Toward Low-Cost Flexible Intelligent OAM in Optical Fiber Communication Networks

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Abstract: Low-cost, flexible and intelligent optical performance monitoring and management is a key enabling technology for network quality guarantee, especially in the era of explosive growth of communication capacity and network scale. However, to the best of our knowledge, it is extremely challenging to implement real-time performance monitoring and operations, administration and maintenance (OAM) in a highly complex dynamic network. In this paper, we propose an innovative optical identification (OID) scheme that can realize both performance monitoring and some advanced OAM sub-functions. The basic concepts, applications, challenges and evolution directions of this OID tool are also discussed.

Keywords: fiber optics communication; optical performance monitoring; pilot tone; wavelength-division multiplexing (WDM)

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1 Introduction

According to Omdia's forecast[1], the revenue of the global optical network market will exceed $17.4 billion by 2025. Driven by the vigorous development of information services, such as 5G, 4K and virtual reality (VR), the optical network served as a data bearer network is evolving from a rigid and homogeneous one to a flexible and heterogeneous one. Predictably, the five aspects of demands for optical transmission networks will be ultra-large capacity, ultra-low transmission delay, flexible service access, intelligent operations, administration and maintenance (OAM), and high reliability. Among them, it is of great importance to achieve refined network management and control so that network performance can be guaranteed, especially for diverse service requirements in vertical industries.

However, the current optical transport network (OTN) lacks mature OAM techniques for the optical layer just like the electrical layer. With continuous system upgrade and network expansion, the backbone network has increased its demand for intelligent OAM in the optical layer, especially for optical channel layer (OCh) performance monitoring, fault location and service scheduling. Moreover, current networks excessively rely on cumbersome manual data collection and complex analysis methods, which is difficult to adapt to the development trend of intelligence.

In 1993, HILL et al. firstly proposed the basic concepts of adding kHz-level pilot tones (PTs) to the high-speed optical signal for signal identification, power optimization and fault management[2]. In 1996, Bell Labs and Lucent Technologies used frequency-shift keying-modulated kHz-level frequency PTs with a date rate of 100 bit/s to achieve end-to-end signal tracking and real-time performance monitoring, fault location, rerouting, and wavelength conversion[3]. Furthermore, Tropic networks Inc. used the fast Fourier transform (FFT) technique to identify PTs with different carrier frequencies, laying the foundation for multi-carrier PT techniques in wavelength-division multiplexing (WDM) networks in 2006[4]. Additionally, the PT technique also shows unique advantages in optical network operations. For example, Lucent realized optical path tracing[5] and topology discovery (TD)[6] using PT signals around 2010. The above is the prototype of the early OCh OAM related to PT techniques, and its common feature is that the PT frequency is less than 1 MHz.

In recent years, PT techniques have been extensively investigated in the large-scale dynamic WDM network for perfor-

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mance monitoring, such as optical power, chromatic dispersion (CD)[7], polarization-mode dispersion (PMD)[8], optical signal-to-noise ratio (OSNR)[9], and nonlinear noise[10]. However, with the expansion of network scale and the increase of transmission distance and capacity, the influence of CD accumulation and nonlinear effect on the system becomes much more obvious. In the WDM system loaded with multiple PTs, the crosstalk induced by stimulated Raman scattering (SRS) effect after long fiber transmission becomes more serious. Fortunately, higher frequency PT signals possess the smoothing properties to the CD walk-off effect on the SRS, thus it can significantly suppress the SRS interference[11]. Therefore, the carrier frequency of PTs has gradually transitioned from a low frequency (<1 MHz) to a higher frequency larger than 10 MHz for optical network monitoring and OAM application in recent years[12]. Overall, there still remain some challenges that require further investigation in the deployment of real-time and intelligent OAM in the optical layer.

In this paper, we develop and demonstrate an OCh monitoring tool based on the PT technique, named optical identification (OID), which can achieve real-time channel-level performance monitoring and signaling issuance over an entire optical network. The modulation frequency and amplitude of the PT signals we used are much lower than those of service optical signals, avoiding performance degradation of the service signal. The OID can be applied into two scenarios. One is real-time optical performance monitoring and management, such as channel power, OSNR and channel loss of signal (LOS) alarms. The other is channel-associated overhead management; for example, the OID can be used to carry service labels and path information, and can even carry a small amount of channel signaling overhead, which is the key to realize intelligent OAM in the optical layer.

