Photonic Network Defragmentation Technology Improving Resource Utilization during Operation

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Recently, various new information services have emerged as a means for sustaining the significant growth of modern applications spearheaded by cloud and smartphones. These new services rely heavily on the underlying network and data center infrastructures. Thus, core networks are demanded to further expand the capacity to support the rapid increase in data traffic. Meanwhile, it is becoming increasingly important for core networks to be more flexible in order to accommodate feature-rich services such as bandwidth-on-demand. Additionally, for the realization of a sustainable human society and eco-friendly IT services, products capable of low energy consumption are strongly desired. In the near future, it is expected that conventional optical networks which operate on a rigid fixed channel basis will be replaced by flexible optical networks in which signals can be freely allocated on arbitrary frequency slots of the optical spectrum. This flexibility enables a more dynamic and efficient utilization of resources, which in turn leads to lowered energy consumption, heightened usable capacity, and superior agility, making it capable of providing adaptive networking services based on the dynamism of user requests. In flexible optical networks, due to the frequent setup and tear down of optical signals that occupy different spectrum slots, the utilization of such slots has the potential to become heavily fragmented. This so-called spectrum fragmentation phenomenon dramatically degrades resource utilization and reduces usable network capacity. Therefore, spectrum defragmentation technology that Fujitsu Laboratories has developed is needed to restore efficient resource utilization by reallocating the fragmented slots to more continuous ones. In this paper, we discuss a photonic network defragmentation technology that can improve resource utilization during network operation by continuous and in-sync reconfiguration of flexible optical nodes (transceivers and optical switches, etc.). We show the effectiveness of this technology through network simulations, as well as experimental results of hitless defragmentation.

1. Introduction

With the propagation of cloud services and smartphones, an enormous amount of information of diverse modes are generated and consumed in daily life. Various services are supplied via networks centered on data centers.

For many years, enhancement of capacity has been promoted through increasing the bit rate speed and wavelength multiplexing in the area of optical networks, as a highly reliable means to transfer a large amount of information in an inexpensive way and with low power consumption. The industry is trying to meet demand related to these services by realizing an optical network system that can address various utilization modes flexibly through optimizing its characteristics.

The flexible optical network described below is the dominant part of this initiative. An optical frequency band is divided into narrower frequency slots (6.25 GHz) compared to its modulation bandwidth on the optical frequency grid. The center wavelength of an optical path is allocated to a slot border so that the occupied slot width is an integer multiple of 12.5 GHz. An optical path can be assigned to arbitrary multiple slots. It is possible to allocate signals based on multiple modulation methods and/or multiple rates requiring different frequency widths to a suitable frequency range requested under a diverse range of circumstances. This approach allows for a drastic improvement in frequency utilization efficiency when compared with the conventional fixed grid system (**Figure 1**).

In such an optical network, utilization of the optical frequency bandwidth may be fragmented depending on the increase or decrease in the number of optical path routes during operation. Fujitsu Laboratories has developed a wavelength defragmentation technology that can enhance resource utilization and achieve more effective use of frequency on a continuous basis by restructuring and consolidating these fragmented slots.

In this paper, we will discuss the flexible network and software-controlled flexible optical nodes (optical transceiver and optical switches, etc.) necessary for its embodiment, describe an analysis on traffic accommodation and defragmentation effectiveness on the network, and cover a verification of the technology's feasibility.

2. Flexible optical network and its effectiveness

The characteristics of the technology to realize the flexible optical network are described below.

