“Conscious Optical Network” with Reliability and Flexibility

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The most important requirements in optical networks have been high speed, large bandwidth, long transmission distance, and reliability of optical fiber communications. In recent years, however, simplicity, flexibility, and efficiency of network operation have been rapidly becoming more important as a wide range of applications are offered by emerging providers of content and other services. In order to respond to changing demand, Fujitsu is developing a conscious optical network that monitors optical fiber communications at an unprecedented level of precision and optimizes the network operation accordingly. It aims to facilitate and speed up service provisioning, optimization of power and signal quality, and early failure detection and preventive maintenance, thus relieving the optical network of complicated operations and making it environmentally more efficient. This paper introduces Fujitsu’s unique light probe technology in the field of optical digital signal processing, and describes its effectiveness for the realization of the conscious optical network.

1. Introduction

Communication traffic has been increasing at an average annual growth rate of 23% owing to the rapid spread of high-speed mobile devices and the global increase in the number of Internet users.1) To cope with this rapid increase in communication traffic, measures are being implemented to increase the speed and bandwidth of backbone optical networks, and currently dense wavelength division multiplexing (DWDM) optical transmission systems capable of 100 Gbps per wavelength are being commercialized. As continued growth of communication traffic is expected, needs for optical networks with even higher speed and larger bandwidth are anticipated. Further, as the increase in transmission capacity per optical fiber means also a larger ripple effect in the case of failure, boosting the reliability of optical networks is becoming more important than ever.

On the other hand, among service providers, carriers owning nationwide networks that have been providing communication services are beginning to see competition from so-called over-the-top (OTT) content providers. In conjunction with this, network operation modes are also becoming more diversified. This includes the emergence of providers who build their own optical networks, and virtual network operators (VNO) who provide communication services using the communication infrastructure of other companies. Therefore, in addition to traditional requirements for optical networks in terms of high speed, large capacity, and high reliability, requirements in terms of ease of network construction and operation, flexibility, and efficiency are rapidly increasing.

In conventional DWDM equipment, wavelengths and paths are set through connection to predetermined fixed ports. By contrast, development and commercialization of technologies that increase optical network flexibility and allow faster service delivery, such as color-less/direction-less/contention-less reconfigurable optical add/drop multiplexers (CDC-ROADM), which allows wavelengths and paths to be set arbitrarily from a remote point, and software-defined networking (SDN), which controls an optical network, are progressing.

Traditional optical networks are guaranteed to be highly reliable through fixed operation in a network configuration that guarantees transmission quality through prior design. On the other hand, when the optical transmission signal path is frequently changed as the result of using the above-mentioned techniques, the state of the optical network keeps on changing. For that reason, maintaining both reliability and flexibility without impairing the speed of service delivery is the next major challenge.

As Fujitsu, we aim to realize optical networks that allow maintenance of optimum signal quality regardless of network status through continuous monitoring, analysis, and control of the entire network, while maintaining network flexibility. We call such a network a "conscious optical network."

This paper describes the way in which a conscious optical network is implemented and the value it offers.

2. Conscious optical network

A conscious optical network is a network that monitors and analyzes the state of the optical network with unprecedented accuracy and in real time, and that autonomously performs optimization control of the network based on various user policies. The architecture of the conscious optical network is shown in **Figure. 1**.

Conventional optical transmission equipment and optical networks are equipped with devices such as optical channel monitors that measure the optical power of each channel and error rate monitors in receivers. However, in order to monitor the detailed parameters related to signal quality, such as optical signal-to-noise ratio (OSNR), and the characteristics of the optical transmission fiber, costly measurement devices such as optical spectrum analyzers are required. Moreover, high-accuracy measurement in actual service is difficult owing to wavelength path allocation and other restrictions.

Light probes, a proprietary technology of Fujitsu that measures the physical parameters of optical transmission fiber, the actual characteristics of nodes, and signal quality and its affecting optical parameters, are equipped with CDC-ROADM nodes. Monitoring the measurement signals for the light probes and the optical signals under actual service allows the network status to be measured in real time at low cost and with a high level of accuracy.

