Invited Paper

Scaling Technologies for Terabit Fiber Optic Transmission Systems

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ABSTRACT

The past decade has seen profound changes not only in the way we communicate, but also in our expectations of what networks will deliver in terms of speed and bandwidth. The coming decade promises to demand more capacity and bandwidth in these networks and it is in this context that we present our work on scaling technologies for terabit fiber optic transmission systems. We discuss several topics that focus on increasing capacity in existing and next generation long-haul and metro fiber optic transmission systems that will carry tens to hundreds of terabits and will be based on coherent optical receivers.

Keywords: Scaling technologies, terabit fiber optic systems capacity, ultra-high bit rate, transport networks, multiaccess networks, pulse shaping and equalization, coherent optical orthogonal frequency division multiplexing (CO-OFDM), burst-mode clock and data recovery circuits (BM-CDRs)

1. INTRODUCTION

Having experienced constant growth for numerous decades, fiber optic system capacities are increasing exponentially with the plethora of data services—most notably by heavily data-centric users[1]—that drive the network traffic growths between 40 and 90 percent per year.[2] In particular, over the last 15 years there has been an increase by more than three orders of magnitude in the capacity of fiber optic networks, resulting in a proportional decrease in the cost to transport data across transport and multiaccess networks.[3]

In this paper, we present our work on ultra-high bit rate optical transport and multiaccess networks, which is based on interconnected research themes and projects that explore key issues associated with increasing bandwidth on these fiber optic networks. More specifically, we investigate pulse shaping and equalization techniques for transport networks, and demonstrate novel receivers for multiaccess networks. Within this context, we also review the scaling technologies and discuss the challenges for the next generation of both long-haul and metro networks.

1.1 Transport Networks

Transmission systems employing advanced modulation formats with channel capacities of 40 Gb/s are widely deployed today. In 2005, 100 Gigabit Ethernet (100GE) was demonstrated in the laboratory.[4,5] As of 2010, major vendors have announced 100-Gb/s products from chip sets to client interfaces to router ports to optical transport gear.[2] Major carriers have also performed end-to-end field trials using prototype 100-Gb/s equipment,[6,7] with significant commercial deployment of 100-Gb/s technology expected to take place during the remainder of 2011. In addition, the IEEE P802.3ba Ethernet Task Force has recently completed the standardization of local area networking (LAN) interfaces for 100GE. With 100-Gb/s systems now a commercial reality, the community has recently started to look at technologies beyond 100 Gb/s. With optical transmission system channels going from 10 Gb/s to 100 Gb/s and with total system capacity increasing from 1 Tb/s to 10 Tb/s, we are now poised to take on a next order of magnitude toward terabit-per-second optical demands. Projections suggesting 1 Tb/s through multiplexing (i.e. 10×100 Gb/s) have been shown to be experimentally possible.[8]

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1.2 Multiaccess Networks

In parallel, the service provider community worldwide is now aggressively deploying fiber-to-the-home/premises (FTTH/P) using single-mode fiber.[9,10] It is no longer a question of "if" FTTH/P is necessary to meet burgeoning residential and corporate user demands, it is a question of "when". Passive optical networks (PONs) are an emerging multi-access network technology based on all-optical core and are recognized as the most promising solution for deploying FTTH/P.[11,12] PONs provide a low-cost solution to alleviate the so called "last mile" problem that remains a bottleneck between the backbone network and high-speed local area networks (LANs). With IEEE 802.3av Task Force recently completing the standardizing of the physical specifications for 10G-EPON to attain a total bandwidth of 10 Gb/s, PONs are projected to operate 10+ Gb/s in the near future. Significant issues facing service providers include architecture and technology choices to support time domain multiplexing (TDM) PON networks and/or wavelength domain multiplexing (WDM) PON networks. Furthermore, the optical market has rationalized, stabilized, and started to solidly rise again, driven by real applications, profitable services, and mature technologies. The promise of fiber-fed services at higher data rates, with superior network capacity, and a better bundle of distributive services and interactive multimedia such as video, voice, data, and fast Internet, to a large number of subscribers with guaranteed quality of service (QoS) by PONs, is compelling.[13]

2. REVIEW OF TECHNOLOGIES/CHALLENGES FOR SCALING NETWORKS

In this section, we review some of the present technologies and discuss the future challenges for scaling of optical transport and multiaccess networks.

2.1 Advanced Modulation Formats

In the area of long-haul optical networks, there has been great deal of recent interest and progress in the study and demonstration of advanced modulation formats for high bit rate systems due to the limitations of fiber optic communications systems.[14–17] These limitations stem from both linear and nonlinear effects. Linear effects including attenuation (losses), chromatic dispersion (CD) due to the wavelength dependent index of refraction, and polarization mode dispersion (PMD) leading to differential group delay (DGD) represent one type of transmission impairment. In addition, system noise manifests itself though optical signal to noise ratio (OSNR) degradation after cascades of optical amplifiers. Nonlinear effects also play an increasingly significant role in limiting transmission distances. These effects include those resulting from the propagation of a single channel in the form of self phase modulation (SPM) arising when the phase of a channel is modulated by its own intensity. Additional wavelength division multiplexing (WDM) nonlinear effects that are often split into cross phase modulation (XPM) and four wave mixing (FWM) also impact performance. Ultimately, system designers must manage optical powers and pulse rise times in order to minimize bit error rate (BER) in the presence of these linear and nonlinear transmission impairments. At one end, the maximum optical power is limited by the nonlinear effects on the performance and at the other end, the receiver sensitivity defines the minimum power per channel. In achieving higher spectral densities, inter-channel crosstalk will also affect the performance of the transmission system. Finally, the filtering effect of cascaded reconfigurable optical add-drop multiplexers (ROADM)s in the optical transport link will impair the spectral profile of the channels.

