WHITE PAPER (Oct. 31, 2022)

Research and Development of Spatial Division Multiplexing Optical Network and Node Technologies: PHUJIN Project

1 . Introduction

In Japan, the 5th generation mobile wireless service was launched in March 2020, and the service area is being expanded sequentially. Meanwhile, research and development for the next generation (Beyond 5G or 6G) has already begun in many countries around the world. In Japan, the National Institute of Information and Communications Technology (NICT) has launched the Beyond 5G R&D Promotion Project in 2021, and industry and academia sectors are working together to promote research and development of Beyond 5G technologies.

Beyond 5G communication services would not be possible without an optical fiber communication infrastructure to economically transport the enormous amount of traffic generated by such services on a nationwide scale. NICT has also set "Research and Development of Spatial Division Multiplexing Optical Network and Node Technologies to Support Beyond 5G Ultra High-Capacity Wireless Communications" as one of core projects. The PHUJIN project described in this white paper is an R&D project (Number 00201)[1), 2)] that started in August 2021, following the R&D plan proposed by an industry-academia collaboration team consisting of Kagawa University, KDDI Research Inc., NEC Corporation, santec Corporation, and Furukawa Electric Co., Ltd. The project name, PHUJIN, stands for "Photonic network research project toward beyond 5G era fully utilizing space and wavelength dimensions by joint industry-academia-government innovation driven team" and was named after Fujin, Japanese god of wind, with the concept of "Supporting future Beyond-5G Communications services by freely transporting the ultra-large data flows generated by these services using lightwave technology.".

This paper is organized as follows. First, Chapter 2 describes the R&D background and the hierarchical optical network employed by the PHUJIN project. Chapter 3 describes the framework of the PHUJIN project, the issues to be addressed, and the approach to be taken. Chapter 4 briefly introduces the five R&D items and their results. Because of the wide range of R&D items, please refer to the references in this paper and the papers listed in the publication list on the PHUJIN project website[2)] for the details of the technical contents.

2. R&D Background

2.1 Challenges Facing Optical Communication Technology

The volume of Internet traffic continues to show exponential growth. For example, assuming a commercial optical fiber link capacity of 8.8 Tb/s (100 Gb/s × 88 wavelengths) around 2010 and assuming that the required link capacity increases at a compound annual growth rate of 30%, it is estimated that optical fiber links supporting these services will require 1 Pb/s class capacity is required for optical fiber links to support the expected commercial introduction of Beyond 5G telecommunication services

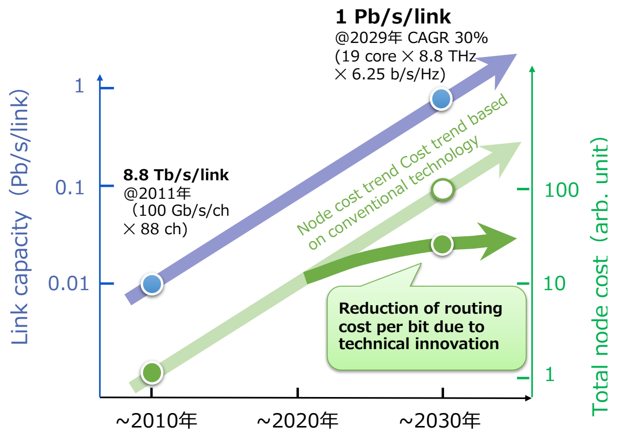

Figure1. Link capacity and node cost trends.

around 2030. To keep pace with the exponential growth in demand for optical link capacity, the approaches used so far have been parallelization based on wavelength division multiplexing (WDM) and highly efficient frequency utilization based on digital signal processing and coherent detection techniques. However, as shown below, both technologies are reaching their fundamental limits. WDM technology, even if practical optical amplification technology is developed, will not be able to significantly increase capacity in the future due to the low-loss wavelength bandwidth (~20 THz) of single-mode fibers (SMFs). The improved frequency utilization efficiency resulting from advances in digital coherent technology has reached a level that approaches the nonlinear Shannon limit, and there is little room for further improvement.

2.2 Necessity of introducing space division multiplexing

It is a common understanding among the research community in the field of fiber optic communications that the only solution to achieve the 1 Pb/s class capacity required around 2030 is to introduce a parallelization technology of a different dimension than WDM, namely, spatial division multiplexing (SDM) technology. For example, if the C-band and L-band with a bandwidth of 8.8 THz and a DP-16QAM modulation format with a frequency utilization efficiency of 6.25 b/s/Hz is employed, a 1 Pb/s optical link can be constructed using 19 SMFs.(Fig. 1).

