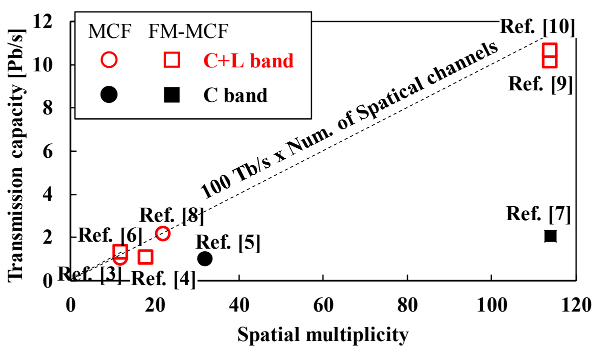

Fig. 1. Relationship between ultra-large-capacity SDM transmission and spatial multiplicity.

MCF and polarization-division multiplexing (PDM) 32-quadrature-amplitude modulation (QAM) signals [3]. In ref [4], 1.05-Pb/s transmission over 3 km of MCF with spectral efficiency of 109 b/s/Hz per fiber was demonstrated using twelve single-mode cores carrying PDM 32-QAM-orthogonal-frequency-division-multiplexing (OFDM) signals and two few-mode cores carrying PDM quadrature-phase-shift keying (QPSK) in their LP 01 and two LP 11 modes. To decrease the number of WDM channels in each SDM channel, the authors of [5] demonstrated 1-Pb/s uni-directional inline-amplified transmission over 205.6 km of a 32-core fiber using higher bit rate transceivers. In the demonstration, 768-Gb/s concatenated-Bose-Chaudhuri-Hocquenghem (BCH)/ Low-Density Parity-Check (LDPC)-

978-3-903176-21-8 © 2020 IFIP

coded PDM-16QAM optical signals were used and an aggregate spectral efficiency of 216.7 b/s/Hz was achieved. Although transmission demonstrations with a capacity over 1 Pb/s had been limited to fibers with cladding diameters larger than 200 µm, 1.2 Pb/s transmission over a 3.37 km 4-core few-mode MCF with a cladding diameter below 200 µm was demonstrated [6]. In the demonstration, PDM-256-QAM modulation and high granularity FEC were used to achieve 300 Tb/s throughput per fiber core.

In 2015, 2-Pb/s transmission has been demonstrated by using SDM transmission technology [7, 8]. In ref [7], transmission of 2.05 Pb/s over 9.8-km 6-mode 19-core fiber with aggregate spectral efficiency of 456 b/s/Hz was demonstrated by using 360-channel super-Nyquist-WDM PDM-QPSK signals. Furthermore, 2.15-Pb/s transmission over 31 km of a 22-core single-mode MCF was demonstrated using 399 x 25 GHz spaced, 6.468 Tb/s spatial-super-channels comprising 24.5 GBaud PDM 64-QAM modulation in each core [8]. In 2017, further capacity enhancement was realized by employing dense SDM/WDM and FM MCF for lower differential mode delay and lower loss across the whole C+L band. 10-Pb/s transmission capacity over 11.3-km 6-mode 19-core fiber across C+L band was demonstrated using 114 SDM channels and a combination of 64 QAM and 16 QAM optical signals [9]. In 2020, another 10-Pb/s transmission experiment was reported [10]. In the report, 10.66-Pb/s transmission over 13-km of a 38-core-3-mode fiber was achieved using 368-WDM 24.5-Gbaud 64-and 256-QAM optical signals. The spectral efficiency of this experiment was as high as 1158.7 b/s/Hz.