These impairments affect 10-Gb/s signals the same way as 40- and 100-Gb/s signals, but the former has a much tighter tolerance to these impairments in part because the spectral profile is ten times larger. Furthermore, a signal modulated at 40 or 100 Gb/s requires in general 6 or 10 dB more OSNR, respectively, for the same modulation format. Beyond dispersion, loss and the nonlinear effects, it has been found that PMD is a major concern for 40- and 100-Gb/s systems. This effect causes pulse broadening because light travels at different velocities depending on its polarization. With a shorter bit duration, 25 ps at 40 Gb/s and 10 ps at 100 Gb/s, compared to 100 ps at 10 Gb/s, the tolerance to PMD decreases by a factor of four and ten, respectively. This is the primary motivation for research alternative modulations beyond conventional on-off keying (OOK), as a means of overcoming the adverse effects of PMD. Furthermore, given that the channel spacing used for a majority of these networks is fixed at 50 GHz and that the spectrum is naturally four and ten times broader at 40 and 100 Gb/s, respectively, than at 10 Gb/s, non-return to zero (NRZ) modulation cannot be readily used. These factors have led to significant research on advanced modulation formats that can operate within the channel bandwidth limitations of existing 10-Gb/s systems and at higher data rates, including 40 and

100 Gb/s. Hence, the approach is to use advanced modulation formats that have narrower spectral profiles to increase their resiliency to fiber impairments. Some modulation formats have already been shown to be more resilient to dispersion and the filtering effects of the transmission system such as duobinary, differential phase-shift keying (DPSK), carrier-suppressed-return-to-zero (CSRZ)-DPSK and differential quadrature phase-shift keying (DQPSK).[16] Duobinary format was also used to demonstrate 100-Gb/s signal generation.[18] DPSK and DQPSK are non-binary modulation formats enabling lower symbol rates at the same bit rate. They operate with a narrower spectral profile that is more tolerant to CD and PMD.[17] For 100-Gb/s transmission, the signal generation can be either achieved through optical time division multiplexing (OTDM) or electrical time division multiplexing (ETDM). The former is less complex and more economically viable.

2.2 Equalization Techniques

A second area of considerable recent research is equalization. Here, techniques are used to capture, analyze, and extract data using advanced signal processing and electronics with the objective of performing equalization in the electronic or optical domain to increase performance. Several signal processing methods have been proposed to enhance the transmission performance and the tolerance to certain impairments including PMD and residual CD. These techniques are often used in conjunction with specific modulation formats. The most straightforward equalization techniques can be applied at the receiver. In this scenario, equalization can be performed in either the optical or the electrical domain. The optimum performance is obtained with optical equalization because phase and polarization information are preserved. However, electrical equalization is more cost effective and is more readily integrated within an overall system. The simplest method used for optical or electrical equalizer is referred to as a feed forward equalizer (FFE).[19] The signal is split into several paths, each path being delayed by a pre-determined duration. The power associated within each path can be varied and the signals are then combined to be detected by a decision element. Electrical equalizers can produce improved tolerance to residual dispersion and can also be used to mitigate the impact of PMD. A decision feedback equalizer (DFE) is sometimes cascaded after an FEE for stronger PMD electrical compensation.[20] When larger tolerances are required the more complex maximum likelihood sequence estimation (MLSE) is used.[21] Here the optical signal is converted into an electrical signal by a photodiode and the electrical signal is then digitalized by using analog-to-digital converter (ADC) working at 2 samples/bit. A processor using a Viterbi algorithm is then used to select the most likely sequence associated with the detected signal. When the distortion effects of changing channel condition are changing, an adaptation equalization approach is required where the eye opening or BER is monitored to obtain information for tap weight adjustment.[22]

Another method is to synthesize the optical signal at the transmitter in order to pre-compensate for distortions which occur during transmission.[23] In this approach, the optical modulator synthesizes the intensity and the phase of the optical signal using a Mach-Zehnder superstructure. In addition to CD compensation, this technique can compensate for single channel nonlinear effects. The transmitter requirements include a complex modulator driven by a digital-to-analog converter (DAC) working at 2 samples/bit and a powerful digital signal processor capable of synthesizing 40-Gb/s signals. Referred to as electrical domain compensation of optical dispersion (eDCO), modems have been realized at 40 b/s that are capable of performing dispersion compensation.[24] A coherent 40-Gb/s modem based on four 20 GSample/s, 6-bit ADCs that digitized the signal recently demonstrated full compensation of dispersion and polarization.[25] Extensions of this technology to 100-Gb/s coherent modems have also been shown.

In parallel significant research on optical equalization has been pursued based on the promise of low power at high data rate. The principle behind optical equalizers is the same as electrical equalizers where the light is split into several paths and delayed appropriately. The delay of a path is set by adjusting the phase of the signal in one branch. These devices are implemented in planar lightwave circuits (PLCs) at 40 Gb/s[22] and 107 Gb/s.[26]

Often a particular equalization technique comes hand in hand with a specific modulation format to enhance its performance. In the eDCO approach, DPSK is used with a balanced detector at the receiver. Optical single sideband (OSSB) modulation has also been shown to map optical phase distortion to electrical phase distortion which can then be compensated electrically.[27] Orthogonal-Frequency Division Multiplexing (OFDM) can efficiently compensate for CD in long-haul systems.[28]

2.3 Burst-Mode Clock and Data Recovery

The challenge in the design of a chip set for PONs arises from the upstream data path as the network is point-to-multipoint (P2MP) where multiple optical network units (ONUs) transmit data to the optical line terminal (OLT) in the central office (CO). Due to optical path differences, successive packets can vary in amplitude (0–20 dB) and phase (-2π to $+2\pi$ rad)—bursty data. To deal with these variations, the OLT requires a burst-mode receiver (BMRx). The front end of the BMRx, a burst-mode limiting amplifier (BM-LA), is responsible for amplitude recovery. Thereafter, fast clock and data recovery (CDR) together with phase acquisition is performed by a burst-mode CDR (BM-CDR) with the help of a clock phase aligner (CPA). The most important characteristic of the BM-CDR is its phase acquisition time, which must be as short as possible to improve the physical efficiency of the upstream PON traffic and/or increase the effective throughput of the system.