On the other hand, new structures of SDM fibers and transmission technologies using them have been rapidly developed over the past decade to improve space utilization efficiency and workability (connector splicing, fusion splicing, fiber routing, etc.) of optical fibers. Among them, uncoupled multicore fibers[5] (MCFs) that are designed so that crosstalk (XT) between cores is negligible in practical use is advantageous in terms of the compatibility with conventional transmission technologies using SMF. With uncoupled MCF technology, link capacity compatible with 19 SMFs can be provided using, for example, one 19-core fiber (19-CF) or five 4-core fibers (4-CF).

Vigorous research and development efforts are currently underway all over the world to ensure the economic viability and verify the reliability of uncoupled MCFs and to develop peripheral technologies including connectors, FIFOs, and optical amplification technology, with a view to their practical application. In particular, the 4-CF, which has the same cladding diameter as conventional SMF and has no reliability concerns, is expected to be the first to be introduced into submarine optical cable systems, where space constraints are severe. It is not certain at this point whether optical links in the Beyond 5G era will be constructed with parallel SMFs that bundle multiple conventional SMFs (or thin SMFs) or with uncoupled MCFs. However, if the growth rate of conventional traffic continues, as we have discussed, there is no question that optical nodes will be built with multiple single-mode cores (whatever the method of realization) between optical nodes after around 2030.

2.3 Optical Network Layering Approach

What should be the architecture of future optical networks and their optical nodes, in which optical links consist of multiple single-mode cores (MCFs or parallel SMFs)? To answer this question, let us review the history of the development of multiplexing and node technologies.

When WDM transmission technology was introduced

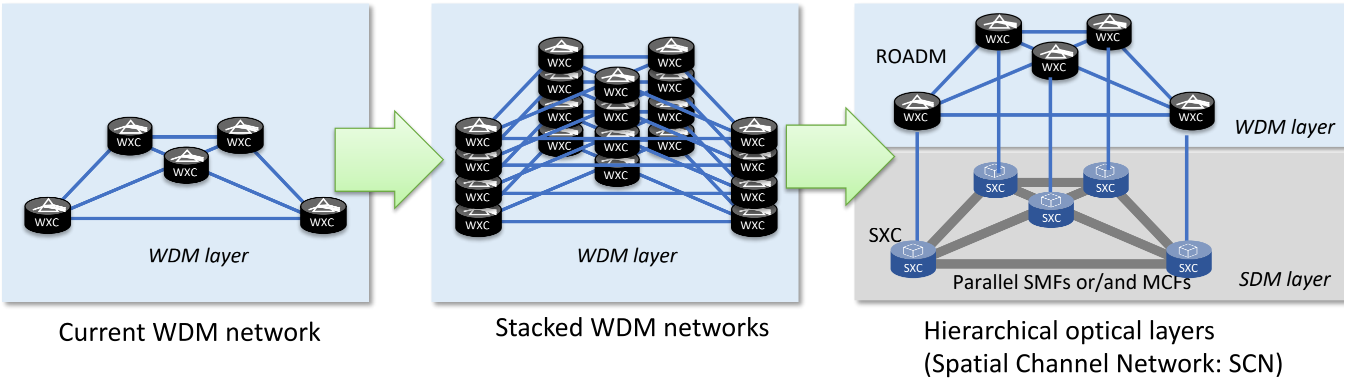

Figure 2. Evolution from WDM network to spatial channel network.

around 2000 (the first parallelization), the large amount of optical-electrical-optical converter (transponder) costs and increased installation space for WDM transmission equipment connecting IP routers and synchronous digital hierarchical (SDH) cross-connects were major problems. The solution was the introduction of bypassing of IP router/SDH cross-connect (conventionally referred to as optical bypass) with a dedicated node device ROADM (Reconfigurable Optical Add Drop Multiplexer) at the WDM layer. ROADMs, also called wavelength cross-connects (WXCs), are optical node devices that provide wavelength demultiplexing, grooming, and multiplexing functions and are now widely deployed around the world, contributing to higher capacity and economy in optical networks.

