Real-Time Single-Carrier Coherent 100 Gb/s PM-QPSK Field Trial

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***Abstract*—The development of 100 Gb/s transponder technology is progressing rapidly to meet the needs of next-generation optical/IP carrier networks. In this paper, we describe the upgrade of an installed 10 Gb/s field system to 100 Gb/s using a real-time single-carrier, coherent 100 Gb/s polarization-multiplexed quadrature-phase-shift keyed channel. Performance sufficient for error-free operation after forward-error-correction was achieved over installed 900 and 1800 km links, proving the viability of 100 Gb/s upgrades to most installed systems. Excellent tolerance to fiber polarization mode dispersion and narrowband optical filtering demonstrates the applicability of this technology over the majority of installed fiber plant and through existing 50 GHz reconfigurable optical add/drop multiplexers.**

***Index Terms*—Communication system performance, optical fiber communication, polarization multiplexing, quadrature phase-shift keying, signal processing.**

I. Introduction

A RECENT trend to keep up with growing bandwidth demands in core networks has been the upgrade of existing links designed for 10 Gb/s channels with 40 Gb/s channels [1]. As network demands continue to grow, carriers are exploring the possibilities for further network upgrades. With 100 Gb/s on the horizon, the important question arises: is it practical to upgrade these existing networks with 100 Gb/s channels? A critical enabler for the 40 Gb/s network upgrades was the introduction of advanced modulation formats, allowing the retrofit of 40 Gb/s data channels into existing 10 Gb/s dense wavelength-division multiplexed (DWDM) transport systems. Improved spectral efficiency to meet Internet and Internet Protocol television (IPTV) bandwidth growth is again expected to be a key stimulus for 100 Gb/s line rates, with support of 50 GHz channel spacing again a key requirement. To facilitate ease of networking, tolerance to transmission through many reconfigurable optical add/drop multiplexer (ROADM) nodes is also essential, as each ROADM permits each wavelength channel to be optically added, dropped, or passed through the node. In highly meshed metro networks, express channels will often transit through a large number of ROADMs, where each ROADM acts as a narrowband optical filter, constraining the signal quality of the DWDM signals. The spectral width of 100 Gb/s coherent polarization-multiplexed quadrature-phase-shift-keyed (PM-QPSK) channels is sufficiently narrow to allow use of powerful forward error correction (FEC) with a 20% overhead [2]–[4]. For this case, the resulting spectral width is about ± 21 GHz for an unfiltered signal and ± 16 GHz for a filtered signal traversing a pair of 50 GHz Mux/Demux. The FEC with higher coding gain enables improved optical SNR (OSNR) sensitivity and thus the possibility for longer propagation reach between optical-to-electrical-to-optical (OEO) regeneration points and thereby reduced network cost. Although the FEC increases the line rate, the symbol rate and spectral width of the signal, measurements have shown that the signal still can propagate through multiple cascaded 50 GHz ROADMs with adequate performance [6].

This paper describes test results, obtained in a laboratory and then in a field environment, of a real-time single-wavelength, coherent PM-QPSK system, indicating the suitability of this technology for upgrades of backbone DWDM networks [7]. For clarity, while these transport systems are colloquially referred to as "100 G," their purpose is to transport a payload of 100 Gb Ethernet across long distances (up to 2000 km). To do so, the overhead needs to be increased (such as the FEC mentioned earlier and other mappings), leading to higher line rates. In our case, the line rate was 126.5 Gb/s.

II. System Description

A prototype development system using state-of-the-art high-speed analog-to-digital converters (ADCs) (used also in digital sampling oscilloscopes) and a field-programmable gate array (FPGA) farm for digital data processing was implemented to enable design verification and assist in product development. Key functional blocks such as carrier frequency and timing recovery, electrical dispersion compensation of chromatic dispersion (CD) and polarization mode dispersion (PMD), carrier phase estimation (CPE), and overhead for high-coding-gain FEC were included. The primary purpose of this system was to test and iterate the modem logic prior to taping out an application-specific integrated circuit (ASIC) chip, as using FPGAs allows the designer to reprogram the logic to optimize

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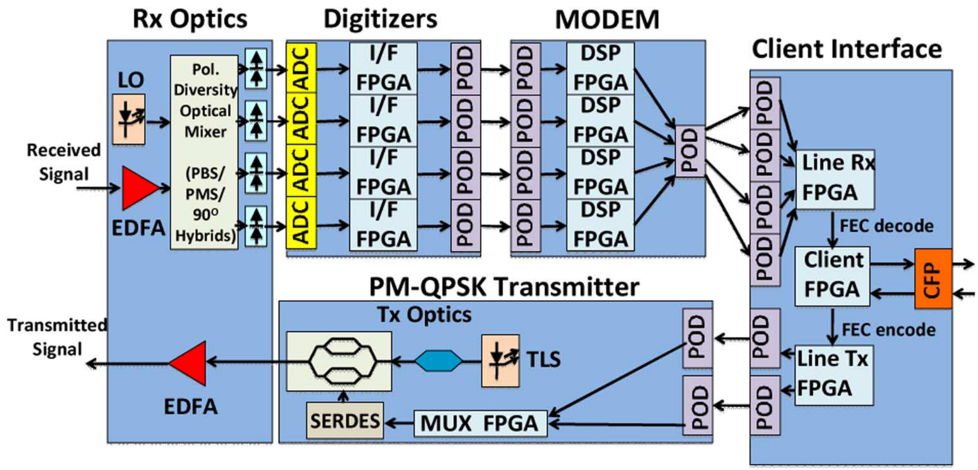

