# Wavelength-routing fault detection in an AON testbed utilizing concatenated pilot tones

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## ABSTRACT

Recently pilot tones have been widely deployed as a path supervisory method for optical switches. We present a wavelength-routing fault detection scheme for concatenated optical crossconnects (OXCs) in all-optical networks (AONs), in which pilot tones are added to wavelength channels as identifiers (CIDs) at input ports. Routing errors within OXCs can be detected by comparing CIDs at output ports with the stored routing information. The scheme is applied to an AON testbed. A unique frequency tone is added at each input port of an OXC. The performances of two sets of candidate pilot frequencies are compared: 101 kHz ~ 117 kHz and 1.01 MHz ~ 1.17 MHz, at the modulation index of 5%. At the output side of each OXC, a modulator is inserted after each output port. We detect the tone before the modulator at the output port and feed the amplified, filtered, and inverted signal forward to that modulator, for removing the tone. The pilot tones are tracked and form the concatenated wavelength-routing fault detection scheme. The pilot tones and associated power penalty results are investigated. More importantly, the impacts of concatenated pilot tones on the overall system performance are evaluated by channel Q-factors.

**Key words:** optical performance surveillance, wavelength routing, fault detection, all-optical network testbed, pilot tone, optical cross-connect (OXC), Q-factor

## 1. INTRODUCTION

Recently optical crossconnects (OXCs) have been widely deployed as enabling equipment to provide dynamic re-configuration, wavelength routing/switching and channel add-dropping for all-optical networks (AONs) deploying wavelength-division multiplexing (WDM) technology [1]. However, the failure of OXCs or any routing/switching faults in OXCs, e.g. wrong port-mappings and port-blockings, may lead to a very high data loss due to the high data rate in such networks. As a result, the design of AONs based on OXCs must take into account some mechanisms of wavelength-routing fault detection and localization, to protect or restore the affected traffic.

Due to the lack of electrical terminations, numerous fault detection mechanisms for traditional communication networks cannot be applied directly to AONs [2]. Even some detection methods deployed in optical networks with opto-electro-opto (OEO) conversion cannot be used in AONs. The schemes for SDH/SONET presented in reference [3] are such examples.

In order to detect and localize wavelength-routing faults in AONs, optical path supervisory schemes using pilot tones as either channel tracking or performance monitoring have been studied in the past years. Such schemes monitor the status of optical path connections at each OXC in networks by assigning a unique pilot tone to every optical channel or path. The pilot tone is usually a unique low frequency signal wave that modulates the intensity of the host signal within the channel or path. The general characteristics of pilot tones and requirements for optical path supervisory had been discussed [4,5].

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Kwang-Uk Chu *et al*, proposed an optical-path supervisory scheme using pilot tones [6]. In this proposal the authors superimposed a unique pilot tone on the WDM input signals at each input port of the OXC. Then the routing status of each channel can be identified by detecting the pilot tone. The pilot tones were superimposed by the erbium-doped fibre amplifier (EDFA) gain modulation method and suppressed after the OXC by a variable optical attenuator (VOA) with a feed-forward control circuit. The pilot frequencies are from 200 Hz to 400 Hz. The power penalty induced by pilot tones is investigated by measuring the channel bit error rate (BER). It is confirmed that such power penalty is negligible (<0.1 dB). In order to improve the performance of pilot tone superimposing and suppression, the same authors revised the design in their follow-up work [7] to superimpose pilot tones by modulating the direct component (DC) of bias currents of transmitter lasers, and remove pilot tones by channel equalizers. The pilot frequencies were also changed to 2.0 kHz ~ 3.5 kHz. However, in above work the quantitative experimental results in terms of the scalability were not provided, although the authors claimed that their proposal was scalable to the number of network nodes (OXCs) and wavelengths. The effects of different pilot frequencies on system performance are also not reported.

Similarly, Eddie Kong *et al* also demonstrated the possibility to monitor the optical path for OXC's by using pilot tones as channel identifiers (CIDs) [8,9]. The authors used additional optical modulators to superimpose the pilot tone at each input port of the OXC, and removed the pilot tones through EDFA gain saturation at output ports. They studied the effects of the residual amplitude of pilot tones after removal on the performance of the proposed scheme. The frequencies of the pilot tones in their experiment were 90 Hz and 100 Hz for two input ports respectively. However, there is still a need to further study the effects of concatenated pilot tones and various pilot frequencies on system performance.

