

# Autonomous OSNR Monitoring and Cross-Layer Control in a Mixed Bit-Rate and Modulation Format System Using Pilot Tones

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**Abstract:** Modulation-format and bit-rate awareness is realized in DLI-based OSNR monitor using pilot-tones. The autonomous signal quality decisions are made even in presence of modulation-dependent cross-talk. This capability facilitates scalable cross-layer impairment-aware-routing in mixed-signal environments.

**OCIS codes:** (060.4250) Networks; (060.4261) Networks, protection and restoration; (060.2340) Fiber optics components

## 1. Introduction

Network traffic is increasing at near exponential rates due to increased penetration of broadband internet and an expanding variety of high bandwidth applications. The rate of traffic growth is higher than the improvements in equipment energy efficiency, leading towards unsustainable increases in network energy consumption. Alternatives to traditional peak traffic capacity provisioning of large static ‘big pipes’ are sought as emerging services such as interactive, real time video communications, virtualized data centers, and grid computing and e-Science applications cause increasing number of unpredictable short-lived but high bandwidth edge traffic flows. A promising direction to address these challenges in a cost-effective, scalable and energy efficient manner is to develop new dynamic network capabilities that leverage novel optical technologies for flexible bandwidth allocation and intelligent resource utilization [1]. Advanced optical performance monitoring (aOPM), which reports signal quality information concerning the native optical signal, may be advantageous for managing signal quality and reliability in a network with continuously changing transmission configurations. This further facilitates real time awareness of the state of the physical layer enabling flexibility, stability and network optimization [2]. Cross-layer enabled network nodes -- which allow bidirectional information exchange between the layers of the network protocol stack -- have demonstrated effective utilization of information provided by the OPMs embedded in the physical layer in conjunction with higher layer service requirements to make intelligent routing and traffic engineering decisions [3].

Although studies have shown the benefits to cross-layer enabled monitoring, for wide-spread use such devices must be cost-effective. A promising monitoring solution is the delay-line-interferometer (DLI) based optical signal-to-noise ratio (OSNR) monitor which supports multiple advanced modulation formats [4] and can be easily integrated in the silicon photonics platform. However, the measurements from the DLI-- which are proportional to the actual OSNR -- are dependent on the data rate and modulation format of the signal under test. For this device to function effectively in future optical networks, which will potentially be operating in a mixed line rate and modulation formats framework, it is imperative to distinguish the properties of the monitored signal. In this work, we demonstrate that low frequency pilot tones -- weak modulation components added to wavelength-division-multiplexed (WDM) signals -- can be used to identify the signal properties at the monitoring site, enabling the use of a DLI-based OSNR monitor for cross-layer impairment-aware routing in a mixed signal environment. Pilot tones have a relatively small effect on the signal quality and can be easily detected at the monitoring site with simple low-power digital signal processing without hampering integration efforts. In addition, pilot tones can be used as an indicator of channel presence, enabling the monitor to detect channel loss rapidly.

The proposed pilot-tone assisted OSNR monitor enables a network node to operate as an autonomous monitoring and control unit, a functionality that becomes highly advantageous as next generation network architectures evolve towards a Unified Control Plane (UCP) paradigm. Centralized control platform provides flexible network management capabilities and is promising for dynamic service-aware optical networks. Software defined networking (SDN), using the OpenFlow protocol based UCP, has already been demonstrated to enable dynamic cross-layer path creation, restoration and transponder control and application aware dynamic path configuration in multi-layer multi-granularity optical networks [5]. However the centralized controller runs the risk of being overwhelmed by the level of signaling that would be required to control the physical layer. Providing autonomous and distributed monitoring and control capabilities within the physical layer has the potential to reduce the complexity of the control plane and improve network performance. If the UCP were to become isolated from a network node or if it were disseminating

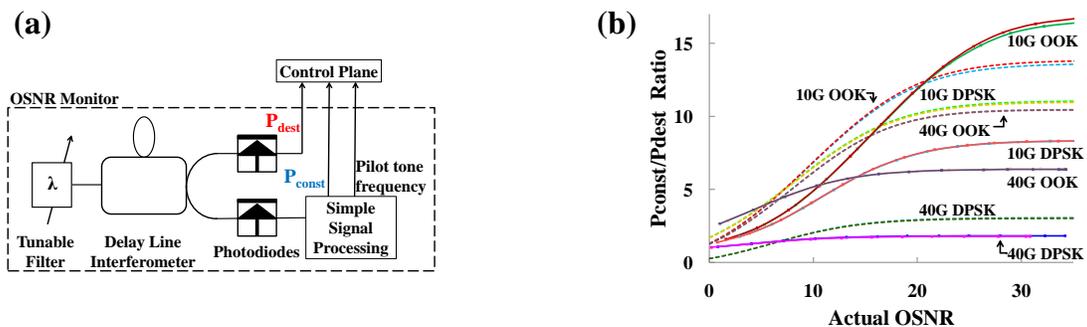
erroneous information regarding the signal type, a network node would continue to operate independently using information from the monitoring device, thus ensuring data protection.