Fig. 1. Block diagram of transponder. LO = local oscillator, PBS = polarization beam splitter, PMS = polarization maintaining splitter, TLS = tunable laser source, POD = parallel optical (interface) device, I/F = interface. The POD is used for transporting multihundred Gb/s data in between functional blocks in a parallel fashion.

performance prior to finalizing the ASIC netlist (gate level description). FPGAs offer a more advanced level of performance evaluation beyond using offline-processing techniques that capture short bursts of data on an oscilloscope and later process the captured data on a computer. A key challenge for the FPGA-based prototype system was to stream the data at 126.5 Gb/s in real-time and fully process all data at the line rate in the modem, requiring sophisticated synchronization of the ADCs and FPGA farm.

The real-time single-carrier, coherent PM-QPSK system block diagram is shown in Fig. 1. The symbols were carved into 67% duty-cycle return-to-zero (RZ) pulses. Using an RZ-pulse format rather than non-return-to-zero (NRZ) provides greater tolerance to fiber nonlinear effects, improving propagation performance [8]. The coherent receiver system consisted of four high-speed ADCs, having an effective number of bits (ENOBs) of $\sim$4.2 bits, to digitize the data followed by an FPGA farm to perform the modem functionalities [5]. The sampling rate of the ADC is $\sim$40 GSa/s and the measured analog bandwidth is $\sim$15 GHz. A single "butterfly" 2×2 equalizer, consisting of eight taps, was used for polarization state demultiplexing and CD and PMD compensation. The equalizer tap length was restricted by the FPGA size and parallel routing. The limited number of taps in the equalizer for the FPGA-based prototype translates into a much lower CD tolerance (approximately $\pm$400 ps/nm) than expected for an ASIC-based solution, which can be designed to have hundreds of taps. Therefore, the field trial did require the use of dispersion compensating fiber (DCF) in the link. The data rate used in the trial was 126.5 Gb/s (31.625 Gbaud), corresponding to the 100 GE payload, mapped into the OTU4 frame plus 20% overhead for high-coding gain FEC [2]–[4]. Both $2^{15}-1$ and $2^{31}-1$ pseudorandom bit sequences (PRBSs) were used, and negligible pattern dependence was observed after transmission. Pre-FEC bit error ratio (BER) data were collected via an integrated BER analyzer measuring the aggregate 126.5 Gb/s signal after the DSP block. Differential encoding and decoding were utilized for the results presented here to improve the performance in the presence of ON/OFF-keyed neighboring signals.

III. Laboratory Results

A. OSNR Test Results

Fig. 2 shows the measured BER versus OSNR taken back-to-back where the amplified spontaneous emission noise loading has been added between two optical filters (Mux and Demux) each with a 3 dB bandwidth of 40 GHz, having a filter shape of super Gaussian order 2. The OSNR is reported with a 0.1 nm noise bandwidth. Shown together in Fig. 2 is a theoretical OSNR curve for 127-Gb/s coherent PM-QPSK with differential decoding as a comparison. As can be seen, there is $\sim$3.7 dB OSNR penalty at 1e-3 BER. The OSNR sensitivity of the FPGA-based prototype has some additional implementation penalties compared with the performance expected of an ASIC-based solution. The prototype system implementation penalties are a result of poorer ADC ENOBs and lower gate count available in the FPGA farm to implement the DSP compared to an ASIC, limiting the number of equalizer taps and quantization in the modem. The prototype performance allows for testing of fiber propagation and the modem algorithms at full line rate, which is its primary purpose.

B. PMD Test Results

In order to test the PMD tolerance of the 100 Gb/s prototype system, the 100 Gb/s PM-QPSK signal was transmitted through several lengths of polarization maintaining fiber (PMF) in the testbed. The resulting Q penalty was derived by monitoring the pre-FEC BER (and converting to Q in dB using the relationship $Q = 20\log[\sqrt{2}\mathrm{erfc}^{-1}(2\mathrm{BER})]$, where erfc $^{-1}$ is the inverse complementary error function) and by comparing the result to that without any PMF inserted. The 100 Gb/s PM-QPSK signal was noise-loaded to a fixed OSNR of 19 dB/0.1 nm for each test case. A polarization controller was used at the input of the PMF to vary the state of polarization (SOP) of the signal hitting the coherent receiver. The results are shown in Fig. 3 for the worst case launch SOP into the PMF. Although the FPGA based 100 Gb/s prototype does have a somewhat larger residual PMD penalty than that expected with the ASIC-based product, primarily due to limited equalizer tap length, these results still