The configuration of the network is indicated in **Figure 2**. In each site, flexible optical nodes are arranged and optical paths connect the universal optical transceivers in such nodes. For instance, quadrature phase shift keying (QPSK) is used for the optical path that connects Site 1 and Site 5 in the case of long-distance transmission. And 16 quadrature amplitude modulation (QAM) is used for the optical path that connects Site 1 and Site 2 in the case of short-distance transmission. Based on this configuration, it is possible to transfer the signals without optical regenerative repeating that converts the signals into electric signals on the transit nodes. A flexible optical node is comprised of a reconfigurable optical add drop multiplexing (ROADM) unit (including the optical switch) and a universal optical transceiver,[1] both of which can be controlled by software. Namely, their setting parameters such as modulation method and wavelength setting can be changed by software. The wavelength selection switch included in the ROADM switches an optical path by allocating a given route on arbitrary frequency slots of the optical spectrum. Based on this procedure, the flexible optical nodes can switch two optical paths passing through and avoiding ADD/DROP to an arbitrary route. The universal optical transceiver is comprised of digital signal processor (DSP), digital to analog convertor (DAC), analog to digital convertor (ADC), electrical to optical convertor (E/O) and optical to electrical convertor (O/E) as illustrated in Figure 2 (b). Mainly by switching the internal DSP operations, the signal transmission via optical paths based on different modulation methods (for instance, those of QPSK and of 16QAM) can be achieved by using the same hardware. Further, the central wavelength of the optical path can be allocated freely on arbitrary frequency slots from outside. By setting these parameters appropriately on networks, it is possible to set an optical path from one given node to another from outside via software.

Then, we verified the effectiveness of the above-described flexible optical network based on a

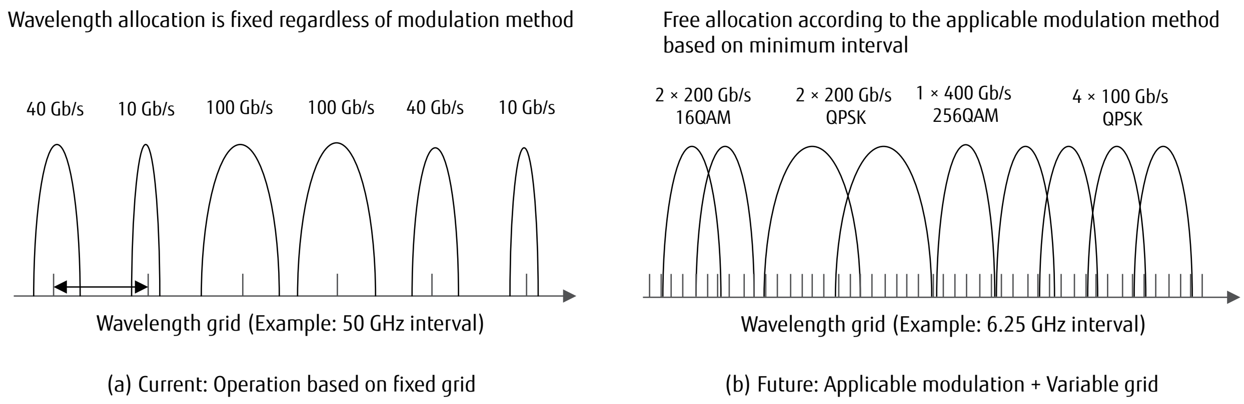
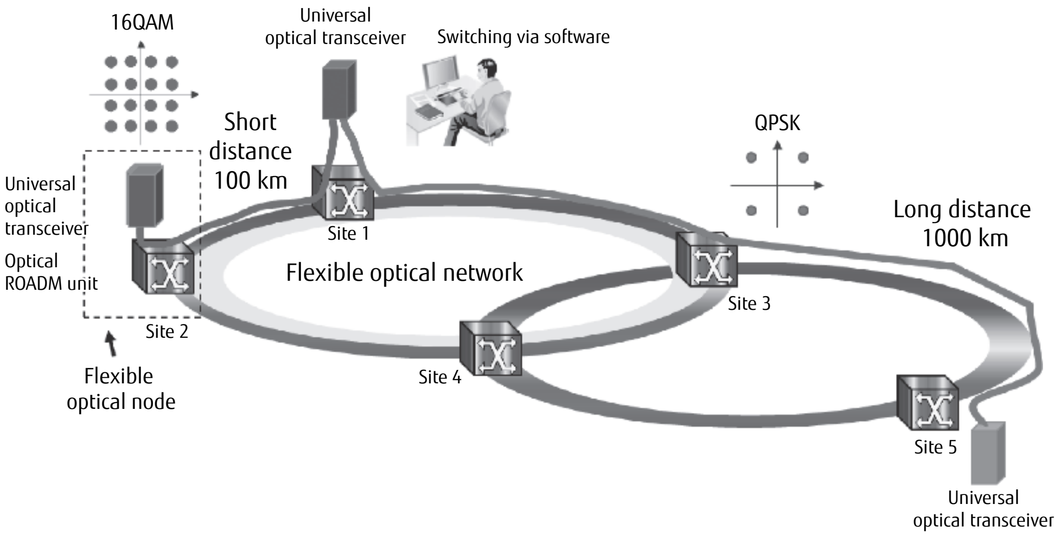
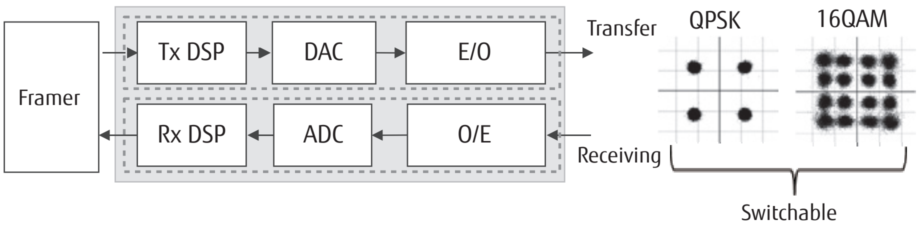