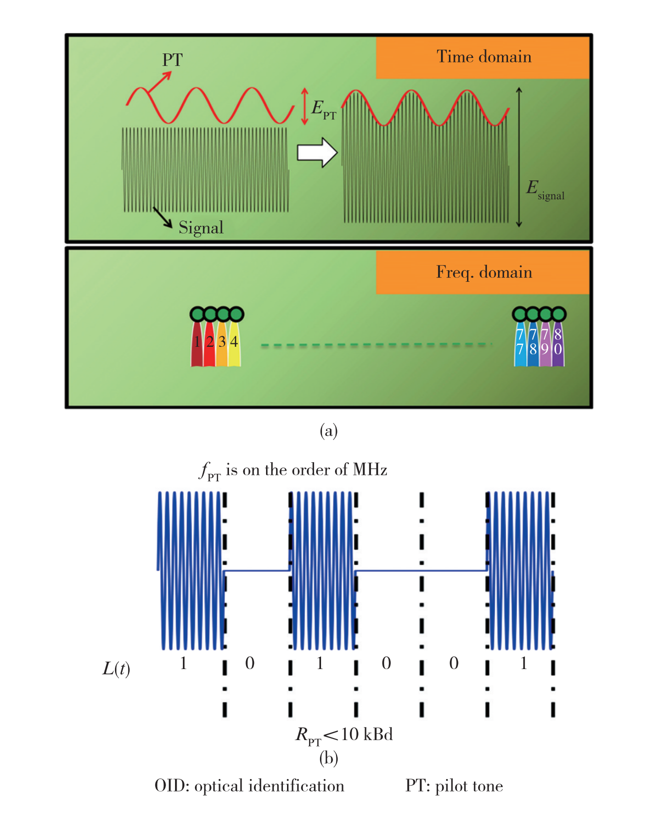
2 Basic Concept of Optical Identification Technique

2.1 Operating Principle

As shown in Fig. 1(a), for a single-channel OID signal, the electric field $E_{\mathrm{PT}}(t)$ expression of the low-speed PT modulated signal can be written as:

$$E_{\mathrm{PT}}(t) = E_{\mathrm{signal}}(t)\sqrt{1 + 2L(t)m_d\cos(2\pi f_{\mathrm{PT}}t + \varphi)}\ , \qquad (1)$$

where $E_{\mathrm{signal}}(t)$ is the electric field of a high-speed optical signal, $L(t)$=0, 1,⋯ is the data stream of the OID in the form of on-off keying (OOK) modulation, f_{PT} is the PT frequency that is generally selected to be greater than 10 MHz. Owing to the degrading effect of subcarrier-signal beating interference (SSBI) on the signal-to-noise ratio (SNR), the OID date rate R_{PT} should not be high, which is recommended to be designed as lower than 10 kBd; m_d is the modulation index (MI) of the OID, which is defined as the ratio of the RF power of PT sig-



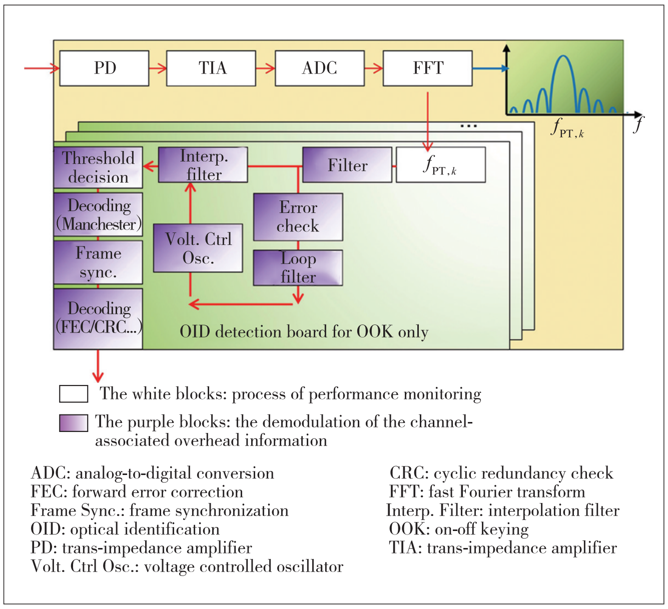
▲ **Figure 1. Schematic diagram of (a) OID loading and (b) channel-associated overhead data**