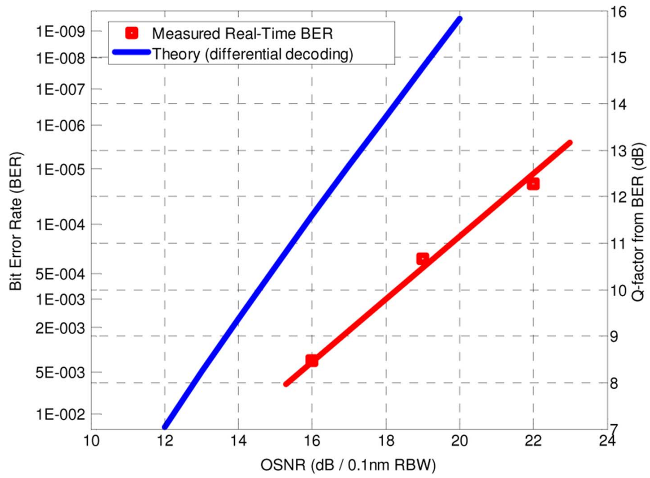

Fig. 2. Measured back-to-back BER performance versus OSNR of the 126.5 Gb/s coherent PM-QPSK systems with differential decoding.

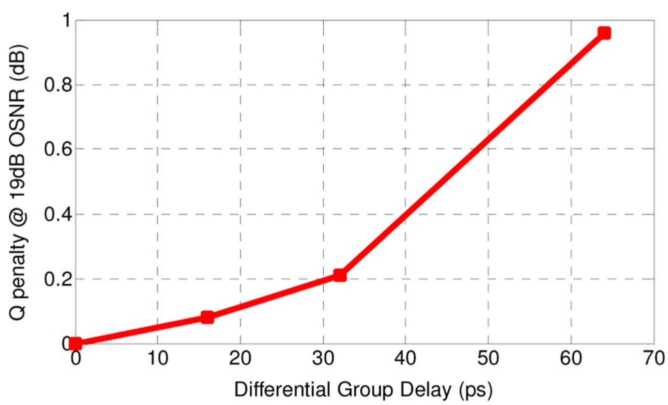

Fig. 3. DGD tolerance of the real-time 126.5 Gb/s PM-QPSK system.

demonstrate very high PMD tolerance of the real-time 100 Gb/s PM-QPSK signal, i.e., larger than the PMD tolerance of 10 Gb/s OOK signals, therefore showing the applicability of this 100 Gb/s technology for older generations of fiber plant with up to 20 ps of mean PMD.

C. Optical Filtering Test Results

The tolerance of the 100 Gb/s PM-QPSK signal to optical filtering was measured by replacing the PMF with a tunable-bandwidth optical filter [6]. The optical filter shape approximates a fourth-order super-Gaussian profile at its widest passband, and the full-width at half-maximum (FWHM) was varied from 44 to 25 GHz. The filter shape gradually reduces to a second-order super-Gaussian profile as the bandwidth is decreased to 25 GHz. For each test case, noise-loading was used to keep the BER constant at 10^{-3} and the OSNR penalty, reported at a resolution bandwidth of 0.1 nm, is derived, normalized to the widest bandwidth case. The results are shown in Fig. 4. These results indicate that the optical filtering bandwidth can be as low as 30 GHz with negligible penalty and that at 27 GHz FWHM the measured OSNR penalty was approximately 0.5 dB at 10^{-3} BER. In Fig. 5, the tolerance to the center frequency drift of the filter is

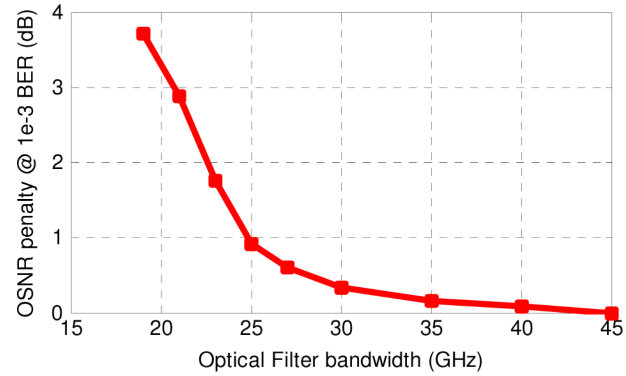

Fig. 4. Measured optical filtering tolerance of the real-time 126.5 Gb/s PM-QPSK system. The optical filter shape is a fourth-order super Gaussian at 45 GHz bandwidth and gradually reduces to second order at 20 GHz bandwidth. The OSNR penalty is reported at a fixed BER of 1e-3.

also investigated. The measured results indicate that for a nominal 3 dB bandwidth of 45 GHz, the frequency detuning tolerance can be as large as +12 GHz, due to the high spectrally efficiency PM-QPSK format, as indicated by the inset showing the signal spectrum as well as the filter shape profile. Both results indicate that 100 Gb/s PM-QPSK signals are suitable for 50 GHz-DWDM systems.