When SDM technology is applied to optical links, problems similar to those encountered with WDM technology are expected to occur in optical nodes. Figure 2 illustrates the reasons for this. As traffic increases, multiple SMFs are gradually installed between optical nodes, and WXCs need to be stacked to accommodate this traffic. Therefore, as long as the current WDM network architecture based on WXCs is followed, even if parallel SMFs are replaced with MCFs, the node cost will increase in proportion to the amount of traffic as shown in the graph in section 2.1 (Figure 1) and will not scale economically. To solve this, some innovation that reduces the per-bit transfer cost is needed.

If we learn from the history during the introduction of WDM, it is reasonable to hierarchically separate the conventional optical layer into a WDM layer and a newly defined SDM layer in order to ensure the scalability of optical networks based on the new multiplexing technology (SDM, the second parallelization) while achieving economization. In this case, the SDM layer should have a spatial channel cross connect (SXC) that demultiplexes, grooms, and multiplexes its media channel, the spatial channel (SCh). Based on this idea, a new optical network architecture (spatial channel network: SCN) was proposed[3].

There are two main advantages of the SCN architecture. First, SXCs are routed at a large granularity (core), resulting in a low per-bit routing cost and thus enabling node cost reduction. Second, since SXC has a very low excess loss, the transmission distance of optical signals bypassing the WXC (hereafter referred to as spatial bypass) can be extended, thus reducing optical repeater costs. The PHUJIN project employes an SDM/WDM hierarchical optical network architecture.

It should be emphasized here that the SCN architecture is effective in realizing ultra-high capacity and economical optical networks "regardless of whether future optical links are built in MCFs or parallel SMFs".

3. Project Framework

3.1 Requirements for future optical networks

The five requirements for optical networks in the Beyond

5G era are listed and described below.

1. Highly scalable and able to accommodate very large volumes of traffic.
2. Low per-bit transfer cost enables both high-capacity and economical operation.
3. Ability to maintain or improve the physical transmission performance of the current WDM-based optical networks.
4. Advanced monitoring and operation without compromising physical transfer performance.
5. Flexible and efficient accommodation of asymmetric traffic.

Requirements 1 and 2 are the primary requirements detailed in Chapter 1. Requirement 3 is a requirement specific to SDM/WDM hierarchical optical cross connect devices: optical signals accommodated in wavelength channels (WCh, the media channel of the WDM layer) that are groomed at the WXC suffer optical signal-to-noise ratio (OSNR) degradation due to two passes through the SXC in addition to one WXC pass. Degradation due to two passes through the SXC in addition to one pass through the WXC. On the other hand, optical signals accommodated in the WCh, where the WXC on the path is spatially bypassed by the SXC, suffer less OSNR degradation if the insertion loss of the SXC is smaller than that of the WXC. It is necessary to devise a way to reduce the insertion loss of the SXC so that the shortening of the transmission distance of the optical signal to be wavelength groomed is suppressed to a negligible level for practical use and the transmission distance extension of the optical signal to be spatially bypassed is maximized.

Requirement 3 is also important in MCF optical repeater systems, where injecting pumping light into each core of MCF-based erbium-doped fiber (MC-EDF) with the lowest possible loss is effective in extending the transmission distance. The technique to achieve this is also an important technology related to the realization of advanced monitoring without compromising the physical transmission performance of requirement 4.

Finally, requirement 5 is a condition for more efficient use of optical fiber resources. In backbone and submarine optical networks, except for optical access systems, a constant transmission rate (e.g., 100 Gb/s) is adopted regardless of the transmission direction. This is because the asymmetry of data flow in access systems is expected to be smoothed out by the statistical multiplexing effect in backbone and submarine optical networks. However, it has been reported that data flow asymmetry in today's Internet also exists in backbone and submarine systems, and in the coming Beyond 5G era, the asymmetry may increase further due to the further development of cloud computing. Under these circumstances, the wasteful use of unused fiber resources in the direction of below-capacity data flow is expected to become a problem that cannot be overlooked, especially in submarine systems where fiber capacity in the cable is severely constrained.

3.2 Project Objectives and Goals

The objective of the PHUJIN project is to establish enabling technologies for ultra-high-capacity optical networks that are economical and have excellent transmission performance for transporting the enormous amount of data that Beyond 5G communication services will generate. These enabling technologies include technologies that can meet the five requirements mentioned above. The numerical target is to demonstrate the feasibility of SDM optical network technology that can reduce the transmission cost by 50% or more and extend the transmission distance by 50% or more in the situation around 2030, when 1 Pb/s-class link capacity will be required.

