Transmission of Nyquist-shaped 32 GBaud PM-QPSK Over a Production Flex-grid Open Line System

Mark Filer[1], Hacene Chaouch[2], Jonathan Chu[2], Raju Kankipati[2], Tom Issenhuth[1]
[1]*Microsoft Corp, Redmond WA;* [2]*Arista Networks, Santa Clara CA*
mark.filer@microsoft.com

Abstract: Nyquist PM-QPSK signals are sent over 4000 km of fiber through an open line system employing colorless flex-grid ROADMs. The signal source is a layer 2/3 modular switch with embedded coherent ASICs and CFP2-ACO optics.
OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (060.4250) Networks

1. Introduction

Optical transmission system requirements have been undergoing a paradigm shift in the last several years as Cloud and Enterprise (C&E) customers increasingly constitute a larger percentage of optical transport market share [1]. Many of the feature sets required by "Tier-1" telco providers don't apply, and an increasing number of products designed to satisfy the specific needs of the growing C&E space have recently been introduced [2].

One such shift in the traditional optical transport space is a requirement for "open" line systems – a disaggregation of the photonic layer in which the optical transceivers / transponders are decoupled from the line system itself (muxes, amplifiers, ROADMs) [3]. An important implication of this approach is the ability to procure coherent optical sources from multiple vendors and platforms; for example, traditional transponder line cards, high-density "pizza-boxes" [2], or layer 2/3 line cards with embedded coherent DSP and optics. This disaggregation fosters greater competition and innovation in the market place, and it gives the flexibility to the cloud provider to choose what platform (i.e., traditional DWDM box, pizza-box, or layer 2/3 line card) best fits their need for a given application. Additionally, this openness enables a path further toward true SDN operation in the optical domain, with northbound interfaces from the line system NMS (and eventually from the network elements themselves) to the network orchestration layer, which is typically developed by the cloud provider.

In this paper, a commercially available line system operating in an open fashion is employed to transport Nyquist-shaped PM-QPSK signals at 32 Gbaud over a mix of G.652 and G.655 fiber. The line system is realized using a colorless, "directional" architecture, which utilizes colorless mux/demux, flex-grid 20-degree ROADMs for terminal nodes, 9- or 20-degree ROADMs for channel balancing pass-through nodes, and hybrid Raman/EDFA amplification. The optical sources reside on layer 2/3 modular Ethernet switch cards, each having multiple embedded coherent ASICs and corresponding CFP2-ACO pluggable optical modules. Transmission performance is demonstrated up to 4000 km for 7 channels spaced 37.5 GHz apart, operating with over 3 dB OSNR margin from the coherent DSP SD-FEC limit.

2. Line System

In order to aid in the development of an open line system suitable for deployment in a production intercity data center network, optical transport hardware was procured for Microsoft's optical transmission lab in the Redmond headquarters. The line system itself was specified to meet the particular requirements of Microsoft's data center architecture. Namely, there is no need for support of electrical OTU switching, optical-layer restoration, sub-line-rate aggregation, optical "bandwidth on demand" (i.e., directionless, contentionless), or true mesh network connectivity.

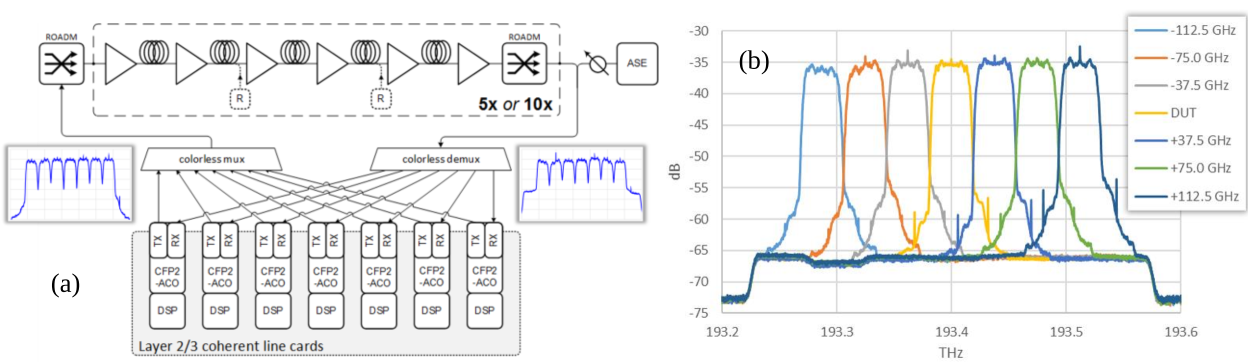

Figure 1. (a) System configuration, (b) Spectrum for 7x 32 GBaud Nyquist (RRC=0.2) PM-QPSK signals at 37.5 GHz spacing