D. ROADM Tolerance Test Results

In modern transmission systems, ROADMs are commonly employed to facilitate rapid reconfiguration of the network. The ability to pass through a large number of ROADMs with negligible penalty allows a simplified network design. The number of ROADMs that can be passed depends on both the optical bandwidth of the device and the filter shape. Modern ROADMs have filter shapes ranging from second- to fourth-order super-Gaussian, depending on the particular technology employed. Their insertion loss spectral shape *IL(f)* can be described by

$$IL(f) = \exp\left(-2^{2n}\ln 2\left(\frac{f}{B_0^i}\right)^{2n}\right) \tag{1}$$

where B_0^i is the individual filter bandwidth (FWHM) and n the order of the super-Gaussian. The tolerance of 100 Gb/s PM-QPSK channels to cascaded ROADMs of varying filter shapes is illustrated in Fig. 6. B_0^i of 45 GHz, a 0.5 dBQ penalty allocation, and a 126.5 Gb/s data rate are assumed. The simulation results indicate that greater than 10, 20, and 40 ROADMs can be passed for $n = 2, 3$, and 4 super-Gaussian filter shapes, respectively, with low penalty. Also shown in Fig. 6 are experimentally measured bandwidths for cascades of an increasing number of commercially available WSSs (to emulate a ROADM node consisting of a passive splitter for the drop functionality and a WSS for the add functionality). The fact that the 3-dB bandwidths of the cascaded WSSs are as large or larger than the 3-dB bandwidth of the fourth-order super-Gaussian indicates that a 100 Gb/s PM-QPSK could be suitable to the ROADM cascades for 50 GHz channel spacing. The simulation and experimental details are provided in [6].

The performance of 100 Gb/s coherent PM-QPSK channels over a transmission link with ROADMs has also been

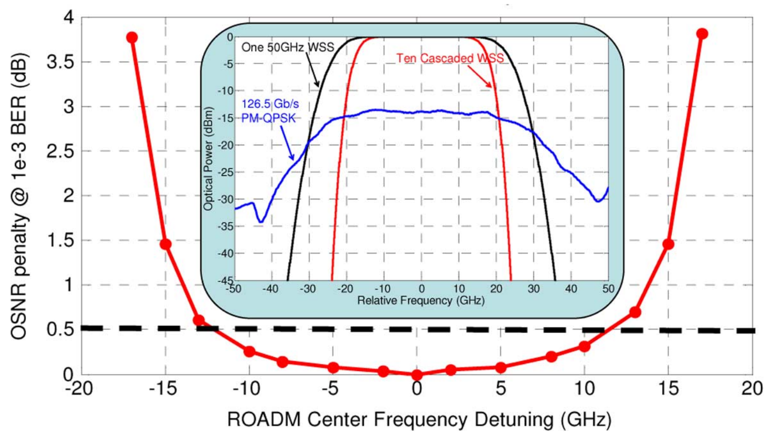

Fig. 5. Measured tolerance to the detuning of the filter center from the real-time 126.5 Gb/s PM-QPSK carrier frequency. The filter bandwidth is fixed at 45 GHz. The OSNR penalty is reported at a fixed BER of 10^{-3}. Both the signal spectrum as well as the filter shape profile are added.

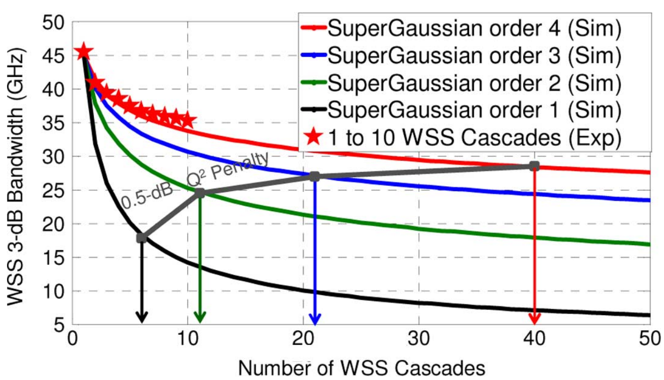

Fig. 6. Simulation data showing the tolerance of 126.5 Gb/s coherent PM-QPSK to cascades of ROADMs with various filter shapes. The simulations assume each ROADM has 3 dB bandwidth of 45 GHz with no frequency offset. The *y* axis indicates the effective optical bandwidth as a function of the number of cascaded ROADMs. The vertical lines indicate the number of cascaded ROADMs the 126.5 Gb/s PM-QPSK channels can tolerate, based on a 0.5 dB Q penalty. The stars show measured 3 dB BW of cascades of increasing numbers of WSSs.

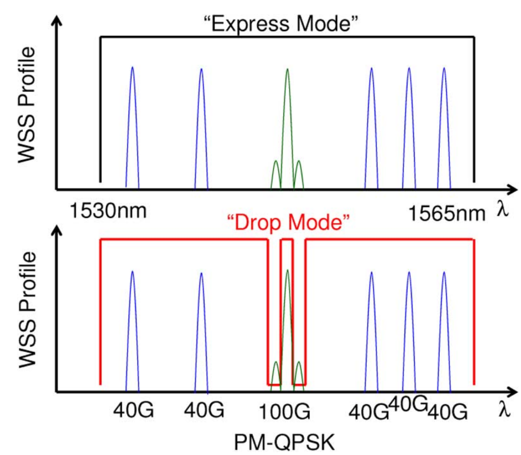

Fig. 7. Two profiles of WSS cascades emulating "express" and "drop" modes, which are compared in the 1500-km transmission experiment.

