Optical Link Planning Guidelines for a Hybrid Packet and Circuit Integrated Network

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Abstract: We demonstrate OSNR requirements below 13dB and system margin above 5dB for a 2-node 100Gb/s hybrid optical packet and circuit network prototype, which can be used for planning further network extension and field deployment.

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1. Introduction

The convergence of packet-switched and circuit-switched technologies on control and data planes has received significant attention as the means to provide both best-effort and guaranteed quality of service communications. Towards this purpose, this group has recently proposed and demonstrated a fully functional optical packet and circuit integrated (OPCI) network prototype [1, 2]. This system uses multi-wavelength packet (MWP) transmission to establish a 100 Gb/s packet communications channel combined with conventional wavelength division multiplexed transmission at 10 Gb/s. Later, the network was extended to multiple ring architecture, enabling the demonstration of a fully functional OPCI network prototype [1–3]. Key technologies towards high quality operation include a polarization-independent semiconductor optical amplifier (SOA)-based switch sub-system [4, 5]; transient-suppressing erbium doped fiber amplifiers (TS-EDFA) [6], and electronic switch control with label processing and optical buffering [3].

The extension of the OPCI prototype network towards field deployment and increased number of nodes and transmission distances requires a thorough analysis of the system performance. In particular, the performance of the MWP transmission, since this is currently more restrictive than the corresponding circuit-switched transmission. This work produces such analysis by defining a normalized optical signal-to-noise ratio (OSNR) independent of the packet traffic pattern. For this purpose, we consider the impact of the traffic pattern on the average signal power as well as modulation of noise in optical switches. The normalized OSNR is then used to measure OSNR requirements and define system margins for planning of optical links using the OPCI prototype nodes.

2. Normalized OSNR Measurements

Conventional OSNR measurements using optical spectrum analyzers in optical packet networks must take into consideration that the average signal and noise powers are strongly dependent on the traffic pattern. However, the performance of the system is mainly dependent on the average signal and noise power during the transmission of a packet [7]. Fig. 1 shows an example of the MWP spectrum at the output of an optical switch for different network loads while maintaining the packet duration. It is shown that the average signal power and noise power spectral density (PSD) vary significantly with the network load. In the first case, the variation results directly from the traffic pattern. However, the performance of the noise PSD results from the modulation of the noise by the optical switch. As such, it is useful to normalize the traffic dependent average values of signal power and noise PSD to equivalent values that are traffic independent. For the signal power, one may define the average power of the i-th packet channel as $\tilde{P}_i = R_i \cdot P_{eq} \cdot \Phi$, where $R_i$
is the \(i\)-th channel power ripple, \(P_{eq}\) is the normalized average channel power during the transmission of a packet and 
\[\Phi = \eta + I_G \cdot (1 - \eta)\] is the normalization factor. The terms \(I_G\) and \(\eta\) are the power isolation during the time intervals without packet transmission and the ratio between the packet duration and period between packets, respectively. The latter will be referred here as network load. For the noise we will approximate the PSD at a given point in the network by \(N_{sp} = N_{BF} + \Phi \cdot N_{AS}\), where \(N_{BF}\) is the modulated noise contribution that has traveled through one or more optical switches, and \(N_{AS}\) is the unmodulated noise contribution, generated by amplifiers succeeding the latest optical switch. Finally, one may define the OSNR for the \(i\)-th packet channel using the aforementioned signal and noise power as 
\[OSNR_i = OSNR_{eq,i} \cdot \Phi \cdot (1 + N_{BF}/N_{AS})/(\Phi + N_{BF}/N_{AS}),\]
where \(OSNR_{eq,i} = R_i \cdot P_{eq}/(N_{BF} + N_{AS})\) is the normalized OSNR, equivalent to the OSNR during the transmission of a packet and traffic independent. The performance of the OPCI test bed will be characterized along this work by experimentally measuring the OSNR in a conventional manner and then applying the aforementioned method to obtain the normalized OSNR.