Figure 1
Wavelength allocation: From fixed grid to variable grid.



(a) Flexible optical network and the switch of modulation method depending on the distance



(b) Universal optical transceiver configuration

E/O: Electrical to optical convertor
O/E: Optical to electrical convertor

Figure 2
Flexible optical network.

simulation. The conditions of the simulation are shown below.

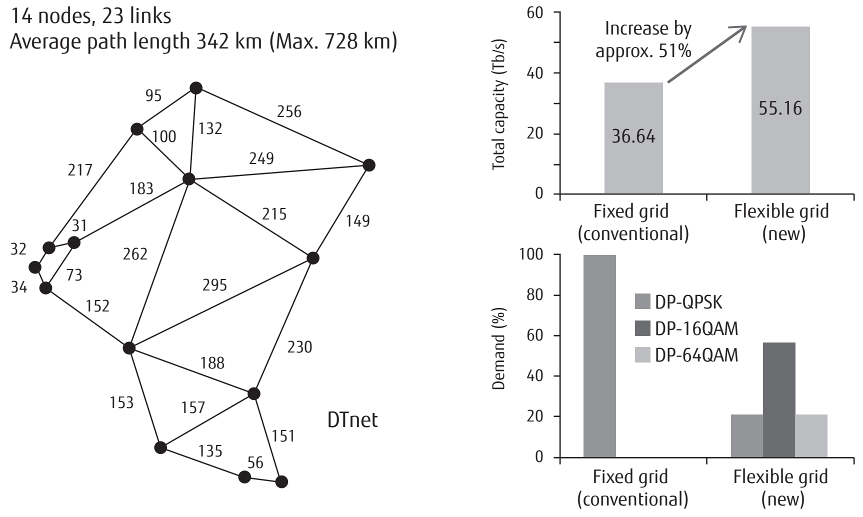
Network conditions:

- 14 node 23 links: mesh network (DTnet)[note 1)]
- Average path length: 342 km (max. 728 km)
- Modulation method: DP-QPSK, DP-16QAM, DP-64QAM
- Number of slots required: 16, 8 and 6 slots, respectively
- Transmission distance: Postulated as 1250, 500 and 200 km

The source and destination were randomly selected within the framework of the above-mentioned network. Then, the capacities of transmission that could be accommodated were compared between the following two scenarios with regard to the optical path that connects the source and the destination: (i) Transmission based only on dual polarization-QPSK (DP-QPSK) (conventional), and (ii) Transmission where three types of modulation methods were used adaptively depending on the transmission distance (new). As a result, it was revealed that, compared to the case where only DP-QPSK was used, the second case [(ii)] indicated an increase of capacity by 51% (**Figure 3**).