Through the use of light probes, the monitored data is accumulated at the network level, and it is

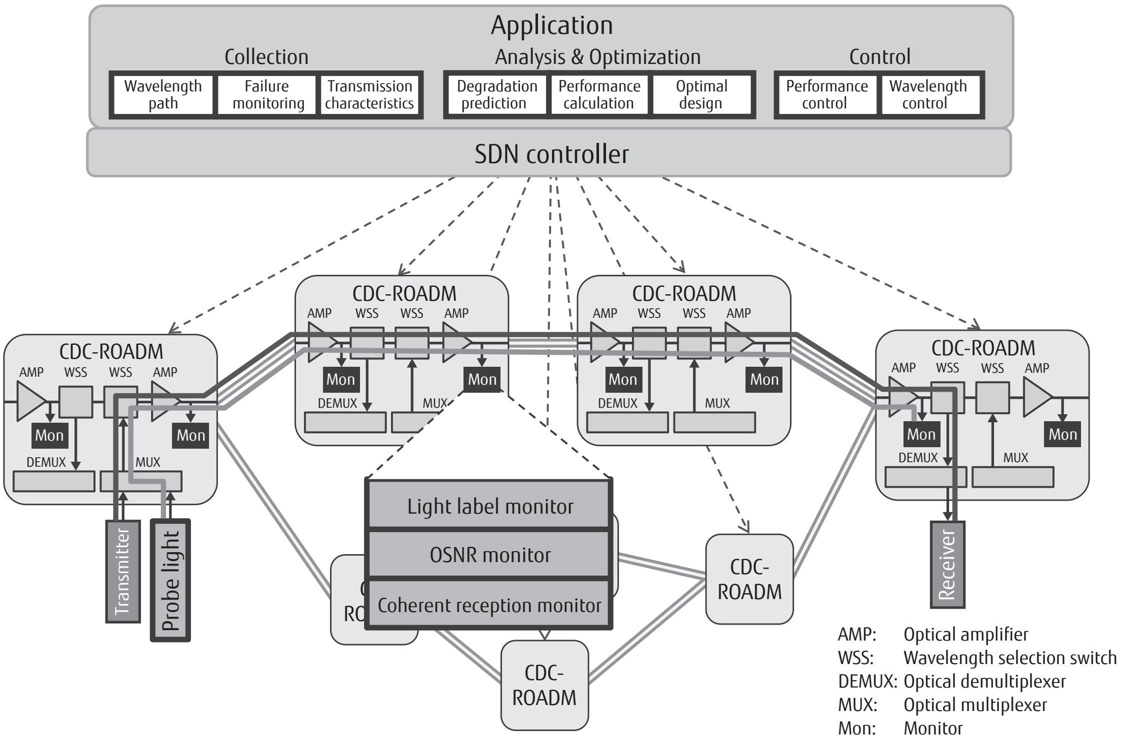


Figure 1
Example of conscious optical network architecture.

analyzed by the SDN controller and upper layer applications, taking into account various factors such as the physical properties of light and the network operation state over time. As a result, the physical parameters of actual optical transmission fibers and the characteristics of nodes can be determined. Further, by analyzing and extracting temporal variations and correlations of various signal quality parameters, for example by determining signal quality degradation factors and locations and estimating future operation quality based on degradation trends, it is possible to not only isolate failures but also practice predictive maintenance.

Moreover, by combining monitoring information about the optical transmission characteristics from light probes and information about node power consumption, delays, and wavelength usage, it is possible to perform optimization control of signal paths, modulation techniques and the like, according to user and service-specific requirements (for example, transmission performance, transmission capacity, power consumption, and delay), while maintaining constant signal quality.

Light probe technology consists of three main parts, light label, in-band OSNR monitoring, and coherent reception monitoring. Details on this technology are provided in following sections: "Light path trace technology using light label," "Optical signal quality monitoring during service operation," and "Monitoring using digital coherent technology."

3. Value offered by conscious optical network

Conscious optical network application allows the construction and operation of safe, secure and economical networks and the provision of the following value merits to customers.

1) Eradication of failures through early failure detection and preventive maintenance

Prediction of failures and their locations is carried out through continuous collection of monitoring information and analysis of quality change trends, and preventive maintenance such as the implementation of route changes to optimize signal quality over the entire network is performed. This results not only in minimization of the effect of failures on user services, but also reduction of operating costs through planned maintenance.