Table 1. Fiber span and amplifier configuration (DRA = distributed Raman amplification)

span	fiber	km	ps/nm	amplifier	span	fiber	km	ps/nm	amplifier
1	G.652 (SMF)	75	1275	EDFA	14	G.655 (LEAF)	90	450	EDFA+DRA
2	G.655 (LEAF)	75	375	EDFA	15	G.655 (LEAF)	65	325	EDFA
3	G.655 (LEAF)	75	375	EDFA	16	G.655 (LEAF)	70	350	EDFA
4	G.655 (LEAF)	110	550	EDFA+DRA	17	G.655 (LEAF)	100	500	EDFA+DRA
5	G.655 (LEAF)	70	350	EDFA	18	G.655 (LEAF)	75	375	EDFA
6	G.655 (LEAF)	65	325	EDFA	19	G.655 (LEAF)	75	375	EDFA
7	G.655 (LEAF)	100	500	EDFA+DRA	20	G.652 (SMF)	70	1190	EDFA
8	G.655 (LEAF)	65	325	EDFA	21	G.652 (SMF)	65	1105	EDFA
9	G.655 (LEAF)	75	375	EDFA	22	G.655 (LEAF)	75	375	EDFA
10	G.655 (LEAF)	70	350	EDFA	23	G.655 (LEAF)	75	375	EDFA
11	G.655 (LEAF)	70	350	EDFA	24	G.655 (LEAF)	120	600	EDFA+DRA
12	G.655 (LEAF)	75	375	EDFA	25	G.652 (SMF)	75	1275	EDFA
13	G.655 (LEAF)	65	325	EDFA	*Total*		*1945*	*13145*	

Instead, Microsoft intercity network requirements are met with a simple line system optimized for coherent transmission, supporting largely point-to-point connections between cities. The system should allow for full add/drop of arbitrarily-shaped channels or super-channels at each of the terminal nodes, and should accept foreign wavelengths from any coherent source, whether originating from a traditional transponder, a pizza-box platform, or directly integrated on a layer 2/3 device (i.e., where no demarcation is required between packet and optical layers).

The fiber and line system in the Redmond lab are configured to emulate a sizable portion of Microsoft's North American backbone network, with enough G.655 NZ-DSF (Corning LEAF) and G.652 standard SMF (Corning SMF-28e LL) to light up bidirectional ~2000 km paths, for a total of ~4000 km fiber. The top portion of Figure 1a shows the line system configuration, which utilizes a colorless architecture. There are colorless mux/demux and flex-grid 20-degree ROADMs at network ingress and egress, and either 9-degree broadcast-and-select or 20-degree route-and-select flex-grid ROADMs after every fifth span, primarily for channel power balancing (these also allow for the option of channel add/drop at these nodes). The spans range in length between 65-120 km, with one span in every five long enough to require backward-pumped Raman amplification (either the second or fourth span, shown by the dotted "R" modules in Figure 1a) in addition to EDFA. A summary of the span fiber types, lengths, and associated amplification schemes are shown in Table 1 for the ~2000 km forward path. To achieve a full ~4000 km, the path is looped back on itself after span 25.

3. Coherent line card

The optical sources used in these measurements reside on a layer 2/3 modular switch card made by Arista (Figure 2), each of which has six embedded coherent ASICs and corresponding CFP2-ACO pluggable optical modules (see lower portion of Figure 1a; two line cards required, but shown conceptually as one). The line card integrates high performance 100-GbE Ethernet layer 2/3 switch silicon with wire-speed MACsec encryption and DSP silicon supporting PM-QPSK transmission and coherent detection over long-haul distances.

The analog coherent pluggable modules used were CFP-ACO OIF class 2 variants (per the OIF Implementation Agreement) from multiple vendors. They are based on maturing III-V processing technologies that enable integration of the tunable laser source with the nested polarization multiplexed IQ Mach-Zehnder modulator (MZM). Monolithic integration of high power laser sources and low drive-voltage modulators offers a significant reduction in power consumption, which is required for the CFP2 form factor housing this technology.

The DSP coherent ASICs are located on the linecard in the front panel vicinity. While this de-coupled configuration provides operational ease in swapping out modules and allows for vendor diversity, it comes at the cost of more careful compensation of the electrical channel loss of the linecard RF traces, CFP2 connector, and the module's own E/O and O/E responses [4]. To achieve this separation, yet mitigate the electrical interface impairments, the DSP