nals to the DC power of service optical signals. Actually, the PT signal can be regarded as a kind of low frequency noise for the service optical signal, so its amplitude or MI should be limited to control the OSNR penalty to be less than 0.5 dB@FEC limit. As a conservative design, its MI is recommended to be controlled below 10%. In the case of multi-channel monitoring, the electric field of OIDs can be derived from Eq. (1):

$$E_{\mathrm{PT}}(t) = \sum_k E_k(t)\sqrt{1 + 2L_k(t)m_{d,k}\cos(2\pi f_{\mathrm{PT},k}t + \varphi_k)}$$
$$(k = 1,2,3\cdots)\ , \qquad (2)$$

where k is the WDM channel number. As shown in Fig. 1(b), the channel-associated overhead data use the OOK modulation format with a specific frame structure. It is worth mentioning that Manchester coding possesses direct-current balance property, so that OIDs may carry the channel-associated overhead data while ensuring its average power is stable. Moreover, the error correction coding, such as forward error correction (FEC) and cyclic redundancy check (CRC), can improve the reliability of the channel-associated overhead data carried by OIDs. The above coding techniques are all adopted in the proposed OID tool.

As shown in Fig. 2, the basic process of OID detection for performance monitoring includes photodetection (PD), amplification by trans-impedance amplifier (TIA), analog-to-digital



▲Figure 2. OID detection process, taking OOK modulation as an example

conversion (ADC) sampling, and FFT operation for extracting the voltage amplitude corresponding to $f_{PT,k}$. Through the derivation of the above process, the single-channel optical power P_k (dBm) and the electrical power of OID $P_{PT,k}$ (dBm) will follow a linear rule, which is the basic mathematical form of using OID for channel monitoring. Furthermore, to demodulate the channel-associated data overhead carried by OID, the following additional process steps are essential: smoothing filtering, clock recovery based on phase-locked loop using the Gardner algorithm, threshold decision, Manchester decoding, frame synchronization, and error correction coding. The purple module is implemented through field programmable gate array (FPGA) in the verification stage.

2.2 Potential Problems

As described in Table 1, there are some factors that limit the measurement accuracy of OID tools, according to our theoretical model and experimental verification. The practical applications are the permutation and combination of the basic scenarios shown in Table 1. Although the complexity has increased, the error analysis method is universal. In addition, the parameters that mainly contribute to the error sources are also listed. It is worth noting that the SRS effect decreases as the OID frequency f_{PT} increases, while the CD fading behaves on the contrary, so there is a tradeoff in the design of the carrier frequency f_{PT}. The error polarities of OCh power monitoring induced by SRS in different bands are inconsistent, which come from the direction of power transfer caused by SRS.

In the case of channel-associated overhead, we are more concerned about signal crosstalk caused by SRS. The G.655 fiber has small dispersion and effective area A_{eff}, so the Raman gain (nonlinear effect) is larger, which leads to larger SRS and crosstalk over different channels.