As indicated by this simulation result, it is possible to drastically improve accommodation efficiency in a flexible optical network by appropriately combining the modulation method selected based on the optical node and the distance of that network and spectrum configuration when compared to the conventional network configuration where the modulation method is fixed to each channel.

note 1) A network topology used by Deutsche Telekom AG. It is open source information used as a standard case in network simulations.



(a) Network configuration

(b) Total capacity and demand distribution

Figure 3
Simulation result on network capacity.

3. Wavelength defragmentation

Future network systems will in general be required to ensure a dynamic response to the current utilization status. Namely, an efficient network will be realized by offering the necessary path and capacity whenever there is demand and releasing the resources as soon as possible once the demand disappears. In this way the resources can be allocated to new service demands. A flexible optical network can address such a requirement with optical layers. In this situation, achieving an efficient resource operation is an important challenge, because the modulation method is different and also the necessary number of slots on the spectrum are different depending on the data rate.[2] For instance, let's assume that we need 7 slots of 400 Gb/s and 4 slots of 100 Gb/s. Let's consider an example where the demand of the signal service for 400 Gb/s disappears and a new signal demand for 100 Gb/s is generated. While there are 7 vacant slots through the former event, the latter requires 4 slots. Therefore, only one circuit can be accommodated on this network and 3 slots remain unused. If such a change of optical path routing is repeated depending on each service demand, the frequency spectrum will become gradually fragmented, and this will make it hard to effectively use slots. This phenomenon is called "fragmentation."

The technology that restores efficient resource utilization by reallocating the thus-generated fragmented slots in the optical wavelength to more continuous ones for large-capacity communication is called "wavelength defragmentation." This technology restores the effective utilization of the unused optical wavelength resources.

Defragmentation is roughly categorized into the following types:

1) A type accompanying the change of optical path route
- A type with wavelength change
- A type without wavelength change

2) Defragmentation with wavelength change not accompanying the change of optical path route

The defragmentation 1) is effective particularly when optical signal paths are concentrated on a specific section of a mesh network or the like. When some optical paths are forced to make an unnecessarily long detour to evade congestion, reconfiguration into optimum optical routes can be achieved by reallocating the routes so that they use the vacant slots generated by the disappearance of services using part of an optical path that transits the congested section. This kind of defragmentation is feasible even with the conventional optical network as long as there is an optical switch node that can be controlled by software.

On the other hand, the issue associated with

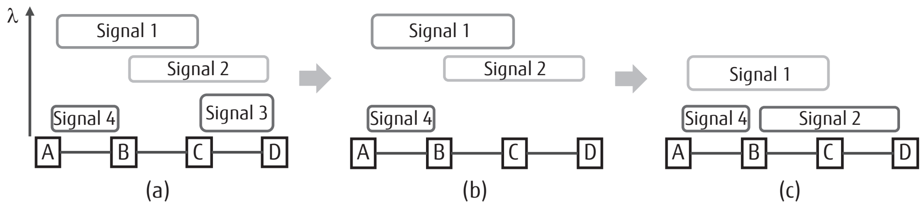


Figure 4
Wavelength defragmentation principle.

this approach is the fact that signal disruption during switching is inevitable because switching of an optical path is involved. Further, the delay time is the difference before and after the change, because the path length will change. Because some services using the said optical path are seriously affected by this phenomenon, there exists a significant barrier to realize defragmentation.

Unlike type (1), there is almost no change in delay time with regard to the approach described in 2), because it does not accompany any route change. While instantaneous signal disruption during the wavelength change is a serious issue, defragmentation is feasible by making optimum use of the characteristics of a flexible optical network. This is the non-disruptive wavelength fragmentation technology developed by Fujitsu Laboratories as a pioneer in this field.[3)]

4. Effectiveness of non-disruptive wavelength defragmentation

The basic concept of the non-disruptive wavelength defragmentation is as below:

1) When there is any vacant slot between a specific signal and its adjacent signal, the wavelength of the said specific signal is shifted so as to fill the gap. Through this procedure, the slot used by the specific signal becomes vacant.
2) The wavelength of the optical switches to all optical devices (for instance, flexible optical nodes) that exist on the relevant receivers and routes is shifted simultaneously.
3) By repeating steps 1) and 2), gaps can be filled up and larger unused bandwidth slots can be created.