3.3 Vertically integrated research system with industry-government-academia collaboration

In order to achieve the aforementioned goals and objectives, the PHUJIN project is a vertically integrated research and development project that includes fiber vendors (Furukawa Electric), module vendors (santec), equipment vendors (NEC), telecommunication carriers (KDDI Research), and academia (Kagawa University).).

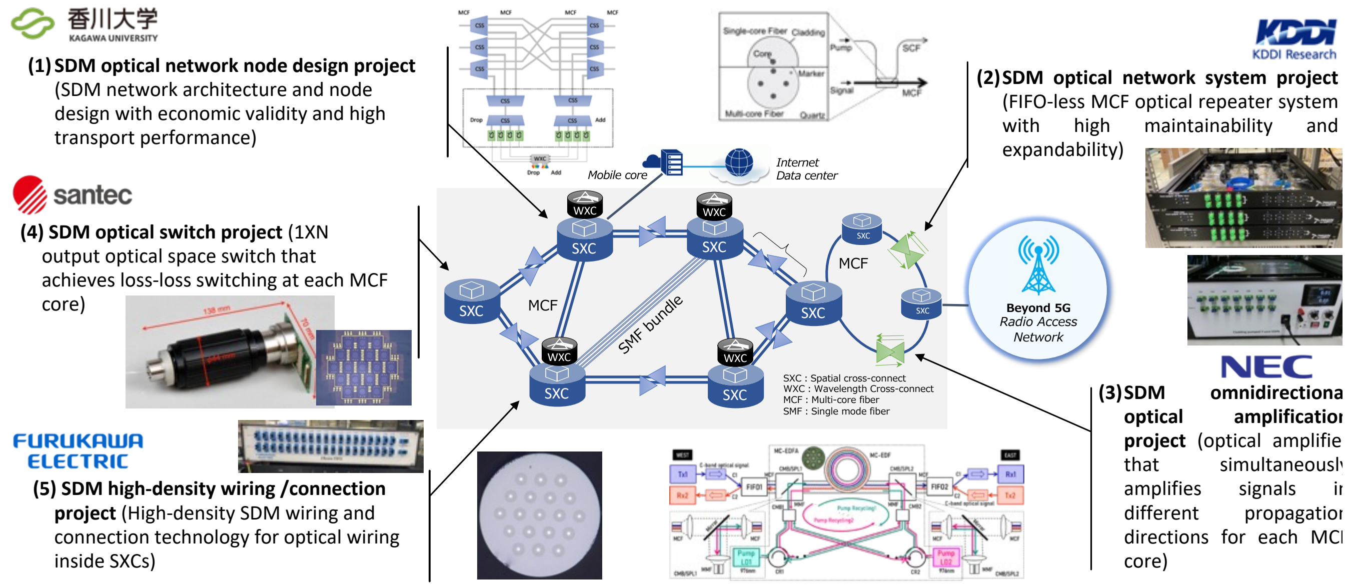

Figure 3. Vertically Integrated Research on SDN Nodes & Networks from Device Level to Equipment/Network Level.

The contents of each R&D item are described in the following Chapter 4.

4. R&D Items

4.1 SDM Optical Network Node Design Technology

In this R&D item, which Kagawa University is in charge of, we will design a hierarchical optical cross connect (HOXC) with a hierarchical arrangement of SXCs[4] (Fig. 3(a)) and WXCs with excellent modularity, pre-prototyping for upgrading the core selective switch (CSS)[5] (Fig. 3(a)), a component of the SXC, and evaluating the economic efficiency of SDM/WDM hierarchical optical networks. In collaboration with the contractors, Kagawa University will also design, build, and evaluate an SDM/WDM hierarchical optical network testbed that interconnects prototype units of each R&D item.

To date, based on a realistic CSS cost model obtained from the CSS package prototyping, we have simulated the construction cost of a layered optical NW without spare systems, and obtained the prospect of cost reduction potential of more than 50% compared to the conventional method[6]. In addition, for advanced SXC (high capacity, high functionality, and high performance), we have conducted pre-prototyping, evaluation, and feedback of 19-CF CSS and 5-CF×3 CSS[7], and obtained prospects for multi-core CSS, low crosstalk, and output optical power control[8].

4.2 SDM Optical Network System Technology

In order to put SDM optical networks into practical use, it is necessary to develop new technologies that not only increase transmission capacity but also meet the requirements for monitoring and operation in the links connected to the SDM optical nodes. In conventional multicore optical amplifiers in SDM network links, a FIFO device is essential for input/output of optical signals and monitoring signals, and for controlling gain (excitation optical power). However, excessive loss in the FIFO affects power consumption and transmission performance.