▼Table 1. Influencing factors on optical performance monitoring using OIDs

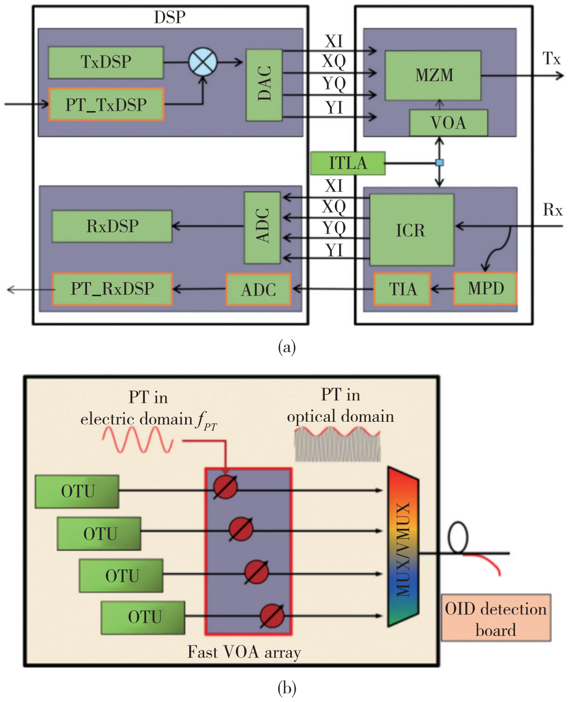
Error Source	Related Application	Error Polarity	Main Contribution
SSBI	Large capacity, multi-wave	+	m_d: Modulation index N: Channel number B_L: Bandwidth of PT signal B_S: Bandwidth of optical signal
ASE	Long haul, multi-span	−	OSNR
CD fading	Long haul, high baud rate, fiber with large D	−	f_{PT}: PT frequency $\Delta\lambda_{eff}$: Effective spectral width of optical signal D: Dispersion coefficient L: Transmission distance
SRS	Long haul, fiber with small D	Longwave: + Mid-wave: relatively small value Shortwave: −	f_{PT}: PT frequency g_{12}: Raman gain coefficient A_{eff}: Fiber effective area L: Transmission distance

Notes: + indicates the measured value of OID is greater than the actual value, while − means the opposite results.
ASE: amplifier spontaneousemission noise
CD: chromatic dispersion
OID: optical identification
OSNR: optical signal-to-noise ratio
PT: pilot tone
SRS: stimulated Raman scattering
SSBI: subcarrier-signal beating interference

3 OID Loading Scheme and Its Features

The current mainstream OID loading tools can be divided into built-in digital signal process (DSP) chips[11] and photonic chips. Fig. 3(a) exhibits the built-in DSP scheme, that is, the digital modulation signal of OID is directly multiplied by the framed XI, XQ, YI, and YQ high-speed digital signals to realize OID loading. Fig. 3(b) shows the photonic chip loading scheme. The variable optical attenuator (VOA) array is driven by the OID analog signal to load the low-frequency PT on the service optical signal. Actually, the latter scheme can also be realized through built-in VOA with silicon photonics (SiP)-integrated transceiver chips or through a semiconductor optical amplifier (SOA) with indium phosphide (InP)-integrated ones. In order to make OID compatible with various future optical modules, the verification of OID loading ability on InP-integrated and SiP-integrated photonic chips is essential. Based on our research, both VOA and SOA can be driven by the OID carrier frequency up to 50 MHz for SiP- and InP-based coherent optical modules, respectively, so the frequency resources are abundant. Additionally, we have noticed other reports about tuning laser current driving amplitude to achieve PT loading. However, the potential impact of this method on service signals[13–14] remains the main concern before its practical application.

The performance difference of the above two mainstream schemes is as follows. The DSP-based method saves the cost of additional devices thanks to its higher integration as OID loading and detection are realized by the built-in DSP. Moreover, its advantages on integration will be more prominent in future optical modules with limited space and power consumption. Additionally, with the help of FFT tools, an entire spectrum can be divided into multiple bands in the digital domain of DSP scheme, and PTs



ADC: analog-to-digital converter
DAC: digital-to-analog converter
DSP: digital signal process
ICR: integrated coherent receivers
ITLA: integrable tunable laser assembly
MPD: monitor photodiode
MUX: multiplexer
MZM: Mach-Zehnder interferometer electro-optic modulator
OID: optical identification
OTU: optical transform unit
PT: pilot tone
Rx: receive
TIA: trans-impedance amplifier
Tx: transport
VMUX: variable optical attenuator plus multiplexer
VOA: variable optical attenuator