experimentally measured using offline processing [6]. In these experiments, 10 WSS modules were incorporated into a fiber transmission link to investigate the interaction between filtering and linear/nonlinear fiber impairments. The 1500 km link is described in [6], with the 10 WSS configured to have either of the two modes, as shown in Fig. 7. In the "Express Mode" all channels are transmitted through the ROADM without optical filtering, whereas in the "Drop Mode," two adjacent 50 GHz channels are blocked, emulating the worst case filtering from the cascade of ten WSS. Since near-identical optical powers are passed through the cascaded WSSs for these two WSS profiles, all 15 EDFAs are operating at the same condition, and thus the OSNRs after 1500 km transmission are the same for these two modes. For 0 dBm fiber launch power, the OSNR at the end of the link is 18.4 dB. Fig. 8 shows the transmission performance as a function of fiber launch power, which is the launch power to all the SMF spans in the link. At low launch power from -4 to -2 dBm, the "Express" and "Drop" modes perform identically, agreeing with the linear cascade results. At 0 dBm optimal launch, only 0.3 dB additional penalty from the "Drop" mode is observed, which can be attributed to the filtering-induced pattern-dependent power fluctuations, resulting in higher nonlinear penalty. At launch powers from 2 to 5 dBm, the difference gradually diminishes as intrinsic fiber nonlinear effects start to dominate. This small additional penalty is due to the large effective bandwidth (36 GHz) after 10 cascaded ROADMs, as indicated by the near-identical signal quality shown by the two inset QPSK constellations (one of the two polarizations) in Fig. 8. The error vector magnitudes (EVMs), defined as the normalized distances between the ideal constellation and the symbol positions, are -12.3 and -12 dB for these two inset constellations, respectively.

IV. Field Trial Link Description

While many tests can be adequately performed in the laboratory, field trials impose more rigorous requirements on the equipment. For example, the only communication between network elements must be over the transmission link; no management signaling over side-channels can occur, and no clock or other synchronization signal can be shared by the two ends. The turn-up procedure, which with a DSP-based coherent receiver includes blind equalization of CD and PMD, must deal with the unknown characteristics of the transmission line. During operation, the system must automatically adjust for changes in the

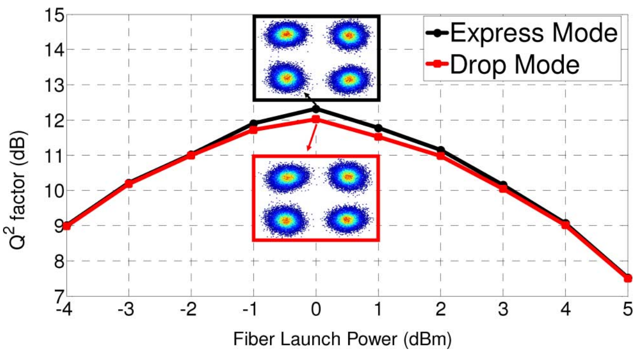

Fig. 8. 1500-km transmission comparison of linear/nonlinear performance with and without cascaded WSS filtering [6]. Less than 0.3 dB Q penalty at optimal launch power shows the nonlinear robustness of 126.5 Gb/s PM-QPSK signals over ten 50-GHz WSS's.

CD (and therefore the propagation delay) and the PMD, both slow and fast. And finally, many aspects of the high-speed optoelectronic components and circuits vary with temperature. By housing each end of the system in different cities, the temperatures are not only different, but vary independently, further stressing the hardware design.

This field trial was conducted over a portion of the existing AT&T network between Florida and Louisiana. This 900 km link consisted of 12 spans of SSMF, where the average span length was 78 km and the average span loss was 16.5 dB, typical of fiber spans in a long-haul terrestrial network. The average PDL in the link is ~0.7 dB. The line system deployed on the link is optimized for 10 and 40 Gb/s and began carrying real service in the AT&T network soon after the trial was completed. In other words, the link was not installed or optimized in any way for the purpose of the 100 Gb/s trial. In addition, the optical link control was running in automated mode, dynamically adjusting the amplifiers to be in the optimum operating point. Standard two-stage C-band erbium-doped fiber amplifiers (EDFA) were used to compensate the fiber loss. The CD of the transmission line was compensated with a DCM at the midstage of each EDFA to provide approximately 96% compensation of each fiber span. For the 900 km link, there was no precompensation of the CD at the system input, nor was there further optimization of the CD before the receiver using optical dispersion compensation. The average PMD of the transmission line was measured to be 0.04 ps/(km$^{1/2}$). With 0 dBm launch power for the 100 Gb/s channel, after 900 km, the received OSNR was approximately 21 dB, and approximately 18 dB for the 1800 km optical loop-back link. Fig. 9 shows a photograph of the 100 Gb/s PM-QPSK prototype system in the field.

V. Field Trial Results

A. 900 km Link

We measured the transmission performance of the single 100 Gb/s channel for both directions of the 900 km link, and as expected based on the very similar properties of the fiber spans and EDFAs, the performance was almost identical. For the single 100 Gb/s channel, as shown in Fig. 10, we measured the BER after 900 km transmission as the launch power into each SSMF span was varied. The launch power into each DCM was held constant at 0 dBm, which is known to be suboptimal, but was a limitation of the trial. Fig. 10 shows that the optimal fiber launch power was around 1 dBm, with the range of 0 to 3 dBm resulting in similar performance. Performance at a pre-FEC BER level below 10^{-2} yields error-free (10^{-15}) post-FEC operation using the latest 20% overhead hard- or soft-decision FEC algorithms [2]–[4]. For the 900 km link, the 100 Gb/s channel passed through three ROADM nodes (one at each terminal site, plus one in the middle).