Figure 4 is a schematic illustration of this theory. In this example, Signal 3 between C and D becomes obsolete. Because of this, continuous vacant slots are generated between B and D. By shifting Signal 2 to these slots, the signals on the routes between A and B as well as B and D can fill these slots. Following this step, by shifting Signal 1 into the slots previously used by Signal 2, continuous slots can be obtained between A and C as well as C and D.

While the foregoing explanation is based on a simplified linear scheme, this approach is also applicable to a mesh network.

Therefore, we carried out simulation-based verification under the following conditions.[4)]

Verification conditions:

- Linear network of 10 nodes and NSFNET[note 2)]
- 88 slots / 10 000 connection requests (generated based on a Poisson distribution, and a Gaussian distribution hold time)
- Three types of signals: Each 33%
  100 Gb/s (1 slot), 200 Gb/s (2 slots) and 300 Gb/s (3 slots)
- The number of blocked connection requests and the number of stranded slots which is newly introduced as an indicator

The simulation result for the linear network is indicated in **Figure 5**. The result shows that by implementing defragmentation, continuous slots of 40% can be ensured. Further, a calculation result when using NSFNET is indicated in **Table 1**. While it depends on the conditions, drastic improvements in the number of blocked connection requests and the number of stranded slots were observed.

While it was demonstrated that wavelength defragmentation is a promising approach to achieve a drastic improvement in frequency utilization efficiency,

note 2) A network topology used in network studies as standard parameters. A network funded by the National Science Foundation (NSF) for academic communities.

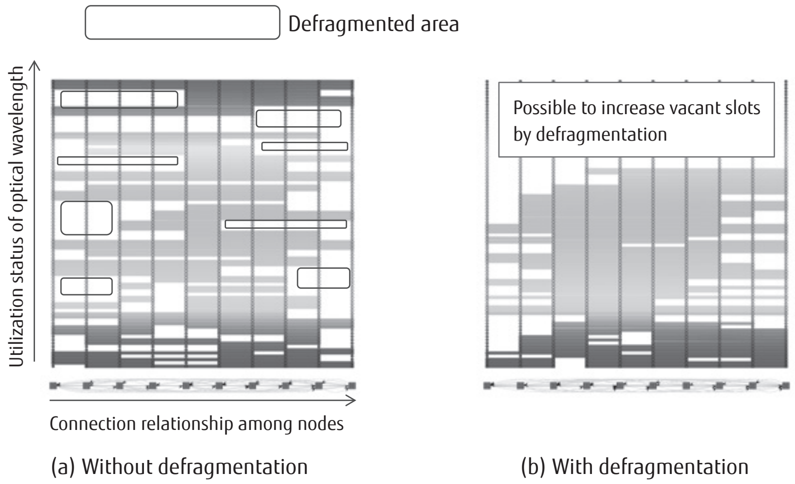


Figure 5
Utilization of wavelength resources when the same amount of traffic load is applied.

Table 1
Effectiveness of defragmentation.

Connection request per unit time	Without automatic defragmentation		With automatic defragmentation			
	Blocked connection request	Number of stranded slots	Blocked connection request	Improvement (%)	Number of stranded slots	Improvement (%)
16	10	496	3	70	305	38
18	42	545	10	76	358	34
20	110	581	79	28	396	31
30	783	653	642	18	478	26
40	1480	671	1377	7	493	26
50	1905	656	1800	5	489	25

It is feasible to have a 76% reduction in blocking and reduce the number of stranded slots by 38%.

there are several issues to be addressed if we are to implement this system on a non-disruptive basis.

1) Shifting of transmission optical wavelength and follow-up by optical receivers

It should be ensured that the system is in a status available for continuous receiving by causing the shifting of a local oscillator (LO) optical wavelength on an optical receiver and ADC/DSP offset compensation at the same time as the transmission optical wavelength is shifted.

2) While shifting the slots of the optical switches for flexible optical nodes, the optical spectrum of the signals should not be affected.