▲**Figure 3. (a) Built-in DSP chips and (b) an example of photonic chip loading scheme by using external VOA array**

are loaded for each frequency band, where each PT has a different phase. It is reported that the CD fading can be suppressed under the above configuration[11]. However, it also has its shortcomings. The first one is that the OID signal and service signal are coupled in the DSP solution, so the sampling rates mismatch between the two and the quantization noise needs to be resolved, which may cause signal distortion. The second is that not all vendors are willing to develop an OID function built-in DSP application specific integrated circuit (ASIC), as it requires more design and verification effort and increases risk of chip failure. On the contrary, the photonic chip loading scheme is decoupled from the service signal, which provides better flexibility. It can also be compatible with the existing networks in the form of a sub-card, which facilitates a smooth upgrade of the OID tool.

4 Application Overview

The demands for intelligent OAM in OCh of the current networks focus on three aspects:

1) Real-time: To query the channel power and OSNR, optical performance monitoring (OPM)-type boards are widely deployed in optical terminal multiplexer (OTM) or reconfigurable optical add/drop multiplexer (ROADM) stations. However, the total measurement time is always at the minute-level, especially in multi-dimensional ROADM systems, as it usually shares an OPM among multiple directions using a time division multiplexing mechanism.

2) Refined: Optical line amplifier (OLA) sites are not equipped with OPM, so it can only monitor the total power without channel power details. Moreover, the channel power inside the ROADM site can hardly be obtained even with OPM.

3) Low-cost: The deployment of large-scale OPM boards increases network costs and occupies more sub-rack space.

Thanks to the basic properties of the OID tools, the above issues can be fully solved.

4.1 OCh Performance Monitoring and Management: Real-Time and Low-Cost

As illustrated in Fig. 4, benefitting from the shorter response time, the real-time performance of OID is better than that of traditional OPM. OID can be integrated into the board due to its small size, which can be deployed in more diverse boards. Each board equipped with an OID detection point has the channel-level monitoring capabilities and there is no need to share a detection point in multiple directions through optical switch multiplexing like traditional OPM. The resource conflict is resolved, so the parallelism could be improved. Furthermore, the power flatness can be adjusted according to all the channel-power sensed by the OID through the detection point. The following is an overview of the application of OID.

1) Power monitoring and optimization: As mentioned before, OPM boards are rarely deployed at OLA sites, because the flatness degradation induced by single-span transmission is relatively small in C band and the power flatness issue is not urgent. However, it should not be ignored in C++ and C+L band scenarios. Including the OLA site in the scope of OID tool deployment provides an efficient solution to the above issues. Our experiment results indicate that the error of OCh power monitoring is less than 1.5 dB under the 80-ch 20-span transmission scenario. We should also pay attention to whether ASE-shaped channels are used in the C+L band scene, as it brings some difficulties to OID loading.

2) OSNR estimation: OSNR of an optical amplifier (OA) can be calculated through OID channel-power monitoring combined with noise figure (NF) model[15] calibration, gain spectrum model[16] calibration and SRS power transfer model[17], which can achieve real-time dynamic monitoring of OSNR over the optical path. Furthermore, the detection range has also been expanded from ROADM and/or OTM sites to any site or even any detection point within a site. The experiment

results prove that the OSNR estimation accuracy of our OID scheme is within 1.5 dB and suitable for most OA types, which could stably replace the existing OPM boards and obtain high integration and low-cost benefits.

3) Channel LOS alarm: LOS alarm based on the OID tool can achieve ms-level response, which is vital for fault location, protection and restoration[18]. The OCh power will replace the total power as the analysis criterion. Such applications as insertion loss and connection loss detection can provide important support for real-time monitoring of network health.