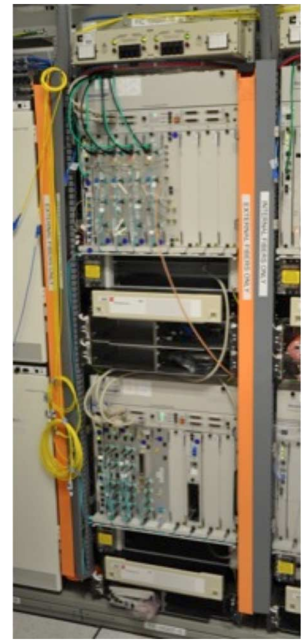

Fig. 9. Photograph of the 126.5 Gb/s coherent PM-QPSK prototype system in the field.

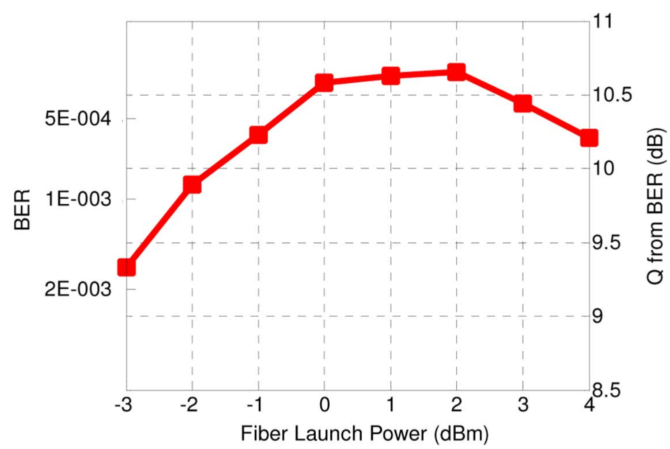

Fig. 10. Single-channel BER performance of the 126.5 Gb/s coherent PM-QPSK signal as a function of channel launch power into the transmission fiber spans for the 900 km link.

In addition to testing the tolerance of the single 100 Gb/s channel to launch power variation, it is important to understand the impact of nonlinear impairments caused by adjacent channels, as could occur in a DWDM system with channels carrying 10, 40, or 100 Gb/s. Figs. 11 and 12 show, respectively, the effect of adjacent, 50 GHz symmetrically spaced 40 Gb/s DPSK and 10 Gb/s OOK channels on the 100 Gb/s channel in the center of the group. The launch power for all channels was

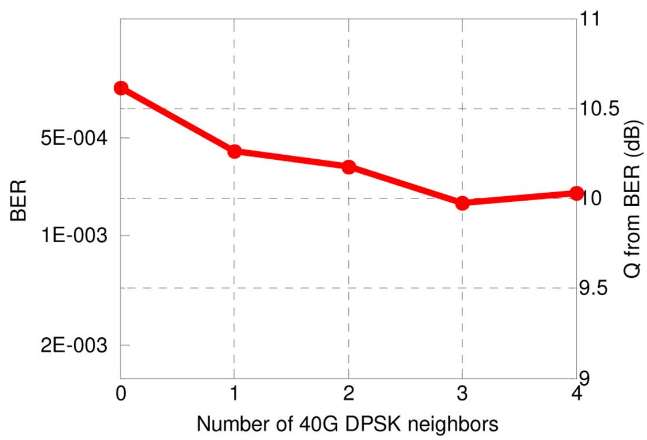

Fig. 11. Performance of the 126.5 Gb/s PM-QPSK channel after 900 km transmission as a function of the number of adjacent 40 Gb/s DPSK channels spaced at 50 GHz. The fiber launch power was 0 dBm/channel.

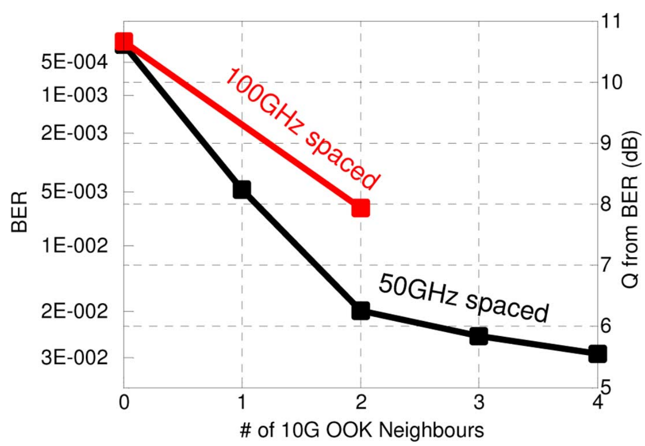

Fig. 12. Performance of the 126.5 Gb/s PM-QPSK channel after 900 km as a function of the number of adjacent 10 Gb/s OOK for both 50 and 100 GHz spacing. The fiber launch power was 0 dBm/channel.