Therefore, in this R&D project, KDDI Research develops an optical device (Fig. 3(b)) that can amplify multicore optical signals independently in each core without FIFOs and monitor the status of the link including multicore optical amplifiers without FIFOs, and develop a design method for FIFO-less multicore optical relay systems.

We have completed the first prototype of a FIFO-less

MCF optical repeater and confirmed that it has the same level of characteristics as a conventional MCF optical repeater. We have obtained the prospect that span loss, including the monitor port of the repeater, can be reduced by 1.5 dB (loss reduction of about two sets of FIFOs)[9] (Fig. 3(b)) compared with the case with FIFOs.

4.3 SDM omni-directional optical amplification technology

In SDM optical networks using MCFs, optical fibers have multiple cores, and the propagation direction of optical signals in all of the cores is not necessarily the same. For example, to improve transmission performance by reducing crosstalk between cores and to flexibly accommodate fluctuating uplink and downlink communication traffic, flexible functions such as switching the propagation direction for each core within the same MCF can be expected. However, conventional optical amplifiers do not support propagation direction switching, which hinders the realization of such flexibility unique to SDM optical networks.

In this R&D item for which NEC is in charge, based on the conventional optical amplifier configuration and layout, we will clarify the configuration that can obtain the expected signal gain even if the propagation direction changes for each input MCF core, and develop an omni-directional SDM optical amplifier that can set the propagation direction for each core.

To date, it has been shown that bidirectional pumping, which uses both forward and backward pumping as the pumping method, and a configuration symmetrical to the MCF input/output (Fig. 3(c)), offers the prospect of achieving optical gain and noise figure independent of the signal transmission direction. The realization of bidirectional cladding pumping has also revealed that the gain can be improved compared to conventional forward cladding pumping multicore optical amplifiers[10], [11].

4.4 SDM Spatial Optical Switch Technology

WDM nodes currently in practical use employ large N x M matrix switches and WSSs that perform add-drop functions. Matrix switches need to be redundantly deployed to avoid service interruptions due to equipment failures, and WSSs have a high failure rate due to their high functionality.

In this research and development project, which santec is in charge of, we will realize a highly reliable optical switch (CSS) that can switch each core in the MCF with low loss in a simple configuration that differs from the conventional optical switch mechanism. In addition, a large-scale optical power monitor for monitoring and controlling optical switch performance will also be researched and developed to achieve both high performance and high reliability in SDM optical networks.

We have fabricated a prototype cylindrical CSS with a total length of 138 mm and a diameter of 44 mm, and confirmed low loss (up to 4.5 dB)[12] (Figd 3(d)). In addition, a prototype core selector (CS) with a total length of 35 mm and a diameter of 9 mm was fabricated, and the prospect of less than 1 dB of optical loss was obtained. Furthermore, we have mounted these prototypes of CSS and CS in a 19-inch case and confirmed that they can be remotely operated via USB.

4.5 SDM high-density wiring and connection technology

Conventional in-device wiring technology assumes the use of tape core wires with a single core fiber in consideration of connectivity with devices, and the wide wiring tape core wires constrain the degree of freedom of wiring within the device.

In the R&D items that Furukawa Electric is in charge of, we will establish compact wiring technology including direct connection to multicore optical devices by optimizing MCFs and connection materials suitable for wiring in devices, and achieve high-density wiring in nodes. Specifically, the wiring components are also made multicore in coordination with the multicore devices to reduce the size of the connection part and improve the flexibility of the optical fiber during wiring. In addition, the miniaturization of optical amplifiers will be addressed by optimizing the intra-node amplifier wiring.

We have optimized a 19-core fiber with a cladding diameter of 240 μm and a core pitch of 40 μm as an MCF that can be routed within a node (both higher-order mode suppression and low inter-core crosstalk at short lengths) (Fig. 3(e)) and provided it as an MCF for the CSS prototype under R&D item 4. In addition, the design of a fiber[13] with a cladding diameter reduced to 188 μm and a core bitch reduced to 30 μm for allowable bending radius bending reduction was completed, and the first prototype of FIFO (Fig. 3(e)) was also made.

5. Summary

The PHUJIN project is an industry-academia collaborative project for research and development of SDM optical network infrastructure technology with superior economic efficiency and transmission performance for the Beyond 5G era. Currently, the first prototypes of each R&D item have been completed, and an SDM optical network testbed has been constructed by interconnecting them to verify the feasibility of the concept.

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