## 2. Pilot-tone assisted delay-line interferometer

The structure of the proposed pilot-tone assisted DLI-based OSNR monitor is shown in Fig. 1.a. The channel to be monitored is selected by the tunable optical filter which iterates through all the channels in a WDM signal. The coherent signal entering the DLI undergoes constructive and destructive interference whereas incoherent noise experiences simple power splitting. The OSNR is calculated from the powers measured at the constructive ( $P_{\text{const}}$ ) and destructive ( $P_{\text{dest}}$ ) output ports of the DLI and is proportional to the  $P_{\text{const}} \setminus P_{\text{dest}}$  ratio [4]. However, as can be seen from Fig. 1b, the mapping of the actual OSNR and the measured ratio varies with the data rate and modulation format. In our proposed solution, a unique low frequency pilot tone is added to each type of signal at the transmitter to act as an identification code. In the past, pilot tones have been shown to be an effective means of labeling signals and for providing signal presence and power information. In this work, we investigate their use in conjunction with advanced OPM to facilitate measurements in a mixed signal environment in conjunction with a cross-layer centralized controller. For the purposes of characterizing and demonstrating the key performance requirements, we use a single frequency intensity modulated tone, however, these results are relevant for a variety of tone modulation techniques [6]. To ensure that pilot tones do not have a significant impact on the DLI measurements, the effect of the following on the OSNR curves of different data signals (10G OOK, 40G OOK, 10G DPSK and 40G DPSK) was investigated:

- i. Different frequency pilot tones (5MHz, 10MHz, 15MHz, and 1GHz) at constant modulation index (0.2)
- ii. Constant frequency pilot tones (10MHz) at different modulation indices (0.1, 0.2, and 0.3)

The worst case discrepancies from both experiment and simulations (Fig. 1b) establish that pilot tones have no significant effect on monitor readings and can be used for signal property identification. The DLI used in the experiment is a commercially available 40GHz optical DPSK demodulator from Optoplex.



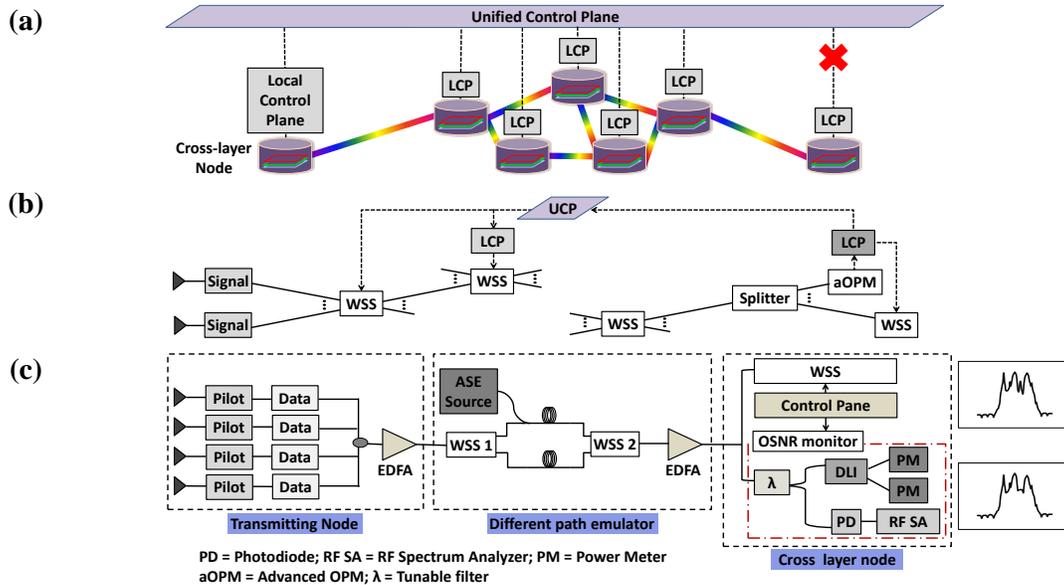
**Fig. 1:** (a) Pilot tone assisted DLI-based OSNR monitor which uses pilot tones to identify signal properties for correct interpretation of OSNR from  $P_{\text{const}}/P_{\text{dest}}$  ratio. (b) Simulated (dashed) and measured (solid) ratio for different signals. Each set consists of no pilot tone and the worst discrepancy pilot tone, establishing that pilot tones have negligible effect on DLI readings