2) Faster service provisioning and simpler network management and operation

Monitoring of light label information specifying the transmitting end during network construction allows automatic detection of erroneous fiber connection and setting errors. Optical signal quality monitoring allows verification of optical path connections. As a result, initial provisioning time can be shortened.

3) Minimization of equipment cost through optimization control of transmission performance and transmission capacity

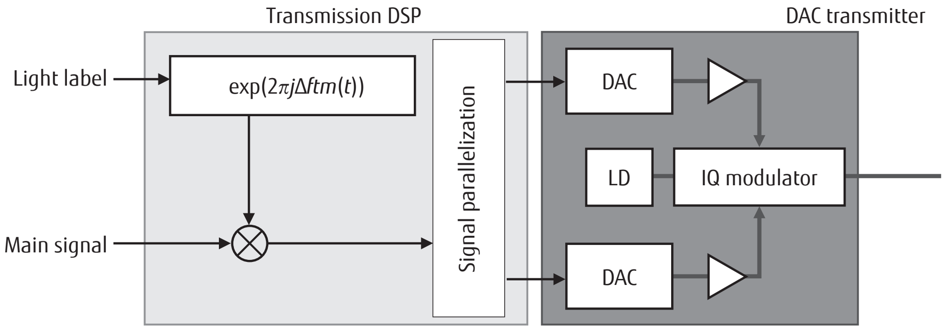
The collection and analysis of monitoring information allows identification of the real characteristics of optical transmission fibers and ROADM, and automatic feedback as design parameters. As a result, precise design that eliminates excess margins is possible, minimizing network equipment costs.

4) Reduction of power consumption

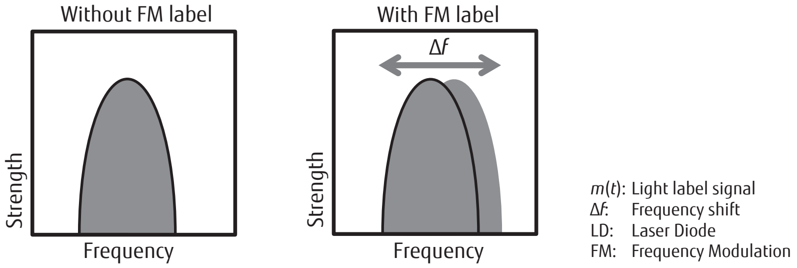
The collection and analysis of power consumption monitoring information along with optical signal quality information allows control of optical properties so as not to affect the signal quality of the network as a whole and also the implementation of power consumption efficiency boosting measures.

4. Light path trace technology using light labels

A possible case that could be assumed is dynamic setting of the same wavelength from ports adjacent to optical add drop multiplexer at CDC-ROADM nodes that allow flexible wavelength path setting and on networks that use such nodes. In this case, regarding the optical channel monitoring function that has been introduced into existing equipment (optical power monitoring), it is difficult to isolate the cause of erroneous connections and failure occurrence locations in ROADM nodes from a remote point. The authors therefore propose a method that superimposes light label signals in the digital signal processing unit (low-speed frequency modulation signals) on the main signal through a universal transceiver2) equipped with a digital-to-analog converter (DAC), and a light path trace technology that monitors only the superimposed signal without terminating the main signal at CDC-ROADM nodes.3) That superimposition principle is shown in **Figure 2**, and the decoding principle in **Figure 3**. Superimposition of a frequency modulated signal on the main signal is done through