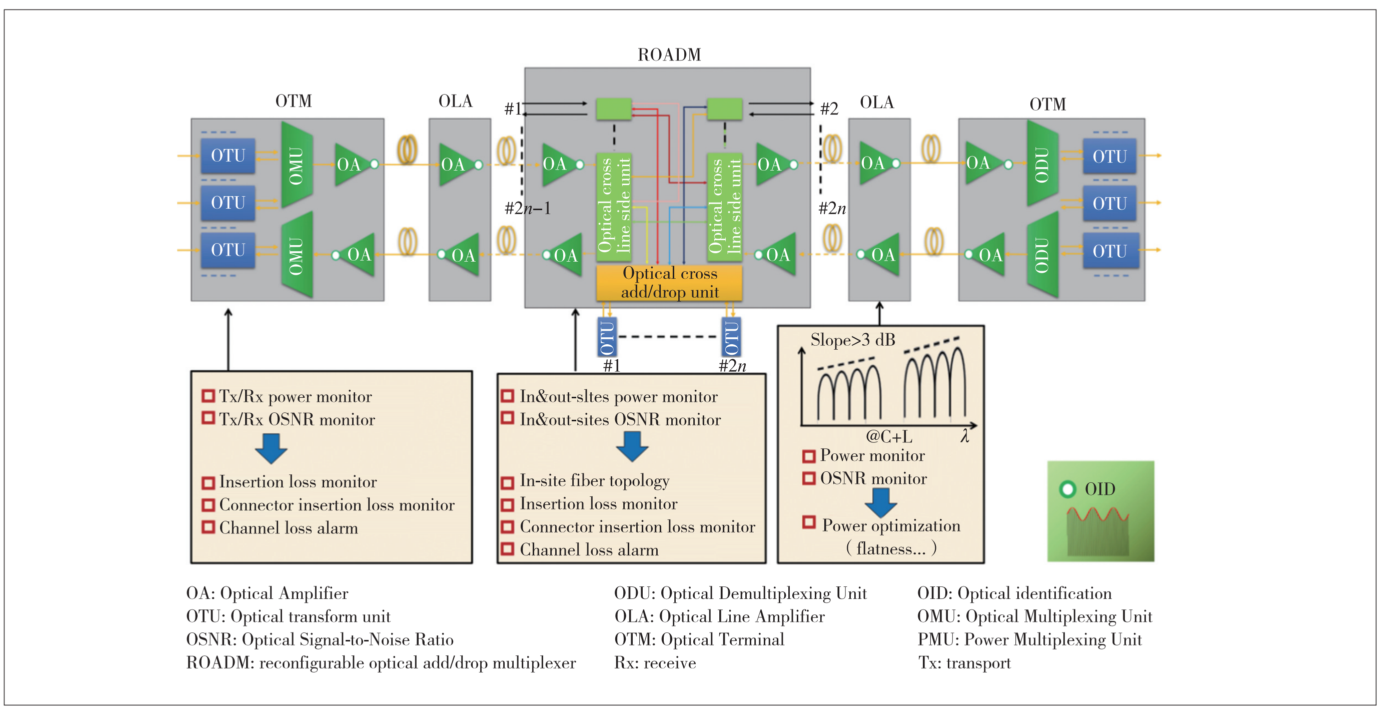
4.2 Optical Layer Channel-Associated Overhead Management: Refined and Intelligent

As shown in Fig. 5, all wavelengths are marked with unique channel IDs and transmitted together with the main optical signal. All the channel IDs can be extracted in each site equipped with the OID detection board. Simplified OAM such as TD in capacity expansion, new service creation/removal, rerouting, service path tracking and fiber misconnection recognition, can be realized by integrating the message of all OID detection points over the entire network. In the past, the topology connection within the site cannot be obtained owing to the limited coverage of the optical supervisory channel (OSC), while the OID tool can just make up for this shortcoming. In the case of TD between ROADM and OTM sites, it is determined whether each network node is in the same topology based on the detection of the same designated channel identifier. Meanwhile, the order of each network node in the topology can be judged by detecting the sequence of the initial time information. For the TD within a site, by tuning the channel attenuation of wavelength selective switch (WSS)-type boards, the OCh power in different sites should be changed accordingly. Once the change occurs, it means that the site is behind the WSS-type board, and thus the complete topological connection sequence within the site can be determined. Based on the OID unique channel identification of the entire network, the practical transmission path of the service wavelength can be realized, which solves another shortcoming of traditional OPM, that is, it can only distinguish wavelengths from the spectrum domain and cannot distinguish different services of the same wavelength. With the compression of channel spacing, it is even difficult to distinguish effective wavelength channels through spectral detection technique.