III. Software-Defined Control for Sliceable SDM Optical Networks

In this section, we review recent SDN control technology for SDM optical networks. SDM leverages parallel conventional fibers or MCFs or MMFs, where multiplexing is implemented in different fibers, cores, and modes, respectively. To appropriately control SDM optical networks considering multi dimensions such as spectral and spatial degrees, several control methods have been proposed and validated through experiments using both control and data planes. Here, we report several demonstrations of control of SDM optical networks. In ref. [11], crosstalk-aware traffic engineering was demonstrated in a single-mode MCF optical network testbed. In the demonstration, with the help of an SDN controller, modulation format and channel route were adaptively configured considering inter-crosstalk of MCF. However, no YANG models [12] for NETCONF [13] to control network equipment were considered in the demonstration. The authors of [14] proposed and demonstrated a YANG model for the NETCONF in order to properly configure network equipment in an FM-MCF network testbed. In the demonstration, an open API based on YANG/NETCONF was defined to interact with an SDN controller. With the help of the SDN controller, an SDN-enabled sliceable SDM-WDM transceiver providing multiple spectral-spatial super-channels spanning different cores and modes over the FM-MCF was realized, allowing the spatial and spectral resources to be used effectively. The authors of [15] proposed and demonstrated an SDN monitoring and restoration architecture for spectral/spatial superchannels with SDM/WDM transceivers that monitor the bit-error rate and optical signal-to-noise ratio to detect soft failures. In the demonstration, an SDN-based monitoring and restoration system to detect soft failures was accomplished by dynamically reconfiguring the transmission format, frequency slot, and mode/core to restore the performance. The authors of [16] proposed and demonstrated an SDM optical network architecture using spatial modes with adaptive MIMO receivers controlled by an SDN controller. In the demonstration, dynamic scaling up/down of SDM super-channels to increase/decrease the transmission capacity by exploiting the spatial modes was realized. Although, several possible use scenarios of SDM have been proposed and demonstrated as described above, SDM and conventional WDM interworking networks were not considered in the reports. Ref. [17] proposed an SDN-enabled multi-domain multi-layer (WDM/SDM) control architecture for partial disaggregated optical networks. This study focused on an SDN-controlled disaggregated multi-OLS domain of SDM and conventional WDM interworking networks. It is noteworthy that the proposed architecture can be considered during a transition period from conventional WDM networks to SDM networks.

IV. Gap Analysis toward SDM Standadization

In this section, we present a gap analysis toward standardization of SDM technology. Recently, IEC has agreed to start discussion on test methods for MCF connectors in order to incorporate measurement methods into the current standard documents [18, 19]. In addition, ITU-T has agreed to establish a new technical report for SDM optical fiber and cable in order not only to share the current status of SDM technology but also to address potential technical issues which should be solved prior to deployment or standardization of SDM technology [20]. Fig. 2 shows a typical WDM transmission system and technical items. In the system, the technical items (i.e. optical fiber parameters, interfaces, optical connectors, optical path parameters, and optical connecting devices) have been standardized by standardization organizations [21]. The SDM approach introduces an additional dimension (i.e. space) for ultra-large capacity transmission and switching flexibility. However, the additional dimension has not been considered in the current standard specifications. Therefore, there are gaps between the current WDM transmission systems and the SDM transmission systems. We describe the gaps regarding the technical items in the following sub-sections.

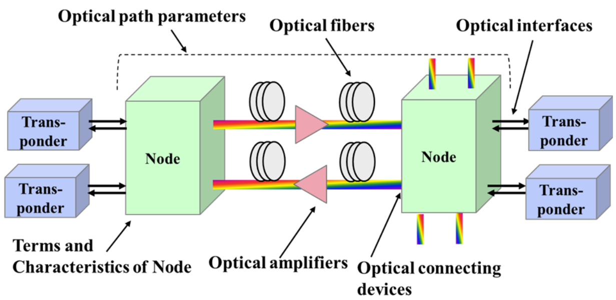

Fig. 2. A typical WDM network system and technical items which are standardized by standardization organizations.

A. Optical Fiber

The simplest SDM approach is based on transmission of information flows being carried over multiple traditional SMF pairs (i.e. bundles of SMFs). However, newly emerging fiber types are specifically designed for SDM, comprising multiple fiber cores or/and supporting several propagation modes per core. To date, the emerging SDM fiber types have not been considered in the current standard specifications [22-28]. Therefore, fiber types (e.g. uncoupled SDM fiber, coupled SDM fiber, partially coupled SDM fiber) including fiber structure need to be defined. In addition, it is necessary to consider new attributes such as mode-dependent loss, differential-mode delay, mode crosstalk, inter-core crosstalk, spatial-mode dispersion and mechanical properties.