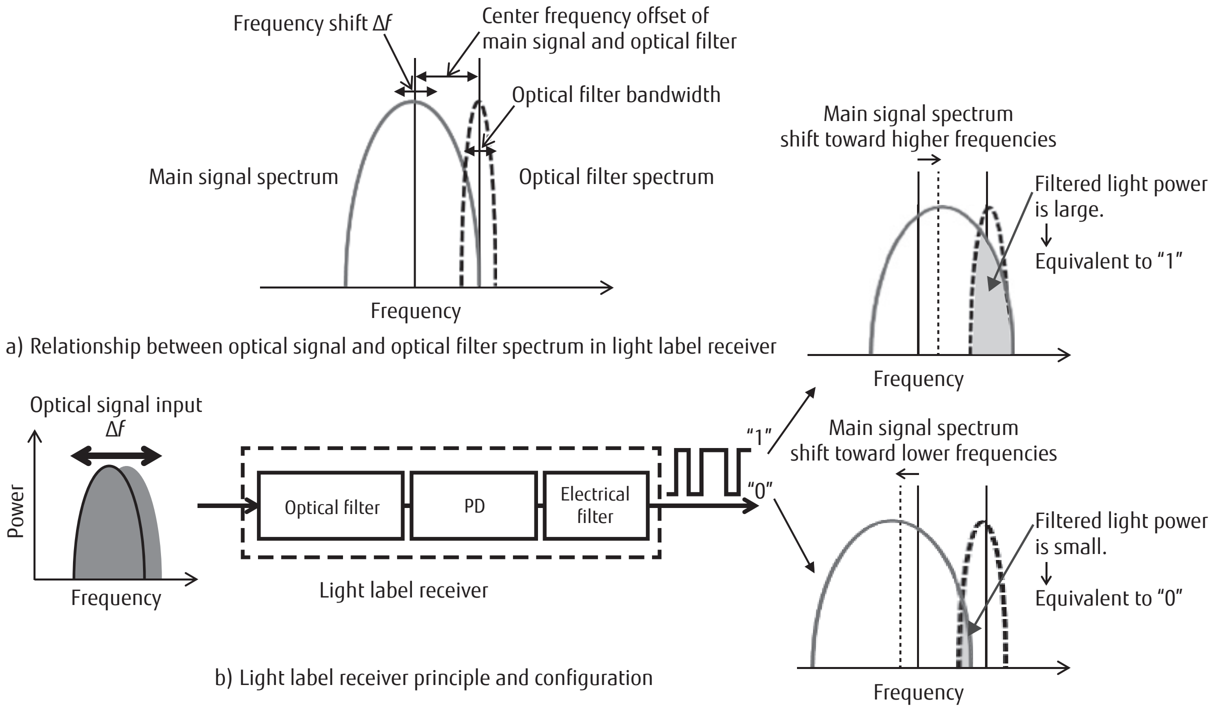


a) Configuration of light label signal superposition transmitter



b) Optical signal spectrum of signal superposed with frequency modulation light label signal

Figure 2
Superposition principle of light label signal.



a) Relationship between optical signal and optical filter spectrum in light label receiver

b) Light label receiver principle and configuration

Figure 3
Decoding principle of light label signal.

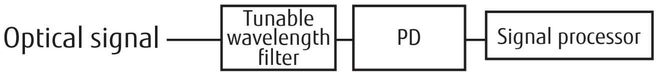
carrier frequency modulation processing by digital signal processor (DSP) on the transmitting side, and shifting (Δf) of the main signal spectrum occurs according to the frequency modulation, as the result of driving the optical IQ modulator by DAC based on the signal generated by DSP. Further, the frequency modulation signal is received as an amplitude-modulated signal through conversion of the frequency shift amount into power deviation based on three factors occurring in the light label receiver deployed in each CDC-ROADM node: the wavelength selectivity of the optical filter, the offset of each center frequency of the filter transmission spectrum, and the main signal spectrum.

5. Optical signal quality monitoring during service operation

The authors propose an in-band OSNR monitoring method for monitoring transmission quality when performing dynamic routing via CDC-ROADM according to user requests. This monitoring method is configured similarly to the light path trace receiver described in the previous section, consisting of a tunable wavelength filter, a photo detector (PD), and a DSP. **Figure 4** shows the conceptual diagram.[4] The OSNR monitoring method for a super channel signal consisting of two sub-carriers is shown in that figure. The input optical signal passes through a wavelength filter at two different frequencies, a sub-carrier center frequency f_{CF} and the center frequency f_{OF} between the sub-carriers. Then, signal optical power P_{CF} and P_{OF}, which include the amplified spontaneous emission (ASE) optical power P_{ASE} component added by the optical amplifier, are monitored respectively, and the OSNR value is calculated from their ratio R, parameter d, which depends on the spectral form of the signal, and correction coefficient α.