In this paper, we apply a pilot tone based approach for wavelength-routing fault detection and localization to an AON testbed, which consists of two concatenated OXCs inter-connected by multiplexers, demultiplexers, and fibre. An additional optical modulator is deployed at each input port of OXCs for superimposing pilot tones to each optical channel as the CID. Then any wavelength-routing fault could be detected and localized by comparing the detected pilot tones at each output port of an OXC with the original pilot tone at the corresponding input port. At each output port, the pilot tone is removed by an in-line optical modulator with forward control circuits. The work in this paper will mainly focus on the effects of concatenated pilot tones and various pilot frequencies on the overall system performance (e.g. BER) in the AON testbed [10].

This paper is organized into the following sections. The AON testbed is described in Section 2. The pilot-tone based approach for wavelength-routing fault detection and localization is discussed in Section 3. Then the proposed approach is applied to the AON testbed in Section 4. Quantitative results are presented and analyzed. Finally, some conclusions are given in Section 5 based on the above analyses.

## 2. PROPOSED FAULT DETECTION AND LOCALIZATION SCHEME

The principle of operation for our fault detection and localization scheme is shown in Fig. 1. At the input sides of OXCs in an AON, an additional optical modulator (Mach-Zehnder) is inserted before each input port and a unique frequency tone (sine wave) is modulated to the incoming optical signal of each wavelength channel. The pilot modulation index, defined as the ratio of the fluctuated power to the average power, is set to 10%. These pilot tones function as CIDs for wavelength channels within an OXC. CIDs within the OXC are drawn out at the output side by a PIN receiver. Then any wavelength-routing faults can be detected by comparing the CIDs drawn at output ports with the routing information stored in the controller of the OXC. When a recognized CID differs from its counterpart in the pre-determined routing table, the OXC controller will send an alarm of wavelength-routing fault to the network management unit. Fig. 1 only depicts the pilot tones for one channel. The others are similar and omitted for simplicity.

The added pilot tones could propagate to the downstream OXCs, accumulate in the AON because of amplifications, generate so-called "ghost tones" due to the slow dynamic feature of EDFAs, and consequently degrade the optical signals and affect the accuracy of detecting CIDs. To suppress such impacts, the pilot tones added to all channels in an OXC are removed at the output side of the OXC. It is well known that pilot tones can be removed through EDFA gain saturation. However, the performance of removing CIDs through gain saturation is limited by the EDFA gain characteristics. If complete saturation cannot be achieved, a fraction of the pilot tones will remain in the channels and residual tones will accumulate due to optical amplifications. Additionally, the cross gain modulation in an EDFA for multi-channel signals also degrades the suppression performance [7].

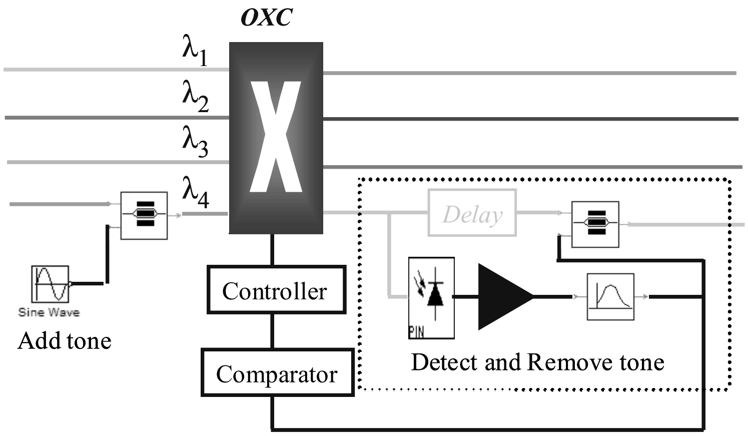

Fig. 1. Add and remove the pilot tone

In order to accurately remove the pilot tones from the optical signals in wavelength channels within an OXC, an in-line external modulator is inserted at an output port. A small portion of the channel signal is tapped out and the pilot tone is detected by a PIN receiver. The electrical signal from the PIN receiver is sent to the CID comparator and, at the same time, is also amplified, filtered, inverted, and then forwarded to the modulator at the output port for removing the pilot tones. For low frequency pilot tones, the electrical control circuit is very simple [11, 12].

Various frequency sets can be considered as candidates for pilot tones. For example, 90Hz and 100Hz pilot tones were applied in reference [9]. A range from 102 to 114 kHz for pilot tones with a 2 kHz separation was used in reference[13]. Pilot tones of 2 GHz and 8GHz were then demonstrated in reference [14]. We classify these candidate frequencies into three ranges,

- Low range: 0.1 – 5 kHz,
- Middle range: 10 kHz – 1 MHz,
- High range: > 1 MHz.