PONs have no repeaters in their data path unlike synchronous optical network (SONET) systems that impose a strict specification on jitter transfer. Jitter transfer refers to the suppression of the input jitter through the CDR circuit. Taking this into account, different approaches have been proposed to build BM-CDRs for PON applications by compromising the jitter transfer characteristics. These BM-CDRs are based on: (1) broad-band PLLs (demonstrated at 2.5 Gb/s[29]); (2) injection-locking techniques (demonstrated at 10 Gb/s[30] and at 20 Gb/s[31]); (3) gated voltage-controlled oscillators (GVCOs) (demonstrated at 10 Gb/s[32–34]); (4) oversampling CDRs without phase-tracking—blind oversampling (demonstrated at 1.25 Gb/s[35] and at 5 Gb/s[36]); and (5) hybrid combination of phase-tracking and blind-oversampling CDRs—semi-blind oversampling (demonstrated at 5 Gb/s[37,38] and at 10 Gb/s[39]). These solutions broadly fall into three categories: (1) feedback architectures; (2) feed-forward architectures; and (3) hybrid architectures—combination of feedback and feed-forward.

Broad-band PLLs based BM-CDRs trade-off the loop-bandwidth of the PLL for fast phase acquisition time and large frequency capture range. The disadvantages include stability issues, jitter peaking, and limited jitter filtering. If additional control logic or a reset signal is acceptable, then a work around consists in using a dynamic loop bandwidth; the bandwidth is increased while the CDR is acquiring lock and restored to its original value for the rest of the packet to minimize output jitter. BM-CDRs based on injection-locking technique extracts the clock by injection locking the local oscillator (LO) to the tiny embedded clock signal, which primarily arises from leakage coupling. This design suffers from severe performance degradation, as the natural frequency of the VCOs deviates from the data rate due to process, temperature, and supply variations (PVT). This consequently limits their frequency tracking range. BM-CDRs built from GVCO or some kind of gating circuit performing clock phase alignment by triggering a local clock on each transition of the input data. This solution provides rapid phase locking but results in higher phase noise as it does not filter out input jitter. More seriously, the gating behavior would cause momentary fluctuation on the recovered clock, potentially incurring undesired jitter and intersymbol interference (ISI). In addition, the truncation or prolongation of the clock cycle during phase alignment induces other uncertainties such as locking (settling) time. The last approach is based on oversampling without or with phase-tracking, that is, blind- or semi-blind oversampling, respectively. One can either oversample in time using a clock frequency higher that the bit rate, or oversample in space using a multiphase clock with a frequency equal to the bit rate. Oversampling in time requires faster electronics, whereas oversampling in space requires low skew between multiple phases of the clock. The oversampling techniques in general suffer from high complexity and power consumption. The key advantage of the semi-blind oversampling technique is that it produces a jitter tolerance, equal to the product of the phase-tracking jitter tolerance and the blind oversampling jitter tolerance, thereby increasing the low-frequency jitter tolerance. Note that jitter tolerance of the CDR refers to the peak-to-peak amplitude of sinusoidal jitter (as function of frequency) that can be applied at the input without causing data recovery errors.

3. ULTRA-HIGH BIT RATE OPTICAL TRANSPORT NETWORKS

Here we present some of our recent work on ultra-high bit rate optical transport networks including pulse shaping experiments to mitigate effects of fiber nonlinearities in 40- and 100-Gb/s QPSK systems, equalization techniques to tackle the problem of excessive overhead in CO-OFDM transmission systems, and demonstration of a 40/100-Gb/s recirculating loop to emulate long-haul DWDM transmissions with unique features.

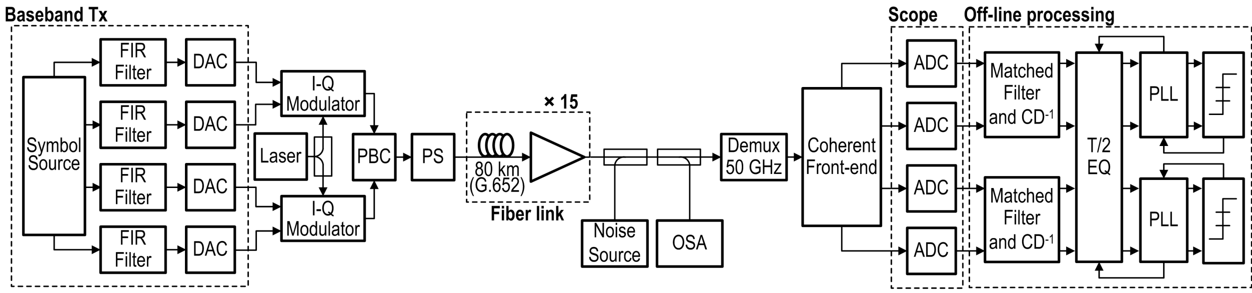


Figure 1. High-level view of the experimental setup for the DP-QPSK and DP-16-QAM transmission.