## 3. Experimental validation of proposed monitor in cross-layer enabled network node

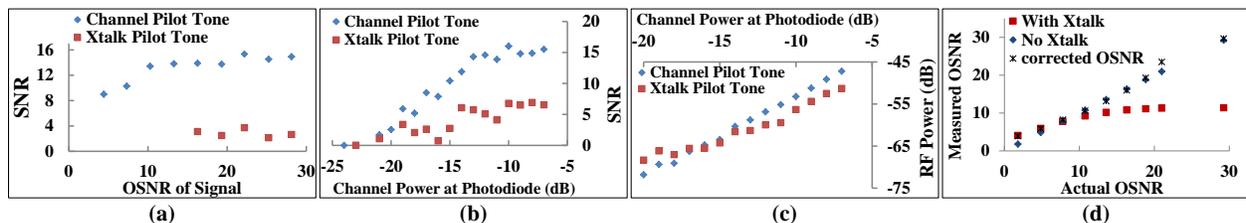
The performance of the proposed monitor in a cross-layer enabled node is experimentally validated using the test-bed depicted in Fig. 2c. The transmitting node injects four different types of signals (10G OOK, 10G DPSK, 40G OOK and 40G DPSK), each with a unique intensity modulated pilot tone, into the test-bed to create a mixed signal environment. To emulate traversal over different distances and paths, wavelength selective switch (WSS 1) switches each signal either onto the “impaired” or the “good” link to vary the OSNR and amount of cross-talk on each signal. At the cross-layer enabled node, a portion of the power is tapped off for monitoring. The tapped signal is divided equally between a photodiode connected to a radio-frequency (RF) spectrum analyzer and a DLI whose output ports are connected to power-meters. A software control plane communicates with these measurement devices and extracts the values for  $P_{\text{const}}$ ,  $P_{\text{dest}}$  and the pilot tone frequency with the highest signal-to-noise-ratio (SNR) to calculate the OSNR of the signal. If the calculated OSNR is below a pre-defined threshold, that particular signal is dropped.

The proposed monitor operates accurately even in a dense-wavelength-division-multiplexed (DWDM) system where cross-talk causes pilot tone “leakage” between neighboring channels. To ensure the robustness of the proposed monitor, we studied the behavior of pilot tones for the worst cross-talk signal configuration in our test-bed (10G DPSK signal surrounded by two 40G DPSK signal on the 50G ITU grid) under different test conditions. In particular, we demonstrate the results of: (i) varying the OSNR of the center channel (signal under test) and (ii) varying the signal power of high OSNR center channel while maintaining high power and OSNR at neighboring

channels. Results show that the pilot tone frequency of the signal under test is always the dominant frequency, ensuring correct operation of the monitor even with significant amounts of cross-talk (Fig. 3a,b,c). The cross-talk frequency can instead be used as a signal to the control plane to correct for the error in the OSNR measurement of the DLI that arises due to cross-talk (Fig 3d).



**Fig. 2:** (a) Cross-layer enabled network with local control plane for autonomous monitoring and control. (b) Component level view of the network illustrating the control loop initiated in response to a low OSNR signal detected at a node. The signal is dropped locally and the LCP communicates with the UCP to implement intelligent rerouting. (c) Experimental test-bed to validate the performance of the monitor in a mixed signal environment. The cross-layer node emulates an isolated node and is demonstrated to have autonomous monitoring and management capabilities. Optical spectra of different test cases at the cross-layer node are shown.



**Fig. 3:** (a) In the presence of high cross-talk, even at low OSNRs, there is a strong enough channel pilot tone and no cross-talk pilot tone. (b) Using SNR at a given frequency, the channel pilot tone can be distinguished from the cross-talk frequency up to -18 dBm input power at detector. (c) Using the RF power at a given frequency, the channel pilot tone can be distinguished from the cross-talk frequency up to -13 dBm input power at detector. (d) Presence of high cross-talk causes errors in the OSNR measured by DLI-based OSNR monitor. The strength of the cross-talk pilot tone can be used as an indicator of the level of cross-talk to determine a correction factor.

#### 4. Conclusion

Distributed optical performance monitoring will facilitate the development of next-generation energy efficient dynamic optical networks. By using unique pilot tone frequencies to identify signal properties, we enable the operation of a modulation-format and bit-rate dependent DLI-based OSNR monitor in a mixed signal environment. This monitor is incorporated in a cross-layer node to demonstrate autonomous monitoring and control, a key step towards realizing intelligent impairment aware networks

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