Low-frequency pilot tones can achieve the best signal-to-noise ratio, however, the performance is limited by the low frequency propagation, accumulation, and ghost tones. For low frequencies, the attenuation and inter-modulation in EDFAs caused by limited lifetime of Er3+ ions in excited state may result in transfer of CIDs to other signals. On the other hand, high-frequency pilot tones introduce smaller impairments but their performance could be limited by stimulated Raman scattering (SRS). The general guidance of selecting frequencies for pilot tones was described in references [4,15]. In this paper, we investigate two sets of frequencies: 101 kHz ~ 117 kHz and 1.01 MHz ~ 1.17 MHz. The effects of various frequencies on system performance such as channel Q-factors are compared. The end-to-end channel Q-factors measured under the following scenarios are compared to the case without any pilot tone, in order to quantitatively evaluate the effects of pilot tones on end-to-end system performance,

- With pilot tones in a single OXC, with/without pilot tone removal. Pilot frequencies are from 101 kHz to 107 kHz, with a 2 kHz separation.
- With pilot tones in a single OXC, with/without pilot tone removal. Pilot frequencies are from 1.01 MHz to 1.07 MHz, with a 20 kHz separation.
- With pilot tones in concatenated OXCs, with pilot tone removal. Pilot frequencies are from 101 kHz to 117 kHz, with a 2 kHz separation.
- With pilot tones in concatenated OXCs, with pilot tone removal. Pilot frequencies are from 1.01 MHz to 1.17 MHz, with a 20 kHz separation.

All measurements for the above scenarios are obtained from an AON testbed based on OXCs using micro-electro-mechanical-system (MEMS) technology. The AON testbed is described in details in the following section.

## 3. AON TESTBED SYSTEM SPECIFICATIONS

The design of the AON testbed involves key building blocks for an all-optical end-to-end WDM network [3,10]. These key building blocks include: optical crossconnect (OXC), multiplexer (MUX), de-multiplexer (Demux), transmitter, receiver, and optical amplifier [3]. The requirements for the testbed are as follows,

- Overall system performance: $BER \leq 10^{-12}$ , equivalently, $Q \geq 7.5\, dB$ .
- Transmission distance: 30 km, typical for metro WDM applications,
- 4 bi-directional channels at 2.5 Gbps/channel,
- 200 GHz channel spacing,
- AON functionality in place (signal transmission, transport, photonic switching, end-to-end transmissions, amplification, system control and signal reception),
- No signal regeneration along the transmission stage, no impairment compensation/control.

The node and link configuration of the testbed is shown in Fig. 2. The testbed has 4 WDM channels. At the transmitters, the source signals (PRBS: pseudo-random bit sequences, $2^{23}-1$ ) are modulated at 2.5 Gbps by directly modulated lasers (DML). The modulated signals pass through an OXC and then they are multiplexed and coupled into a standard single-mode fibre (with loss of 0.2 dB/km). A typical metro environment transmission distance, say 30 km, is applied here. The output power of the transmitter is –3 dBm. Such a low power level can avoid penalties introduced by fibre non-linearity. Finally the signals are de-multiplexed and passed through another OXC before they are detected with PIN receivers. The receiver sensitivity is optimized to –17 dBm [10]. Optical power ripple generated at an earlier stage in the network can be equalized by variable optical attenuators (VOAs) before the multiplexer and after the demultiplexer respectively. An optical amplifier is optional in the testbed, e.g. an erbium doped fibre amplifier (EDFA) with a gain of 10 dB and noise figure of 6.0 dB. The pilot tone adding and removing units described in the previous section are appended to OXCs in the testbed. The testbed specifications are summarized in Table 1.