3.1 Pulse Shaping and Equalization

We have been exploring several techniques for managing nonlinear impairments, including pulse shaping, Volterra filtering, and feedforward carrier recovery algorithms for M-quadrature amplitude modulation (M-QAM) systems.[40,41] Below we highlight our work on pulse shaping, a technique that targets intra-channel nonlinear distortion which is an important source of signal degradation in systems using modulation formats such as QPSK and QAM. Its main effects is to reduce the maximal power that can be launched into the fiber, thereby limiting optical signal-to-noise ratio (OSNR) levels at the receiver, reducing system margins and reducing the maximum propagation distance that can be achieved. In this work, an optimized pulse shape is experimentally shown to improve the nonlinear tolerance of a long haul, dispersion-unmanaged, 10 Gbaud dual-polarization QPSK (DP-QPSK)and 16-QAM systems relying on erbium-doped fiber amplifiers (EDFAs) and G.652 fiber. The specialized pulse was obtained by numerical optimization, with the primary objective formulated to reduce its width, but constrained to have a bandwidth equal to the bandwidth of a root-raised cosine (RRC) pulse with a roll-off factor of 1.

Fig. 1 illustrates the experimental setup that was used for both DP-QPSK and DP-16-QAM transmission. The symbol sources consist of random symbol sequences and were followed by the optimized pulse shaping finite impulse response (FIR) filters. DACs with 6-bit resolution drive the in-phase-quadrature (I-Q) modulators associated with the two polarizations. The emitting wavelength was set to 1547.715 nm. A polarization scrambler (PS) was inserted after the polarization beam combiner (PBC) in order to randomly rotate the polarization state. A fiber link consisting of 15 spans of 80 km G.652 fiber was used, together with EDFAs at each span. At the receiver, a noise source and an optical spectrum analyzer (OSA) were used to adjust and measured the OSNR level. A coherent front-end integrates polarization beam splitters, optical hybrids, a local oscillator and photodetectors. It provides four signals corresponding to the in-phase and quadrature components of the two polarizations. These baseband signals were sampled using a 50-GSamples/s oscilloscope with 8-bit ADCs and post-processed in a personal computer. The receiver signal processing functions include matched filtering and chromatic dispersion compensation (CD^{-1}) by FIR filters, polarization recovery by a 13-tap fractionally spaced (T/2) butterfly equalizer (EQ), carrier offset removal and carrier phase recovery by a phase lock loop (PLL) and finally, detection.

In comparison to the RRC pulse, the optimized pulse shape was shown to improve the nonlinear performance of DP-QPSK dispersion-unmanaged systems and to increase the maximum transmission distance by 23%. Figs. 2(a) and 2(b) show the measured propagation results of the DP-16-QAM system, for 800 km and for 1200 km, respectively. At 800 km and considering a BER threshold of 8×10^{-3}, the optimized pulse reduces the OSNR penalty by 0.6 dB and 2.8 dB, for launch powers of -2 dBm and 0 dBm, respectively. At 1200 km and for a launch power of -2 dBm an improvement of 1.2 dB is observed. At 1200 km and for a launch power of 0 dBm, the system with optimized pulse shaping almost reaches the BER threshold, while the system using RRC pulses is limited to a BER of 1.8×10^{-2}. At this level, the optimized pulse outperforms the RRC pulse by 4.3 dB.

The presented nonlinearity mitigation technique best suits systems using multi-bit DACs operating at the Nyquist rate. For these systems, the proposed approach is implemented at no extra hardware or computational cost, since the optimized pulse shaping function replaces the existing shaping filters. Future investigations include

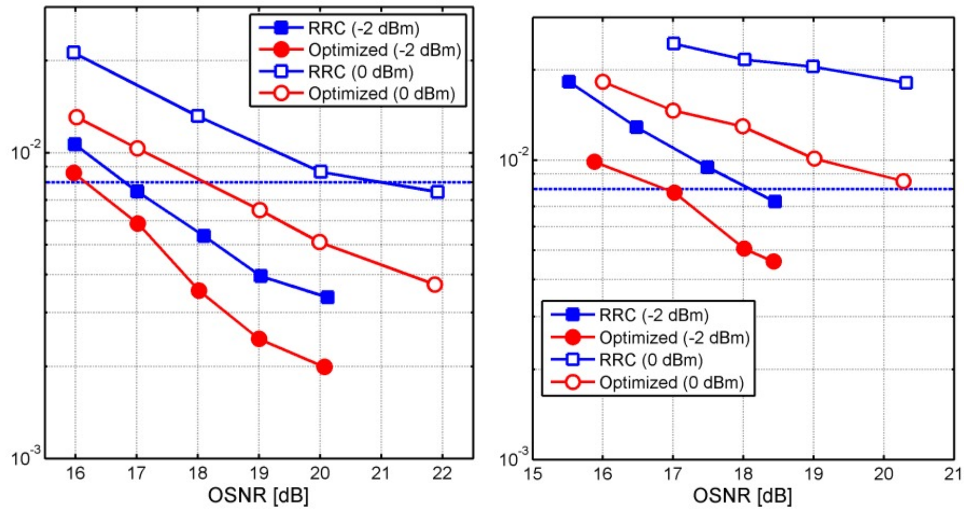


Figure 2. Measured BER vs OSNR (noise bandwidth = 0.1 nm) for the DP-16-QAM system for (a) 800 km and (b) 1200 km.