For the above-mentioned path trace function as well as verification of OSNR monitoring, experiments were carried out using a test bed consisting of five CDC-ROADM nodes.[5]

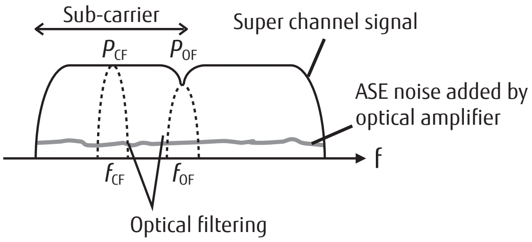
Its configuration, received light label signal waveform, and OSNR monitor measurement accuracy results are shown in **Figure 5**. A 128-bit frequency modulated signal that includes two different light labels at 10 kbps communication speed (labels = 12345, 65535) was superimposed on the different wavelength paths of a 112 Gbps dual polarization quadrature phase shift keying (DP-QPSK) signal received at an adjacent branch port at receiving ROADM node 5 after passing from an adjacent insertion port in the apparatus of transmitting



$$\begin{cases} P_{CF} = P_{ASE} + P_{sig} \\ P_{OF} = P_{ASE} + d \cdot P_{sig} \end{cases}$$

$$d = P_{OF\_Tx}/P_{CF\_Tx}$$

a) Configuration of OSNR monitor



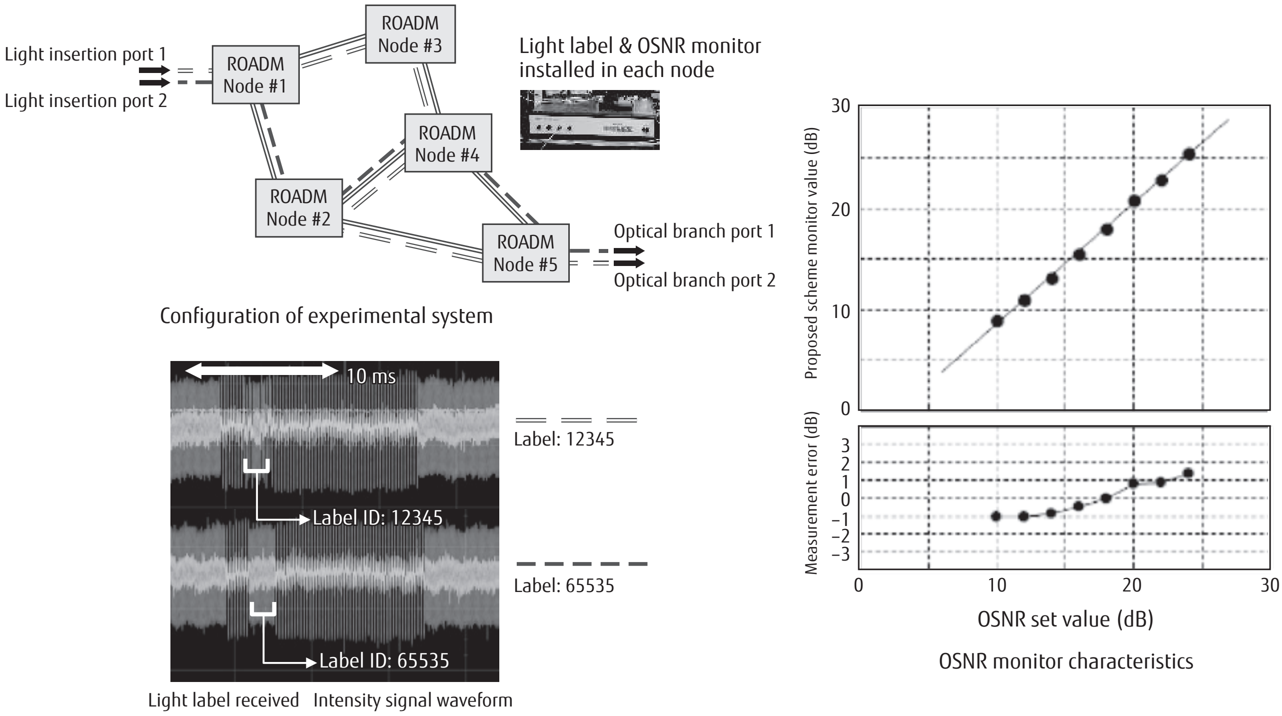
$$\mathrm{OSNR[dB]} = 10\log_{10}\left(\alpha \frac{P_{sig}}{P_{ASE}}\right) = 10\log_{10}\left(\alpha \frac{1-R}{R \cdot d - 1}\right)$$