3. OPCI Network Prototype

A simplified diagram of the considered test bed is shown in Fig. 2. On each OPCI node, the packet mapper in the MWP transponder splits incoming 10 GB-Ethernet frames onto 10 packets at 10 Gb/s. These are used to modulate 10 optical carriers within a 100 GHz grid. Each optical packet is preceded by a 16-byte preamble and one will include a label for downstream processing. The 10 signals are multiplexed by an arrayed waveguide grating (AWG) and fed to the optical switch. There a 4 by 4 SOA switch sandwiched between TS-EDFAS is used to route the MWP signal according to the incoming label. For transmission, an add wavelength selective switch (WSS) combines the MWP with the signals from 7 conventional transponders prior to amplification at the booster. The inset of Fig. 2-b) shows the spectrum at the output of the booster, containing the MWP signal with two groups of circuit signals from the conventional transponders. On the receive side, a drop WSS isolates the circuit channels and the MWP signal, sending the latter to the optical switch for appropriate routing. Node 2 has the same structure as node 1. The signal at the input of the MWP transponder will be degraded with an amplified spontaneous emission (ASE) noise generator. The direction from node 1 to node 2 is linked by 50 km of standard single mode fiber (SSMF) and appropriate dispersion compensating fiber (DCF) for a total loss of 20 dB. The reverse direction uses a 15 dB attenuator to simulate the span loss. Due to the limited power range of the MWP transponder burst-mode receivers and the optical switch electronic label processor, the input power of these components has been optimized for short packets (18 ns) with high network loads (20%).

Three scenarios will be used with this test bed: (i) data looped at the optical switch in node 1 - 1 node; (ii) data traveling from node 1 to node 2 and terminated there - 2 nodes; and (iii) data traveling from node 1 to node 2 and from there, routed back to node one - 3 nodes. In the case of scenario (ii), the performance will be estimated at the MWP transponder of node 2, unlike the representation in Fig. 2-b). In scenario (iii) we will neglect the impact of crosstalk on the SOA-switch, since the isolation of this component has been shown to exceed 30 dB [4, 5].

4. OSNR Requirements of the OPCI Network

The performance of the MWP depends mainly on the performance of the worst-case packet channel, which may vary due to power ripple from the optical amplifiers and switch. As such, we consider only the worst-case OSNR for our performance estimates. Fig. 3 shows the dependence of the frame error rate (FER) on the OSNR and normalized OSNR for the three scenarios defined above. In the case of scenario (i), with 1 node (Fig. 3-a), it is shown that the traffic dependency of the performance is strongly reduced when using the normalized OSNR, as opposed to the conventional OSNR. Note that the normalized OSNR requirements are higher than the average OSNR values since they refer only the OSNR during the transmission of a packet. In that scenario and considering an error-free FER of

![Fig. 3: FER dependence on the OSNR (empty symbols) and normalized OSNR (filled symbols) for multiple traffic patterns.](image-url)
10^{-4} \cite{8}, one may estimate the normalized required OSNR between 12.2 dB for 18 ns packets and 14.6 dB for 753.3 ns packets. The difference in performance between short and long packets results from the optimization of the power at the MWP transponder input for the first case. This behavior would not be directly observable when considering the average OSNR values, as shown in the same figure. In the case of scenarios (ii) and (iii) presented in Fig. 3-b and -c, respectively, the longer routes followed by the MWP will lead to degradation of performance, which becomes more significant with longer packets. In the case of scenario (ii) with 2 nodes, the OSNR requirements are between 12.2 dB for 18 ns packets and 16 dB for 753.3 ns packets. For scenario (iii) with 3 nodes, the OSNR requirements are between 12.2 dB for 18 ns packets and 17.3 dB for 753.3 ns packets. This shows that the OSNR penalty is hardly affected by transmission when using shorter packets, degrading significantly as the packet length is increased.

We may define the system margin for the considered OPCI test bed as the ratio between the actual and the required normalized OSNR. Fig. 4 shows the evolution of the worst-case normalized OSNR at the output of the optical switches and booster amplifiers along the optical route corresponding to Scenario (iii). The components at the output of which the OSNR has been measured and normalized are represented to clarify the graphic. The normalized required OSNR estimated above is also represented for various combination of network load and packet length. It is shown that the available system margin after three nodes varies significantly with the traffic pattern. After transmission through 3 nodes, we have estimated system margins of 2.8 dB for 753.5 ns packets and 10% network load in the worst case; and 5.4 dB for 18 ns or 24.8 ns packets with network load of 5%. Note that in the latter case there is no significant degradation after transmission. This reflects the power settings for the MWP transponder and label processor receivers and is in agreement with the results presented in \cite{3}, where an OPCI link with 5 switches using short packets is demonstrated with error-free performance.

5. Conclusion

This work has presented guidelines for the planning of a hybrid optical packet and circuit network. Experimental OSNR measurements have been normalized to remove traffic dependent variations. It has been shown that using normalized OSNR estimates allows defining a system margin for the optical packet link, similarly to what is commonly conducted for optical circuit links. Furthermore, it has been shown that in a 3 node link, the system margin reaches 5.4 dB for 24.8 ns packets, degrading to 2.8 dB for 753.5 ns packets.

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6. References

\cite{8} ITU-T Recommendation Y.1541