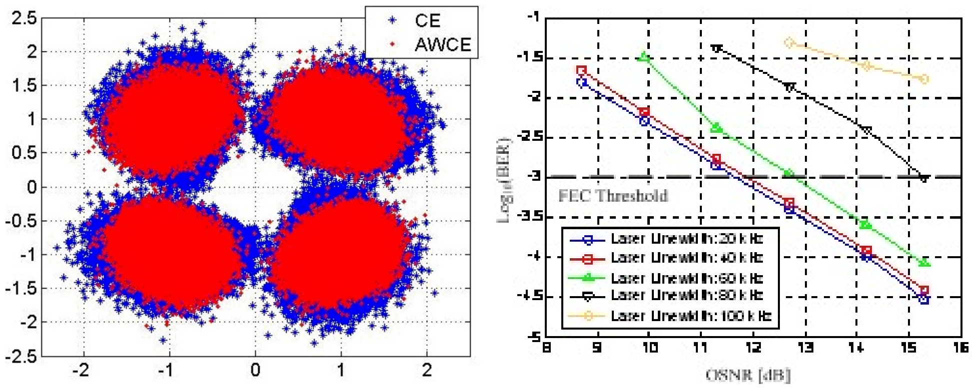
the evaluation of the optimized pulse shape performance in the presence of timing jitter and in multi-channel transmission scenarios.

3.2 Coherent Optical Orthogonal Frequency Division Multiplexing

Following the recent surge of interest in digital signal processing (DSP) for optical fiber communications, coherent optical orthogonal frequency division multiplexing (CO-OFDM) has been intensively investigated as a powerful scenario for the future uncompensated optical transmission links.[42–45] This is because of the ease of equalization and therefore, the robustness with respect to fiber transmission impairments such as CD and PMD. However, there are new challenges to be overcome due to the strong fiber nonlinearity and the excessive amount of required overhead for OFDM transmission. OFDM and its impressive channel estimation capacity provide the opportunity to exploit more complex channel estimation techniques to reach higher throughput and performance. Recently, we introduce two novel equalizers for CO-OFDM transmission systems: adaptive weighted channel equalizer (AWCE) and decision-directed phase equalizer (DDPE) to tackle the problem of excessive overhead. Both equalizers update the equalization parameters on a symbol-by-symbol basis and operate based on decision-directed channel estimation which is an alternative to the pilot-assisted (data-aided) channel estimation. It uses previous demodulator decisions to help estimate channel fading factors during the current symbol period. In decision-directed channel estimation, since the equalization parameters are not from pilot symbols, they might not be as reliable, so the estimator's performance may suffer from error propagation. However, it does not require the overhead of the pilot-assisted estimators. To overcome the shortcomings of decision-directed and pilot-assisted channel estimators, the two methods can be combined.

AWCE utilizes both receiver decisions and pilot symbols to produce better results when the receiver decisions are correct. In this way, by updating the equalization parameters on a symbol-by-symbol basis, the receiver can track the slight drifts in the optical channel. Consequently, this allows the system to increase the periodicity of sending the PSs which leads to overhead reduction. AWCE can also improve the performance of the RF-pilot enabled or pilot subcarrier enabled phase noise compensation (PNC) by providing a more accurate estimation using both data-aided and decision-directed phase noise estimation techniques. Fig. 3(a) compares the received constellation of QPSK signal equalized by CE and AWCE after 2000 km transmission. It can be clearly observed that AWCE provides better equalization and subsequently separated constellation points.

DDPE, motivated by recent progress in external-cavity laser (ECL) technology in manufacturing low linewidth telecom lasers, utilizes pure decision-directed phase noise estimation and compensation. This means that there will be no need for any extra overhead due to RF-pilot or PSC insertion. DDPE updates the equalization



(a) (b)

Figure 3. (a) Comparison between the received constellations after 2000 km of uncompensated transmission, equalized by CE and AWCE. The PS overhead is 0.3% for both cases. (b) BER performance of DDPE after 2000 km of uncompensated transmission for different laser linewidths.

parameters, initially acquired by PSs, on a symbol-by-symbol basis after an initial decision making and then retrieves an estimation of the phase noise value for the time interval of one OFDM symbol by extracting and averaging the phase drift of all OFDM sub-channels. Subsequently, a second equalization is performed using this estimated phase noise value and afterwards, the equalized symbols are sent to the final decision making stage for detection. Due to the vulnerability of decision-directed estimation algorithms to error propagation, a safe range of laser linewidth and received OSNR have to be determined to guarantee the error-free transmission. Fig. 3(b) compares the BER performance of DDPE versus received OSNR for different laser linewidth values. As one sees, DDPE cannot provide a good PNC due to the error propagation for relatively higher phase noise scenarios, that is, laser linewidths of 80 kHz and 100 kHz. However, for relatively lower phase noise scenarios, it provides a good equalization and the FEC threshold, the commonly-reported BER value of 1×10^{-3}, is achieved at the OSNR values of 11.6 dB, 11.9 dB and 12.7 dB for the laser linewidth values of 20 kHz, 40 kHz and 60 kHz, respectively.

As the next step, the performance of AWCE and DDPE will be experimentally characterized in the lab using the recirculating loop discussed next.

3.3 40/100-Gb/s Recirculating Loop

We have recenelty completed the design and construction of a 40/100-Gb/s recirculating loop. The loop is used to emulate long-distance fiber transmission by circulating data within one loop several times. In our case, the loop is 320 km in length, therefore 2×, 3×, and 10× around the loop represents 640 km, 960 km and 3,200 km, respectively. Fig. 4 shows a schematic of our assembled loop. The recirculating loop is built such that both standard single-mode fiber (SSMF) and LEAF are supported. As such, 600 km of LEAF fiber has been loaned by Corning and research collaboration with Corning is underway to investigate the use of LEAF fiber for higher data rate optical transport networks.