To comply with these requirements, simultaneous control of these pieces of hardware is imperative. Because a step-wise change is possible with regard to the actual hardware, it is relatively easy to have a follow-up by hardware if the step width per time is narrow. However, the total shifting time for filling up the gaps becomes longer. Therefore, the defragmentation process cannot catch up with demand if there is any demand change during the defragmentation process. The impact of the sweep rate in such a case, i.e., the optical wavelength dependency on the amount of shift per unit time, was verified via a simulation based on the universal DTnet topology configuration (a network topology used by Deutsche Telekom AG) for 14 nodes and 23 links. The simulation conditions are as below:

- 100 000 dynamic connections
- Transmission rate 400 Gb/s
  Dual 200G DP-16QAM Super Channel
  Necessary bandwidth 75 GHz

Transmission distance 400 km
Quad 100G DP-QPSK Super Channel
Necessary bandwidth 137.5 GHz
Transmission distance 2000 km

- Sweep rate
  Step width 2.5 GHz 1, 10, 100, 1000 ms/step

Figure 6 indicates the blocking rate by using the sweep rate as a parameter. It is observed that, with the increase in the sweep rate, the blocking rate drops. The speed at the 10 ms/step is considerably close to an ideal status, while the load capacity improves by 15% at a blocking rate of 10^{-3} as a positive effect of the defragmentation.

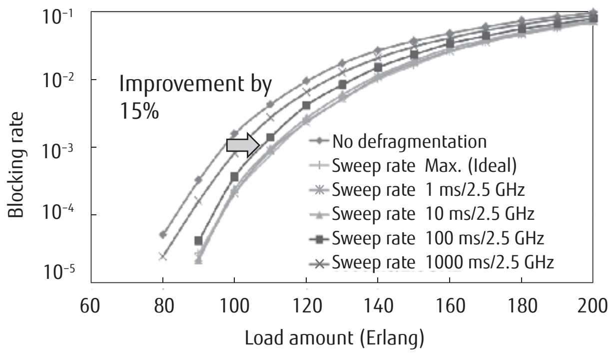


Figure 6
Blocking rate vs. load amount.

5. Experiment-based verification

To implement effective wavelength defragmentation, it is essential to perform sweeping at a rate higher than a certain level while keeping synchronization of the receivers and optical switches as described in the previous section. Particularly, when frequency offset compensation (an algorithm that compensates fluctuation of modulation signals on frequency such as those related to fluctuation of a local oscillation light) is functioning insufficiently, a bit error may occur while the optical wavelength is changing. Therefore, by using an actual transmission system as described below, we verified that the sweep of the optical wavelength and the fluctuation of the bit error rate occurred based on the actual measurements.

The configuration of the experiment system is illustrated in **Figure 7**. The main components of the system are as below:

- 112 Gb/s DP-QPSK modulation PN15 steps
- Four flexible optical nodes
  Comprised of grid-less wavelength selectable switch and optical amplifier
- Variable wavelength laser diode (LD) (local oscillation light on sender side and receiver side)
- 80 km Single mode fiber (SMF) × 3 span transmission
- Sweep rate 20 pm (2.5 GHz) /100 ms