B. Optical Amplifier

Generic specification and characteristics of optical amplifiers (i.e. erbium-doped fiber (EDF) amplifier) have been standardized in the IEC 61291 series [29-32]. These documents describe single and multichannel applications, and qualification specifications. IEC 61290 series documents [33-34] specify methods of testing optical amplifiers such as power and gain parameters and noise figure parameters. These documents define conventional parameters (e.g. input/output power range, gain, noise figure, and input/output reflectance) for optical amplifiers, and these parameters can be applied to emerging SDM amplifiers. However, it is necessary to consider new additional optical parameters for SDM optical amplifiers because the structures of SDM optical amplifiers are different from conventional optical amplifiers. Possible new parameters include not only the structure of SDM optical amplifiers such as multicore (MC) EDF, FM EDF, FM-MC EDF, but also inter-core crosstalk, inter-mode crosstalk, inter-core gain deviation, and inter-mode gain deviation.

C. Optical Connecting Devices

Optical attenuation grades and return loss grades of optical connecting devices have been standardized in several standard documents [35-38]. These optical parameters can be applied to MCF and FMF connector specifications. It is necessary to consider new study items for SDM connectors because the structures of SDM connectors are different from conventional optical connectors for SMF. Possible new study items on MCF and FMF connectors are precise rotation alignment and precise axis alignment, respectively. In addition, new test methods need to be considered in order to realize precise insertion loss measurement. Related to optical connectors, it is necessary to study optical parameters for new optical devices such as Fan-in/Fan-Out and mode multiplexers/demultiplexers.

D. SDM Node

Several standard documents define terms and characteristics of ROADM [39-43]. The SDM networks will require new node (e.g. new ROADM) architectures that are able to perform signal switching that takes the new spatial dimension into consideration. The simplest SDM node implementation, comprising N fiber pairs, could be based on wavelength-selective switch (WSS) technology with N inputs and M outputs (in contrast to current single input/output solutions). More complex node implementations will interface with a multimode fiber (an FMF), an MCF with a single mode per core or even an MCF with several modes supported over each core. The switching device would be based on selective diffraction and reflection of each frequency by means of WSS or mechanical mirror matrices. This means that breakout devices are required at the line input and output. A breakout device for an MCF will direct the optical signal coming from/to every fiber core to/from independent SMF fibers; and the WSS/optical mirror will switch the light being carried over those fibers on a frequency basis. In the case where every core is supporting multiple propagation modes, the device must multiplex and demultiplex the modes on each core and send them to/from independent fibers into/out of the switching device. With these as background, it is necessary to consider new study items on the SDM node. Examples of possible new study items are flexible switching function, optical signal equalization function, maximum node degrees, spatial mode switching function, resolution of switching function, and inter-core crosstalk monitoring function.

E. Other items

The abovementioned items are just some of the possible study items for SDM systems and there are more study items for SDM technology. One example is parameters for optical interfaces such as a signal bitrate and modulation format. Another example is anticipated target applications (e.g. metro application and short-reach application). These study items need to be defined taking into account network architecture and end-to-end system performance.

V. Conclusions

This paper reviewed the recent technical progress in SDM-based ultra-large-capacity transmission experiments with a fiber capacity over 1 Pb/s, and software-defined control experiments for sliceable SDM optical networks. To date, remarkable results have been reported and it is expected that research and development of SDM technology for commercialization will accelerate based on the reported technology. This paper also introduced gap analysis toward standardization of SDM technology. Although, SDM technology has been the subject of intensive study in the research and development field, there has been no discussion in the area of technology standardization. However, several standardization organizations have started discussion on SDM technology in order to realize timely standardization in the future. The development of SDM technology has entered a new phase toward practical application.

Acknowledgments

The authors would like to thank Dr. Raul Munoz, Dr. Ramon Casellas, Dr. Ricard Vilalta, Dr. Michela Svaluto Moreolo, Dr. Ricardo Martínez, and Dr. Josep M. Fàbrega of the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Spain for their continued great support in the joint projects. This work was partially supported by "Massive Parallel and Sliced Optical Network", NICT, JAPAN.

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