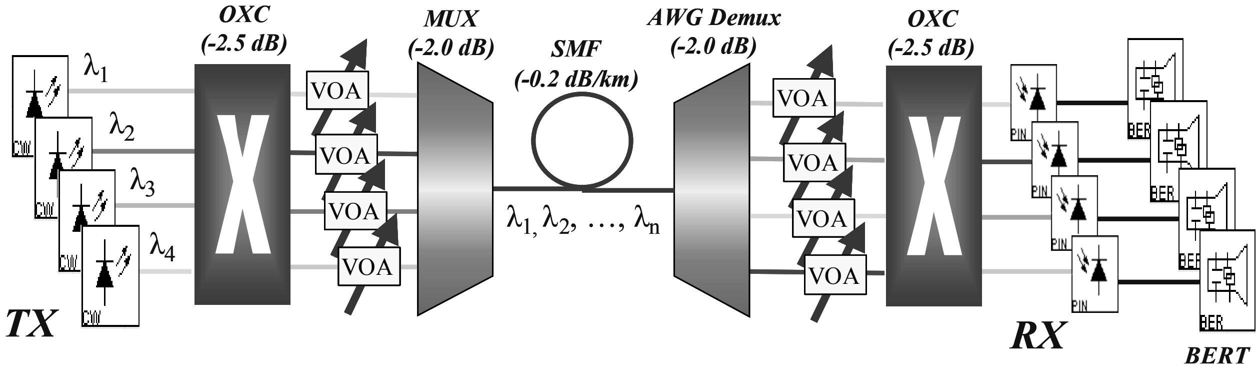

Fig. 2. Node and link configuration of the all-optical network testbed

Table 1. Summary of AON Testbed Specifications

| | | | |
|---|---|---|---|
| Data rate per channel | 2.5 Gbps/channel | Mux/Demux insertion loss | 2.0 dB |
| Transmitter | Directly modulated laser | Receiver sensitivity | -17 dBm |
| Channel spacing | 200 GHz | EDFA noise figure | 6.0 dB |
| Tx output power | -3 dBm | Fibre loss | 0.2 dB/km |
| PXC insertion loss | 2.5 dB | Pilot tone index | 5% |

The OXCs in our testbed are based on micro-electro-mechanical system (MEMS) technology to provide strictly non-blocking photonic switching of fibre-optic traffic. The operational wavelength ranges are 1290-1330 nm (1.3-µm band), 1530-1570 nm (C-band) and 1570-1610 nm (L-band). The switching time is less than 12 ms and the crosstalk below -50 dB. These optical switches provide dynamic switching by using customer developed control software running on control workstations. The control can be either centralized or distributed. A control workstation is connected to the switch via an RS-232C interface. Such a configuration demonstrates the dynamic wavelength switching. The provisioned switching information (OXC port mappings) is stored in the control workstation and compared with the recognized CIDs at the counterpart ports to find any wavelength-routing faults of OXCs in the testbed.

In the transmission stage, optical signals inevitably suffer from both noise and distortion that lead to system performance degradation. The system and component parameters of our testbed are optimized to minimize such performance degradations [10,16]. The NRZ signal is employed at channel sources based on the comparison results among candidate modulation formats [17]. In such a typical metro environment with optimum system parameters, system performance degradation due to signal impairments (both noise and distortion) for the 2.5 Gbps/channel with 200 GHz channel spacing WDM testbed (4 channels) are quite small and could be negligible. Thus there is no need of impairment compensation or control for our testbed.

## 4. SIMULATION RESULTS AND ANALYSES

In this section, the overall system performance of end-to-end channels in the testbed is evaluated by Q-factors (equivalent to BER). To accomplish the tasks described in Section 2, the effects of pilot tones on channel Q-factors are analyzed in terms of frequency selection, tone removal, and received optical powers. All simulations are modeled and set up by the tool VPITransmissionMaker$^{TM}$. For each scenario given in the end of Section 2, the relationship between system performance (Q-factor) and the received optical power is numerically analyzed.

### 4.1 Single stage of pilot tones

Fig. 4 gives the end-to-end Q-factors of a typical wavelength channel (channel 1 in our testbed) when the pilot tones are added to all channels at the first OXC stage. Fig. 4(a) shows the relationship between Q-factors and received optical powers in this channel for using pilot frequencies of 101 – 107 kHz and 1.01 – 1.07 MHz respectively, while no pilot tone removal is applied. The above Q-factors are also compared to their counterparts when no pilot tones are in use. Similarly, in Fig. 4(b) the added pilot tones are removed after the first OXC stage, and again, the Q-factors for using the same two sets of frequencies as in Fig. 4(a) are depicted along with the received channel powers.