$R = P_{CF}/P_{OF}$ α: Correction factor

b) Relationship between spectrum and light intensity during OSNR monitoring

P_{sig}: Optical power of optical signal
P_{ASE}: Power of amplified spontaneous emission (ASE) noise light added by optical amplifier
P_{CF}: Power of sub-carrier center frequency f_{CF} during OSNR monitoring (CF: Center Frequency)
P_{OF}: Power of sub-carrier offset frequency f_{OF} during OSNR monitoring (OF: Offset Frequency)
P_{CF_Tx}: Power of sub-carrier center frequency f_{CF} in optical transmitter (CF: Center Frequency)
P_{OF_Tx}: Power of sub-carrier offset frequency f_{OF} in optical transmitter (OF: Offset Frequency)

Figure 4
Operating principle of OSNR monitor.



Prepared based on figure published in "Demonstration of Integrated Optical Path Monitoring Sub-system in CDCG-ROADM Network"5)

Figure 5
Light label signal, OSNR integrated monitor system evaluation.

ROADM node 1 through a different fiber path and ROADM node.

At that time, the light labels at the transmission path input/output monitor ports of all the relay ROADM nodes and at the drop ports of receiving ROADM node 5 were detected as error-free. Moreover, with regard to the monitoring values of the OSNR monitor provided for each node, an error of 1.5 dB or less in relation to the set value was achieved.

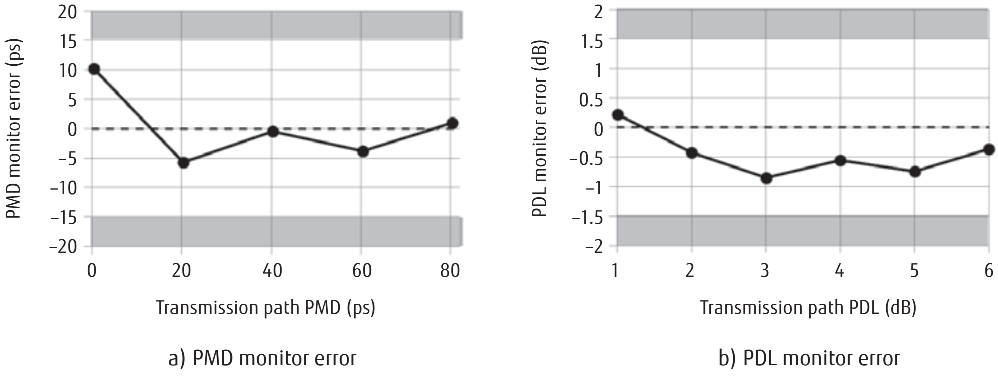
By making full use of these optical monitoring technologies, the optical signal quality of each subcarrier in the super channel is perceived by the OSNR monitor, particularly with the 400 Gbps and 1Tbps class super channel transmission technology, and through optimization,6) longer transmission distance can be achieved.

6. Monitoring using digital coherent technology

In the digital coherent receiving unit, the optical electric field information extracted by the optical front end, which consists of a Local oscillator source, 90-degree hybrid coupler, and photodetector, is A/D converted, and the received signal is equalized and demodulated by performing digital signal processing for distortion occurring on the transmission path. Through analysis of the tap coefficient of the adaptive equalization filter used in this digital signal processing unit, real-time monitoring of polarization mode dispersion (PMD) and polarization dependent loss (PDL), which are factors of distortion in optical fiber and CDC-ROADM nodes, is possible. **Figure 6** shows the experimental results of monitoring PMD and PDL based on the adaptive equalization filter coefficient of the LSI that processes the 100 Gbps DP-QPSK signal in a 40 km × 15 span transmission path system using single-mode fiber. The monitoring accuracy for the amount of generated PMD and PDL that enters the transmission path system was found to be ±10 ps (picoseconds) for PMD and ±1.0 dB for PDL. High-precision transmission design excluding any margin is possible through direct monitoring of the cause of fiber strain that causes such transmission quality degradation, and combination with the OSNR monitor.