Because key transmission parameters can be measured (e.g. BER, Q-factor, pulse shape, optical and electrical spectrum), we can experimentally research all of the topics including advanced modulation formats, optical digital signal processing algorithms, and impairment mitigation (linear and nonlinear). This loop is unique in Canada, and is one of only a few worldwide, and has the following distinguishing features: (1) 16 dense WDM (DWDM) channels; (2) multiple advanced modulation formats (e.g. DP-QPSK, 16-QAM, CO-OFDM); (3) various fiber types (SSMF, LEAF); (4) four in-line EDFAs with $<$ 1.3 dB gain flatness and a noise figure at maximum gain of 4.9–5.6 dB; (5) polarization diverse four channel optical coherent receiver; and ; (6) advanced signal processing algorithms for long haul transmission systems.

4. MULTIACCESS NETWORKS

This research investigates both, theoretically and experimentally, the design, implementation, and application of high-speed BM-CDRs for PON applications. More specifically, we have demonstrated novel BM-CDRs ar-

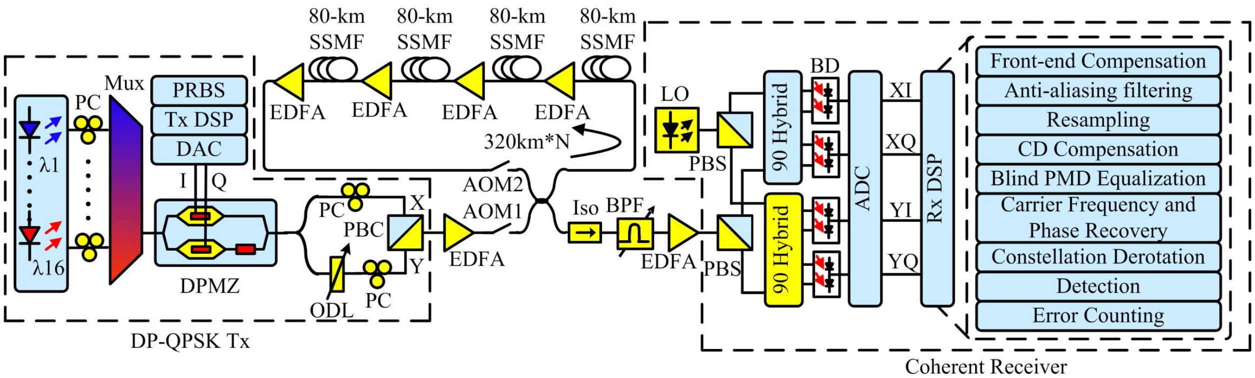


Figure 4. Recirculating loop setup for 40/100-Gb/s DWDM transmission.

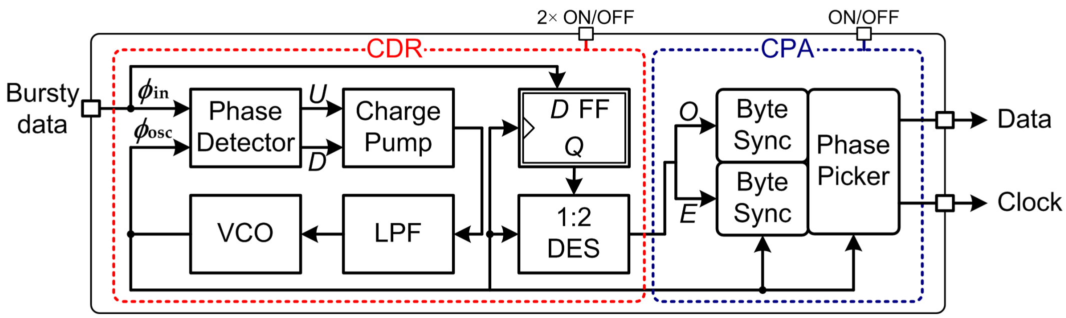


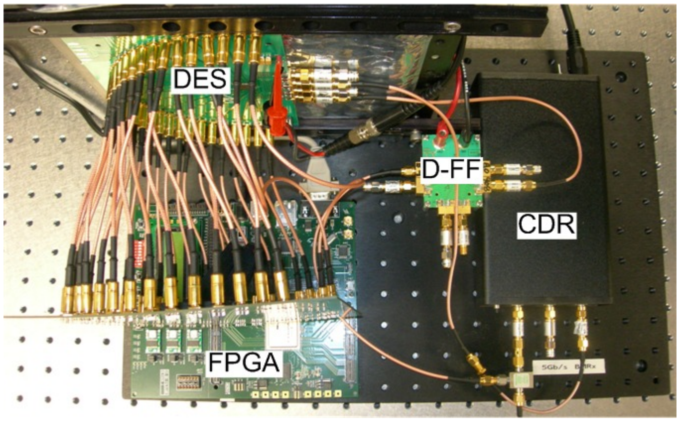
Figure 5. Block diagram of the BM-CDR architecture (CDR: clock and data recovery; CPA: clock phase aligner: DES: deserializer; FF: flip-flop; LPF: low-pass filter; Sync: synchronizer; and VCO: voltage-controlled oscillator).

chitectures based on *time-oversampling* techniques; that is, BM-CDRs built from conventional (SONET) CDRs operated at 2× the bit rate and CPAs that makes use of a simple phase picking algorithm for automatic clock phase acquisition. This design provides low latency and fast response without requiring a reset signal from the network layer. A block diagram of the proposed BM-CDR is shown in Fig. 5. A photograph of the current implementation of the BM-CDR is depicted in Fig. 6(a).