The impacts of frequencies can be obtained from Figures 4 (a-b) for one stage of pilot tones: without removing the pilot tones from the testbed, the channel Q-factors are degraded ~1.5 dB and ~4 dB at most for ~100 kHz and ~1 MHz pilot frequency sets respectively. Furthermore, a degradation of no more than 2 dB is found for ~1 MHz compared to ~100 kHz. The degradation increases along with increasing received power. At the required system performance in the design ($Q = 7.5\ dB$), the degradation is quantitatively measured as a power penalty of 0.5 dB. On the other hand, if all pilot tones are removed from the testbed after the OXC, the degradation of Q-factors due to the pilot tones is no more than 2 dB for both frequency sets. The difference of degradation between the two frequency sets is no more than 0.5 dB and thus is negligible, although the Q-factors for ~1 MHz frequencies are still slightly worse than for ~100 kHz. At $Q = 7.5\ dB$, the measured power penalty for ~1 MHz pilot tones is only 0.1 dB compared to ~100 kHz tones.

For various pilot frequencies, the channel Q-factors are compared in Figures 4(c-d). It is shown that for ~100 kHz tones, the difference of Q-factors is very small and negligible ($\leq 0.5\ dB$) between the case with and without tone removal, whereas such difference increases to 2 dB for ~1 MHz frequencies.

The impacts of single stage pilot tones on channel performance are summarized in Table 2.

Table 2. Channel power penalty at *Q = 7.5 dB* comparing to the case with no pilot tones

| Pilot frequency | 101 – 107 kHz | | 1.01 – 1.07 MHz | |
|---|---|---|---|---|
| Pilot removal | Without removal | With removal | Without removal | With removal |
| Power penalty | ~ 0.50 dB | < 0.50 dB | ~ 0.75 dB | ~ 0.50 dB |

### 4.2 Concatenated pilot tones

When concatenated pilot tones are applied to the testbed without removing them after OXCs, the channel Q-factors cannot reach the minimum system requirement. A measured Q-factor of 6.0 dB is obtained for the typical

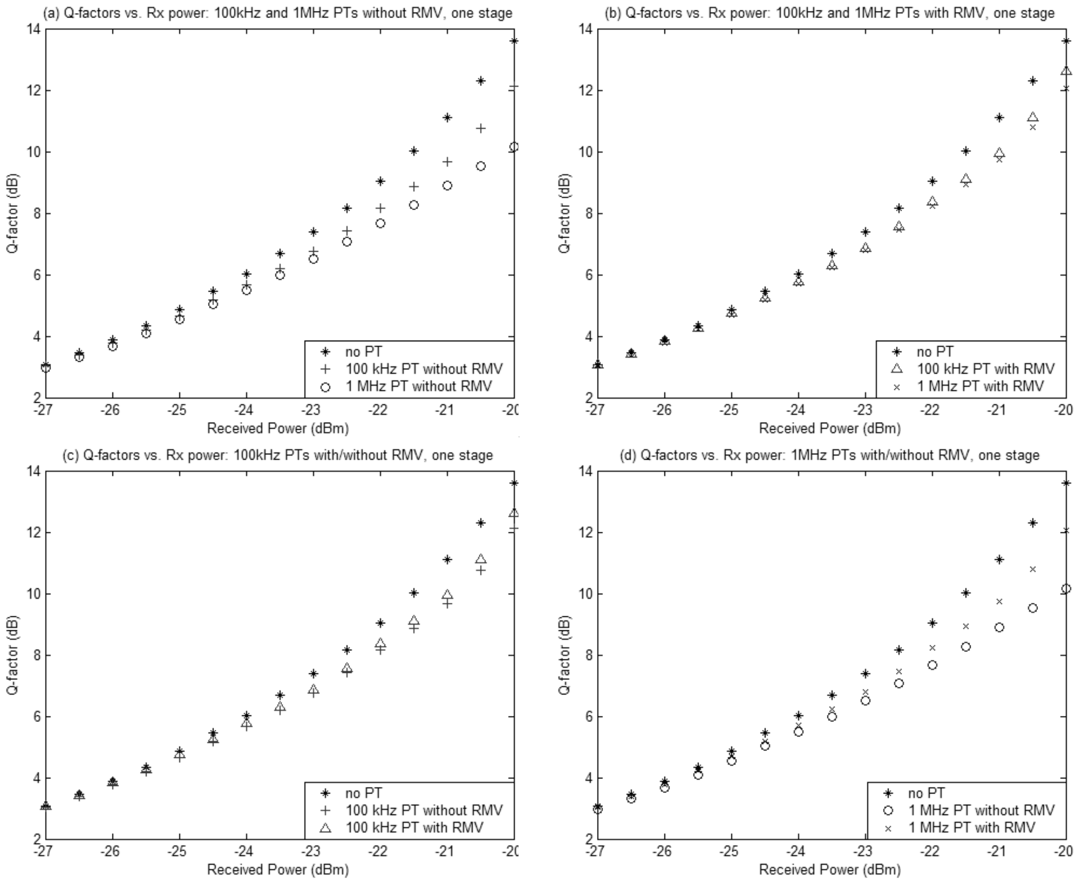

Fig. 4. End-to-end Q-factors and received channel power when using one stage of pilot tones