To increase the transmission capacity per fiber, Nyquist filtering, which enforces bandwidth constriction for the digital filter of the transmission unit is recommended. This is a technique for increasing the bandwidth utilization efficiency, but degradation through inter-channel crosstalk occurs unless channel spacing is precisely set. However, according to the integrated tunable laser assembly (ITLA), whose standardization is progressing, bandwidth utilization efficiency declines in the case of wavelength arrangement (5 GHz and above) that secures a certain laser setting wavelength accuracy margin. As a means of solving this problem, the authors propose a method for feedback to the transmission unit by running Fast Fourier Transform (FFT) analysis of the data of the main signal that is captured in the digital coherent receiving unit, and monitoring the spacing between adjacent channels. **Figure 7 a)** shows the spectrum waveforms captured using this method. The spectrum data of adjacent channels is also visible in the spectrum, and the channel spacing can be monitored by reading the spacing with adjacent channels. **Figure 7 b)** shows the actual verification results for the channel spacing monitor that have been acquired with this method. Actual monitoring accuracy at the target frequency interval of 0.5 GHz has been achieved, and by performing feedback control to the transmitter based on this monitoring result, an increase in bandwidth utilization efficiency of approximately 10% can be achieved when compared to the control not being performed (5 GHz).

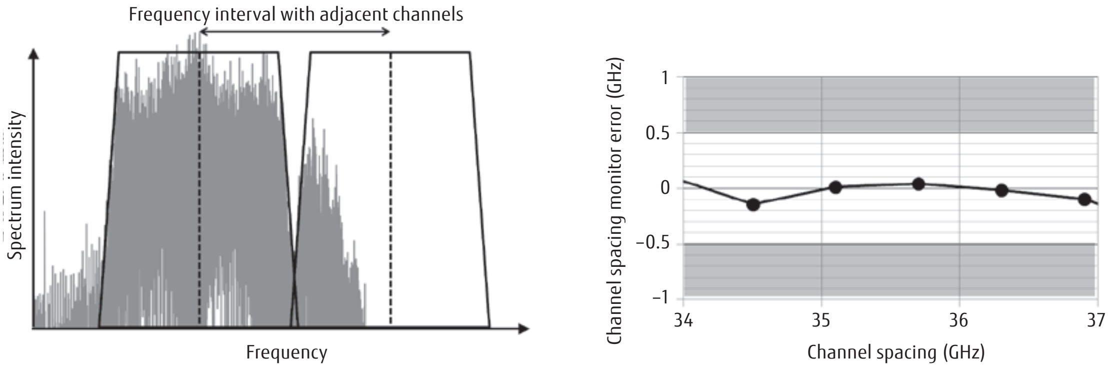
Digital coherent monitor is almost the same configuration as currently used transceivers. Thus, even



a) PMD monitor error

b) PDL monitor error

Figure 6
Measured values of PMD monitor error and PDL monitor error.



a) Spectrum waveform

b) Measurement error

Figure 7
Spectrum waveform and measurement error of wavelength interval monitor.

without special measuring instruments, monitoring values can be displayed in real time at each node by using transceivers installed at each node.

7. Conclusion

This paper describes the way the "conscious optical network" aimed for as an optical network by Fujitsu, and the value it offers. The conscious optical network is an architecture that offers value in terms of fast service provisioning, signal quality maintenance, and failure eradication through the use of Fujitsu's proprietary light probe technology.

Conventional optical networks require manpower for monitoring of physical properties and optimum control. The technology presented herein makes it possible to automate these tasks. Going forward, this technology will be applicable broadly, not just for control of optical characteristics, but also to further enhance the availability of entire networks through bandwidth control of other networks with different domains (for example, mobile networks, IP network), according to the state of the transmission path.

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