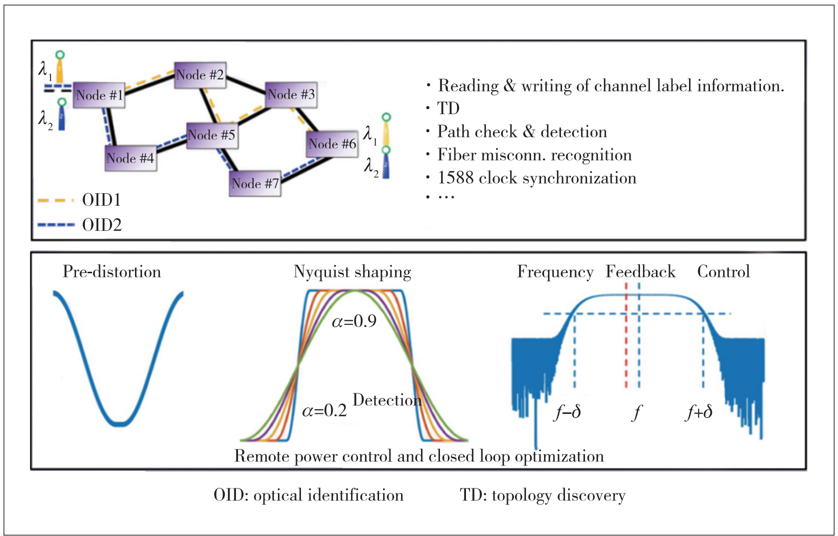
If the planned path is known, the service path check can be achieved by querying whether all the nodes on the planned path have detected the expected identification overhead. The service path check is a simplified version of the service path detection that adds an OCh power verification stage to further improve the accuracy of path detection and fiber connection judgment.

The OID channel can also be used to achieve 1588 clock synchronization. The 1588 clock synchronization system has large asymmetric delay through the optical module DSP, while the DSP for OID is relatively simpler and the delay for 1588 clock is fixed, which can ensure stable results.

For remote power control and closed-loop optimization, the channel-associated overhead could also include performance and remote control signaling information. Especially, the performance of the receiver is fed back to the transmitter in real



▲**Figure 4. Schematic diagram of optical channel layer (OCh) performance monitoring and management based on OID tool**



▲**Figure 5. Schematic diagram of channel-associated overhead management based on OID tool**

time through the reverse channel to form a closed loop mechanism, and then the best system configuration can be selected. With the closed-loop mechanism, it is possible to realize automatic optimization and opening up of new services or rerouting, as well as real-time performance optimization. For example, we can optimize the signal spectrum through pre-distortion[19], Nyquist shaping[20], central wavelength adjustment[21] and so on, and then select the best configuration based on the Q value of the opposite end in real-time feedback loop.

5 Conclusions and Outlook

In this paper, the basic concepts, applications and challenges of OID for optical layer intelligent OAM are discussed. We propose a low-cost OID implementation scheme and verify its applications in both optical performance monitoring and optical layer channel-associated overhead management. The proposed OID tool is proved to be effective and helpful for intelligent OAM in optical networks. However, there still remain some challenges that require further investigation: how to gradually upgrade and replace current network monitoring equipment such as OPM boards, and to make a tradeoff among the various negative factors discussed in the paper. In the future, this scheme is expected to evolve mainly towards two directions:

1) Faster optical layer sensing network needs to be constructed. The OID tool integrated on the board offers a sensitive detection way for real-time performance monitoring. The highly integrated feature facilitates its wide deployment in optical networks. With the full deployment of optical layer sensing networks based on this OID tool, the perception of OCh performance will become ubiquitous, and the collection of massive data should provide more real-time reliability for the optical layer intelligent engine basis for decision-making.

2) A more complete optical layer overhead system should be constructed. The OID tool provides a transmission channel for the overhead data in the optical layer, opening up new prospects for the improvement of the optical layer overhead system with diverse OAM functions.

It is expected that the wide deployment and application of OID tools will elevate the operation and maintenance capabilities of optical networks to a new level.

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