0 dBm/channel for these measurements. Pre- and postcompensation of -480 and -200 ps/nm, respectively, were added to the link to optimize the 10 and 40 Gb/s channel performances, resulting in a nominal 0 ps/nm residual dispersion after 900 km. With up to four neighboring 40 Gb/s DPSK channels at 50 GHz spacing, the Q penalty of the 100 Gb/s channel was within 0.6 dB compared to its single-channel performance. However, the impact of the 50 GHz-spaced 10 Gb/s OOK channels on the 100 Gb/s PM-QPSK channel was severe and can be attributed to the strong nonlinear cross-phase modulation. Increasing the channel spacing to 100 GHz alleviated the degradation somewhat, as shown in Fig. 12. A CPE filter length of 20 symbols was used for all measurements in this paper. It is expected that reducing the CPE length would improve the 100 Gb/s performance with adjacent 10 and 40 Gb/s channels [8]. We also measured the impact of a 100 Gb/s channel placed between two 100 GHz-spaced 40 Gb/s DPSK or 10 Gb/s OOK channels for the 900 km link. As summarized in Table I, the results indicate that the 100 Gb/s channel has little impact on the performance of either the 10 or 40 Gb/s neighboring channels.

TABLE I
BER PERFORMANCE OF 10 OR 40 GB/S CHANNELS OVER THE 900 KM LINK WITH AND WITHOUT AN ADJACENT 100 GB/S CHANNEL

BER	Without 100 Gbit/s	100Gbit/s @ 194.5 THz
10 Gbit/s OOK @ 194.45 THz	8.20E-9	4.30E-8
10 Gbit/s OOK @ 194.55 THz	2.80E-8	2.50E-8
40 Gbit/s DPSK @ 194.45 THz	4.00E-11	1.20E-10
40 Gbit/s DPSK @ 194.55 THz	6.00E-9	4.30E-7

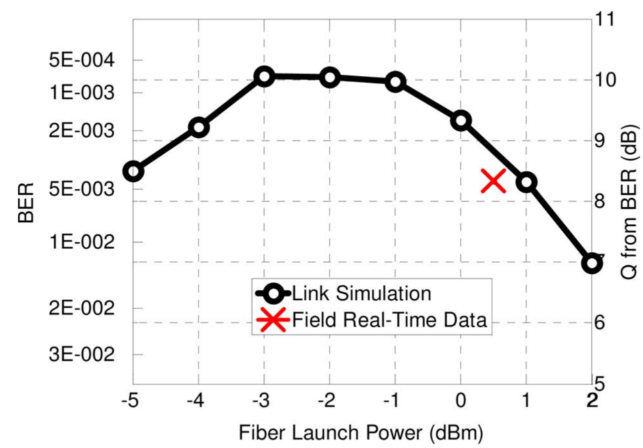

Fig. 13. Measured BER versus fiber launch power of the 126.5 Gb/s PM-QPSK channel over the 1800 km loop-back link overlaid on simulated performance.

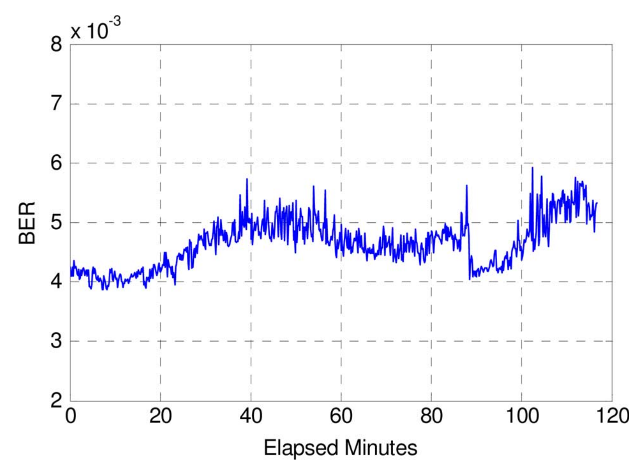

Fig. 14. Measured BER variation of the 126.5 Gb/s PM-QPSK channel over 2 h for the 1800 km loop-back link, operating at 0.5 dBm per channel launch power into the transmission fiber spans.

B. 1800 km Optical Loop-Back Link

We also measured the performance of the 100 Gb/s channel over an 1800 km link with five ROADM nodes by optically looping back the signal in Louisiana. Precompensation and postcompensation of -480 and -450 ps/nm, respectively, were used for the link, resulting in a nominal residual dispersion of 0 ps/nm. The results are summarized in Figs. 13– 15. Fig. 13 compares the measured BER of the single 100 Gb/s channel