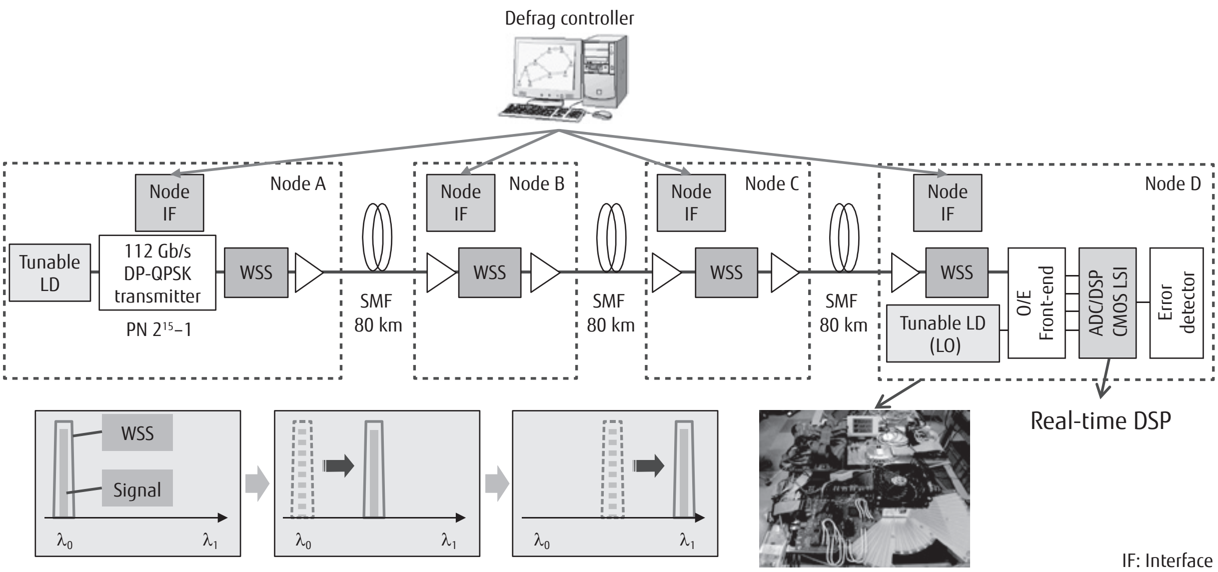


Figure 7
Experiment system for non-disruptive defragmentation.

By sending a control signal from a controller, the wavelength of the wavelength selectable switch (WSS), sender LD and receiver LO/LD was shifted by 1 step. Across bandwidth C (1530–1560 nm), the bit error rate (BER) was measured by changing the wavelength. A snapshot of the measurement is shown in **Figure 8 (a)**. X-polarization, Y-polarization and the average BER can be observed.

The measurement results on "wavelength and BER" as well as "wavelength and Q Penalty" are shown in **Figure 8 (b)** and **Figure 8 (c)**, respectively. The dispersion of Q value during the sweep is within 1 dB and also BER is less than 10^{-3}. This result suggests that, by applying the standard forward error collection (FEC), it is feasible to have a wavelength sweep in which the number of errors is reduced to an acceptable level. While it takes approx. 3 minutes in the C-band, it is still within a range where a sufficient level of effectiveness is obtained based on the network simulation.

6. Conclusion

This paper proposed a flexible optical node configuration for a flexible optical network. It was demonstrated based on a simulation that effective resource utilization at the network level is feasible by appropriately allocating routes and frequency slots. Further, based on the wavelength defragmentation technology developed by making optimum use of the characteristic where there is no limitation in the shifting of wavelength, it was demonstrated based on a simulation that wavelength resources can be effectively used on a continuous basis during operation. Then, the validity of the non-disruptive defragmentation, a basic technology to prevent errors on the circuit, was verified through an experiment.

By using these technologies, the optical network can easily change its configuration depending on each service and optimization of network resources can be achieved in an autonomic manner. The optical network will play an essential role in future as a technology to efficiently cope with the increasing demands placed on networks and the diversifying service demands with a low-energy-consumption system.

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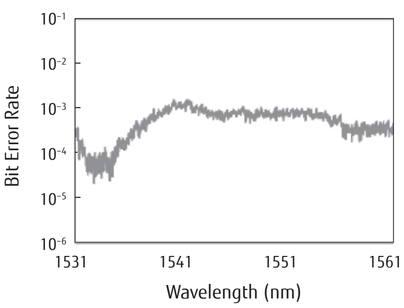
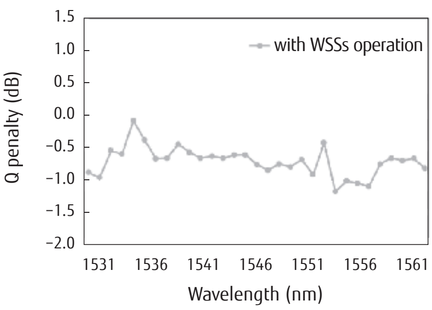
(a) Spectrum and BER during the measurement of BER



(b) Wavelength vs. Bit Error Rate (BER)



(c) Wavelength vs. Q penalty

Figure 8
Bit Error Rate (BER) change during defragmentation.

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