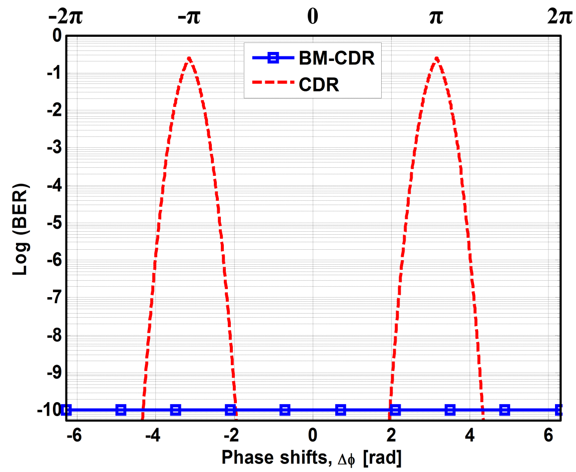
We have experimentally tested variants of this BM-CDR in various experimental testbeds including: (1) 20-km TDM GEPON uplink at 5 Gb/s;[37] (2) 20-km TDM GPON uplink at 625 Mb/s;[46] and (3) 7-user 20-km spectral amplitude coded optical code-division multiple access (SAC-OCDMA) PON uplink at 625 Mb/s.[47,48] In each case, the BM-CDRs have shown to achieve BER $< 10^{-10}$ and packet loss ratio (PLR) $< 10^{-6}$ while featuring *instantaneous* (0 preamble bit) phase acquisition for any phase step ($\pm 2\pi$ rad) between successive bursts. In addition, the BM-CDRs have BER/PLR sensitivities less than −24 dBm with negligible burst-mode sensitivity penalty. Fig. 6(b) compares the performance of the BM-CDR and a conventional CDR as a function of phase steps between consecutive packets with *no* preamble bits.

Instantaneous phase acquisition can increase the effective throughput of the system by increasing the information rate, and also dramatically improve the physical efficiency of the upstream PON traffic to 99% for 32 ONUs. The price to pay to obtain instantaneous phase acquisition is faster electronics. On the other hand, our solution is to leverage the design of components for long-haul transport networks using low-complexity, commercial electronics including evaluation kits and field-programmable gate arrays (FPGAs), to provide a cost-effective solution for PON BM-CDRs. These components are typically a generation ahead of the components for multiaccess networks. Thus, our solution will scale with the scaling for long-haul networks. Based on this approach, we have also experimentally demonstrated burst-mode reception with instantaneous phase acquisition in a 1300-km deployed fiber link spanning Montreal to Quebec City and back.[49]

We have also developed for the first-time, a unified probabilistic theory for modeling and analyzing BM-CDRs.[37,50] This theory can quantitatively explain the performance of BM-CDRs in terms of the BER and PLR. The theoretical model accounts for the following parameters: (1) the phase step between consecutive packets; (2)



(a)



(b)

Figure 6. (a) Photograph of the current implementation of the BM-CDR. (b) BER performance of the BM-CDR compared to a conventional CDR as a function of phase steps between consecutive packets with no preamble bits.

preamble length; and (3) jitter on the sampling clock. Based on this theory, we have performed a comprehensive theoretical analysis to validate the theoretical model. This analysis coupled with the experimental results can be used to refine theoretical models of PONs and provide an input for establishing realistic power budgets.

Moving forward, we are developing power-efficient BM-CDR architectures based on *space-oversampling* techniques with multiphase clocks.[39] The key research findings are directed towards architecture and technology deployments of 10 Gb/s 100-km long-reach PONs. This BM-CDR will achieve instantaneous phase acquisition with no trading-off in the CDR loop-bandwidth. Hence, the BM-CDR could also find applications in future high-speed optical burst/packet switched networks, which may require a cascade of BM-CDRs that each consumes some of the overall jitter budget of the system.

5. CONCLUSION

Transport networks have scaled dramatically with 100 Gb/s commercially deployed today. These 100-Gb/s systems use polarization-multiplexed multilevel modulation on a single optical carrier. We have reached a point where optical developments will be needed to reduce optical noise which figures prominently in the discussion of what's next. With some optical parallelization for the interface bit rate and spectral efficiency, 400-Gb/s systems seem to be the next technologically viable step, with even more parallelization coupled with substantial improvements in photonic integration technologies for 1-Tb/s systems.

In the area of multiaccess networks, a rapidly growing number of households across North America are connecting directly into fiber optic networks, and thereby tapping into a new generation of high-bandwidth applications and services. FTTH networks now pass 18 percent of the homes on the continent, with more than six million households now receiving Internet, telephone and/or cable television services over direct fiber connections.

In this optic, we have discussed several topics and presented our research that focuses on increasing capacity in existing and next generation long-haul and metro fiber optic transmission systems. More specifically, we have shown that optimized pulse shaping can considerably mitigate SPM effects for high dispersion and low dispersion fiber, in 40- and 100-Gb/s DP-QPSK and DP-16-QAM transmission systems. In CO-OFDM transmission systems, we have proposed two novel equalizers, AWCE and DDPE, to tackle the problem of excessive overhead. In addition, we have also constructed and deployed a 40/100-Gb/s recirculating loop to emulate long-haul DWDM transmissions, that supports advanced modulation formats, various fiber types, and a coherent receiver with advanced signal processing algorithms. To keep up with the scaling of multiaccess networks, we have proposed novel BM-CDR architectures at 5 and 10 Gb/s that achieve instantaneous phase acquisition in various PON architectures, dramatically improving the PON traffic efficiency to 99% for 32 users. Our eloquent, cost-effective, and scalable solution leverages the design of low-complexity and commercially available off-the-shelf components.