(a) PT frequencies of 101 – 107 kHz and 1.01 – 1.07 MHz, without removing PTs;
(b) PT frequencies of 101 – 107 kHz and 1.01 – 1.07 MHz, with removing PTs;
(c) PT frequencies of 101 – 107 kHz, with and without removing PTs;
(d) PT frequencies of 1.01 – 1.07 MHz, with and without removing PTs.

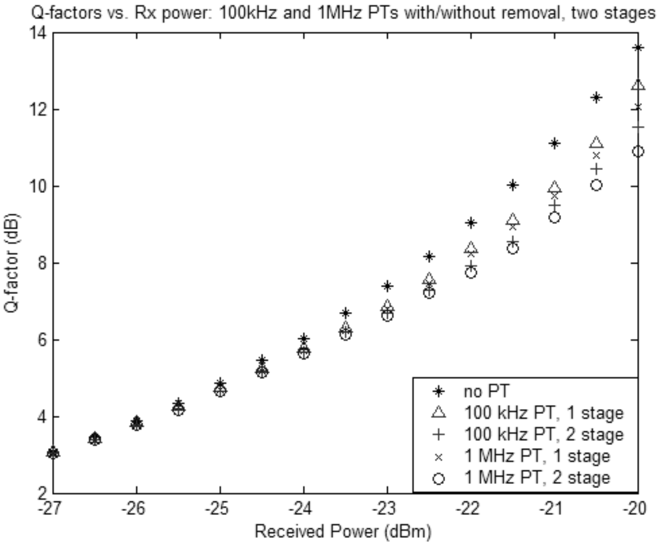

Fig. 5. Concatenated pilot tones with removal: frequencies of 101 – 117 kHz and 1.01 – 1.17 MHz

channel in Section 4.1 at the optimized system parameters and transmitter power [10]. Therefore, in this paper we investigate only the concatenated pilot tones with their removal at the output sides of OXCs.

Fig. 5 gives the end-to-end Q-factors of the typical channel when pilot tones are added to all channels at both OXCs in the testbed. The performances of two sets of pilot frequencies, 101 – 117 kHz and 1.01 – 1.17 MHz, are investigated. The Q-factors are compared to the case with no pilot tones and one stage of pilot tones respectively. It is shown that the performance difference between the two sets of frequencies is very small (< 0.5 dB) when concatenated pilot tones and their removal are applied to the testbed. Comparing to the single stage of pilot tones, the extra tones introduce another 0.5 dB degradation to the channel performance. Table 3 summarizes the power penalty of concatenated two stages of pilot tones compared to the single ones.

Table 3. Channel power penalty for two stages of PTs at $Q = 7.5\ dB$ compared to the single stage of PTs

| Concatenated pilot frequency | 101 – 117 kHz | 1.01 – 1.17 MHz |
|---|---|---|
| Power penalty | < 0.5 dB | < 0.5 dB |

## 5. CONCLUSIONS

In this paper, we present a scheme under which concatenated pilot tones are added to all channels as identifiers (CIDs) for detecting wavelength-routing faults in OXCs of an AON testbed. The testbed involves key building blocks for typical all-optical networks and support dynamic wavelength switching and routing. The performance of two frequency sets for pilot tones are investigated: 101 –117 kHz and 1.01 – 1.17 MHz. The end-to-end system performances, Q-factors of a typical channel, are measured to evaluate the impacts of various pilot frequencies. The impacts of pilot tone removal are also studied when they're applied in a single OXC stage. The simulation results show that when only one stage of pilot tones is in use, the impacts of pilot tone removal are trivial and negligible, whereas the lower frequencies, say ~100 kHz, has a better performance than higher frequencies (~1 MHz). For concatenated pilot tones, the required system performance cannot be achieved without pilot tone removal. Furthermore, the frequency selection has trivial impacts on the system performance when the pilot tone removal is applied, although the lower frequencies have slightly better performances than higher ones. In conclusion, the proposed fault detection scheme based on concatenated pilot tones is feasible and practical.

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