Figure 2. Arista's layer 2/3 coherent DWDM line card

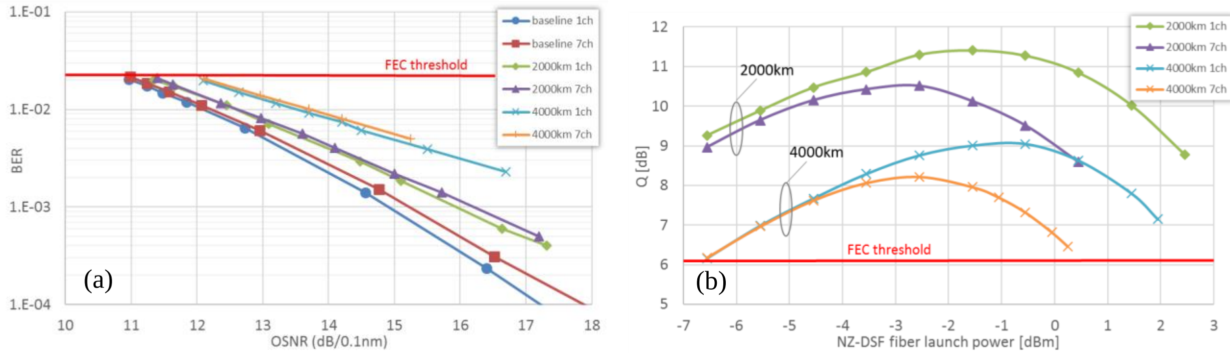

Figure 3. (a) BER vs OSNR results, (b) Launch power optimization

egress-side 40-tap FIR filter coefficients are carefully calculated by time-domain convolution of the complete RF channels' inverse S21 responses with the theoretical root raised cosine (RRC) sampled impulse response. An 8-bit resolution DAC generates the final analog Nyquist-shaped waveform feeding the CFP2 modules' linear drivers.

4. Results

For this experiment, two Arista line cards and 7 CFP2-ACO alpha units were employed to generate 7 channels of 32 GBaud Nyquist-shaped PM-QPSK signals at 37.5 GHz channel spacing (Figure 1b). A RRC with roll-off factor of 0.2 was used for all the 37.5 GHz-spaced channels as it provides the best compromise between maximum spectral confinement and minimum BER penalty due to jitter that may exceed the DSP ingress-side timing recovery tolerance. During calibration, no significant OSNR penalty was measured between Nyquist-shaped signals with 0.2 and 1.0 roll-offs, confirming that RF channel loss pre-compensation was sufficient in the full [0, 16] and [16, 32] GHz frequency ranges (Figure 3a "baseline" curves). As seen in the optical spectrum (Figure 1a inset and Figure 1b), some carrier leakage, with varying severity, affected a few neighboring channels, suggesting that further improvements in bias control algorithms are still possible.

After being characterized back-to-back, the signals were launched first into the 2000 km forward path to measure BER performance, and then looped back through the reverse path fiber to achieve the full 4000 km transmission. Launch power was swept over a range to find the optimum before making BER versus OSNR measurements. Figure 3b shows Q-factor versus launch power per channel into NZ-DSF (launch powers into the SSMF spans were nominally 3 dB higher than powers shown on the x-axis). A clear nonlinear impact is seen when going from single-channel to multi-channel transmission for both distances, with a Q-penalty of nearly a dB and a reduction in optimum launch power ranging from 1 to 2 dB. Next, BER versus OSNR measurements were performed at the optimum launch powers for each case (Figure 3a). After 2000 km, there is about 0.5 dB OSNR penalty at 1e-2 for both single-channel and multi-channel transmission, and for 4000 km, this penalty increases to about 1.3 dB. Even at 4000 km, the system was operating with over 3 dB of OSNR margin from the coherent DSP SD-FEC threshold.

5. Conclusion

Long-haul transmission was demonstrated over a flex-grid open line system employing a fully colorless architecture, with 20- and 9-degree ROADMs and hybrid Raman/EDFA amplification. The sources resided on a layer 2/3 modular switch line card with integrated coherent DSP and CPF2-based analog coherent optical modules. The line card generated Nyquist-shaped 32 GBaud PM-QPSK signals at 37.5 GHz channel spacing, achieved with a RRC function with roll-off of 0.2, with virtually no penalty. Transmission of up to 4000 km of mixed NZ-DSF/SSMF fiber was shown with only 1.3 dB OSNR penalty at a BER of 1e-2 and over 3 dB of OSNR margin from the SD-FEC limit. All of the CFP2-ACOs used were alpha units and were in some cases sub-optimally performing (e.g., carrier leakage). As ACO vendors continue to optimize for linear applications, such as Nyquist shaping and 200G 16QAM, this will pave the way for higher capacity long haul and metro data center interconnects in the near future. In parallel, the open line concept will enable this type of vendor and platform diversity for data center scale deployment, fostering more competition in the marketplace, and forging the path toward true SDN-enabled optical networking.

6. References

[1] www.lightwaveonline.com/articles/2015/09/web-2-0-capex-increases-offset-service-provider-capex-declines-in-1h15-lightcounting.html
[2] see e.g.: www.advaoptical.com/en/products/scalable-optical-transport/fsp-3000-cloudconnect.aspx; www.ciena.com/products/waveserver; www.infinera.com/products/cloud
[3] J. Cox, "SDN Control of a Coherent Open Line System", Proc. OFC, M3H.4 (2015).
[4] T. Duthel et. al., "Challenges with Pluggable Optical Modules for Coherent Optical Communication Systems", Proc. OFC, W3K.2 (2014).