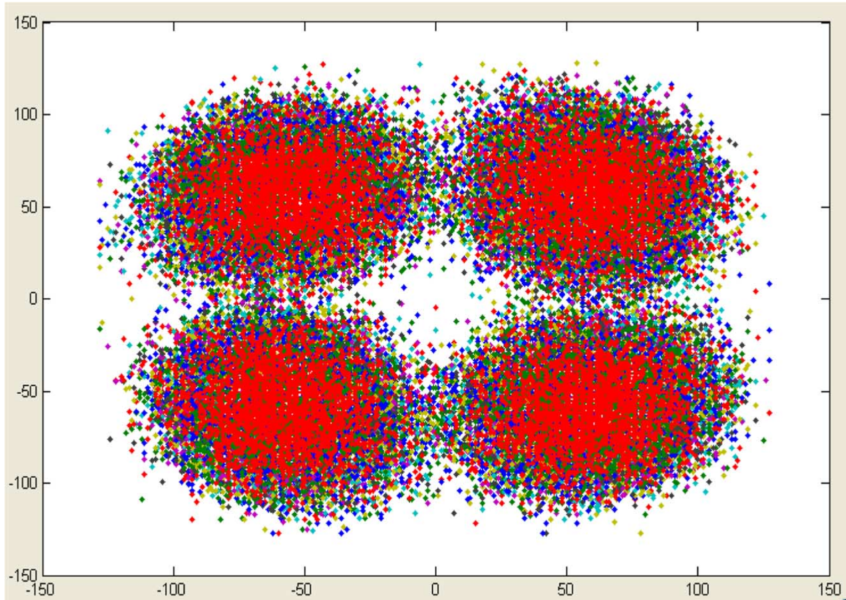

Fig. 15. Measured constellation of the 126.5 Gb/s PM-QPSK modem (prior to the slicer) after 1800 km, with a fiber launch power of 0.5 dBm/channel. The EVM is -8.31 dB.

at one launch power to simulation results for several launch powers. The optimal launch power for the 1800 km link, restricted by the fixed 0 dBm launch power into the DCM, was found to be around 0.5 dBm, resulting in the best measured BER of 4×10^{-3}. We also simulated the single 100 Gb/s channel performance over the 1800 km link using offline processing and varied the channel launch power into each fiber span while maintaining the DCM launch power at 5 dB lower than the transmission fiber launch power. As can be seen from Fig. 13, simulation predicts a >1.5 dBQ improvement in performance of the 100 Gb/s channel over this 1800 km link with the optimization of both fiber and DCM launch power. Fig. 14 shows the measured BER of the 100 Gb/s channel with 0.5 dBm fiber launch power over a 2-h observation window. During that time, the BER was stable around 4.5×10^{-3}; such a pre-FEC BER will yield error-free performance after FEC decoding [2]–[4]. Fig. 15 shows the constellation at the modem output after 1800 km transmission (at 0.5 dBm fiber launch power). The EVM for the received constellation is -8.31 dB.

VI. Summary

We have discussed the primary drivers for transmission systems operating at 100 Gb/s per wavelength channel and summarized the advantages of the polarization-multiplexed QPSK modulation format as a cost-effective and practical 100 Gb/s transponder technology. We have presented laboratory measurements of the tolerance of a real-time 100 Gb/s PM-QPSK channel to PMD and optical filtering and have discussed the results of the first demonstration of a network upgrade of an existing 10/40 Gb/s terrestrial link with a real-time single-carrier coherent 100 Gb/s PM-QPSK channel. The measured pre-FEC BERs were sufficient over 900 and 1800 km links in AT&T's installed network for error-free performance after FEC, proving that 100 Gb/s-channel upgrades to existing 10 and 40 Gb/s DWDM systems are possible and practical in most cases, improving the channel capacity by up to an order of magnitude.

References

[1] M. Birk, C. Skolnick, R. Curto, R. Marlieb, T. J. Schmidt, and R. Saunders, "Field trial of a 40 Gbit/s PSBT channel upgrade to an installed 1700 km 10 Gbit/s system ," presented at the Optical Fiber Communication 2005, Los Angeles, CA, Paper OTuH3.

[2] I. B. Djordjevic, O. Milenkovic, and B. Vasic, "Generalized low-density parity-check codes for optical communication systems," *J. Lightw. Technol.*, vol. 23, no. 5, pp. 1939–1946, May 2005.

[3] M. Scholten, T. Coe, J. Dillard, and F. Chang, "Enhanced FEC for 40 G/100 G," in *Proc. ECOC*, 2009 [Online]. Available: http://conference.vde.com/ecoc-2009/programs/documents/ws1_06_mikescholten.pdf

[4] F. Chang, K. Onohara, and T. Mizuochi, "Forward error correction for 100 G transport networks," *IEEE Commun.Mag.*, vol. 48, no. 3, pp. S48–S55, Mar. 2010.

[5] M. Taylor, "Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 674–676, Feb. 2004.

[6] B. Zhang, C. Malouin, S. Liu, T. J. Schmidt, L. Guangxun, P. Wang, H. Washburn, and J. Yuan, "Penalty-free transmission of 127-Gb/s coherent PM-QPSK over 1500-km of NDSF with 10 cascaded 50-GHz ROADMs," in *Proc. OFC/NFOEC*, 2010, pp. 1–3, Paper NTuC5.

[7] M. Birk, P. Gerard, R. Curto, L. Nelson, X. Zhou, P. Magill, T. J. Schmidt, C. Malouin, B. Zhang, E. Ibragimov, S. Khatan, M. Glavanovic, R. Lofland, R. Marcoccia, R. Saunders, G. Nicholl, M. Nowell, and F. Forghieri, "Field trial of a real-time, single wavelength, coherent 100 Gbit/s PM-QPSK channel upgrade of an installed 1800 km link," in *Proc. OFC/NFOEC*, 2010, pp. 1–3, Paper PDPD1.

[8] M. Alfiad, D. van den Borne, T. Wuth, M. Kuscherov, B. Lankl, C. Weiske, E. de Man, A. Napoli, and H. de Waardt, "Effect of carrier phase estimation for 111 Gbit/s POLMUX-RZ-DQPSK equalization in presence of 10.7 Gbit/s OOK neighbours," in *Proc. LEOS Summer Topicals*, 2008, pp. 175–176, Paper WE 1.3.

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