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REFERENCES

[1] Tkach, R. W., "Scaling optical communications for the next decade and beyond," *Bell Labs Tech. J.* **14**(4), 3–10 (2010).

[2] Winzer, P. J., "Beyond 100G ethernet," *IEEE Commun. Mag.* **48**(7), 26–30 (2010).

[3] Roberts, K., Beckett, D., Boertjes, D., Berthold, J., and Laperle, C., "100G and beyond with digital coherent signal processing," *IEEE Commun. Mag.* **48**(7), 62–69 (2010).

[4] Duelk, M., "Next generation 100G ethernet," in [*Proc. Eur. Conf. Opt. Commun. (ECOC)*], (2005).

[5] Winzer, P. J., Raybon, G., and Duelk, M., "107-Gb/s optical ETDM transmission for 100G ethernet transport," in [*Proc. Eur. Conf. Opt. Commun. (ECOC)*], (2005).

[6] Birks, M. et al., "Real-time single-carrier coherent 100 Gb/s PM-QPSK field trial," *J. Lightw. Technol.* **29**(4), 417–425 (2011).

[7] Xia, T. J. et al., "End-to-end native IP data 100G single carrier real time DSP coherent detection transport over 1520-km field deployed fiber," in [*Proc. Opt. Fiber. Commun. (OFC) Conf.*], (2010).

[8] Raybon, G., Winzer, P. J., and Doerr, C. R., "1-Tb/s (10 × 107 Gb/s) electronically multiplexed optical signal generation and WDM transmission," *J. Lightw. Technol.* **25**(1), 233–238 (2007).

[9] Koonen, T., "Fiber to the home/fiber to the premises: what, where, and when?," *Proc. IEEE* **94**(5), 911–934 (2006).

[10] Lee, C.-H., Sorin, W. V., and Kim, B. Y., "Fiber to the home using a PON infrastructure," *J. Lightw. Technol.* **24**(12), 4568–4583 (2006).

[11] Abrams, M., Becker, P. C., Fujimoto, Y., O'Byrne, V., and Piehler, D., "FTTP deployments in the United States and Japan-equipment choices and service provider imperatives," *J. Lightw. Technol.* **23**(1), 236–246 (2005).

[12] Wagner, R. E., Igel, J. R., Whitman, R., Vaughn, M. D., Ruffin, A. B., and Bickham, S., "Fiber-based broadband-access deployment in the United States," *J. Lightw. Technol.* **24**(12), 4526–4540 (2006).

[13] Angelopoulos, J. D., Leligou, H.-C., Argyriou, T., Zontos, S., Ringoot, E., and Caenegem, T. V., "Efficient transport of packets with QoS in an FSAN-aligned GPON," *IEEE Commun. Mag.* **42**(2), 92–98 (2004).

[14] Charlet, G., "Progress in optical modulation formats for high-bit rate WDM transmissions," *IEEE J. Sel. Topics Quantum Electron..* **12**(4), 469–483 (2006).

[15] Kahn, J. M. . and Ho, K.-P., "Spectral efficiency limits and modulation/detection techniques for DWDM systems," *IEEE J. Sel. Topics Quantum Electron.* **10**(2), 259–272 (2004).

[16] Bosco, G., Carena, A., Curri, V., Gaudino, R., and Poggiolini, P., "Modulation formats suitable for ultrahigh spectral efficient WDM systems," *IEEE J. Sel. Topics Quantum Electron.* **10**(2), 321–328 (2004).

[17] Winzer, P. J. and Essiambre, R.-J., "Advanced optical modulation formats," *Proc. IEEE* **94**(5), 952–985 (2006).

[18] Winzer, P. J., Raybon, G., Doerr, C. R., Duelk, M., and Dorrer, C., "107-Gb/s optical signal generation using electronic time-division multiplexing," *J. Lightwave Technol.* **24**(8), 3107–3113 (2006).

[19] Franz, B. et al., "43 Gb/s SiGe based electronic equalizer for PMD and chromatic dispersion mitigation," in [*Proc. Eur. Conf. Opt. Commun. (ECOC)*], (2005).

[20] Nakamura, M., Nosaka, H., Ida, M., Kurishima, K., and Tokumitsu, M., "Electrical PMD equalizer ICs for a 40-Gbit/s transmission," in [*Proc. Opt. Fiber. Commun. (OFC) Conf.*], (2004).

[21] Farbert, A. et al., "Performance of a 10.7Gb/s receiver with digital equalizer using maximum likelihood sequence estimation," in [*Proc. Eur. Conf. Opt. Commun. (ECOC)*], (2004).

[22] Bohn, M., Rosenkranz, W., and Krummrich, P. M., "Adaptive distortion compensation with integrated optical finite impulse response filters in high bitrate optical communication systems," *IEEE J. Sel. Topics Quantum Electron.* **10**(2), 273–280 (2004).

[23] Roberts, K., Li, C., Strawczynski, L., O'Sullivan, M., and Hardcastle, I., "Electronic precompensation of optical nonlinearity," *IEEE Photon. Technol. Lett.* **18**(2), 403–406 (2006).

[24] Weber, C., Fischer, J. K., Bunge, C.-A., and Petermann, K., "Electronic precompensation of intrachannel nonlinearities at 40 Gb/s," *IEEE Photon. Technol. Lett.* **18**(16), 1759–1761 (2006).

[25] Roberts, K., O'Sullivan, M., Wu, K.-T., Sun, H., Awadalla, A., Krause, D. J., and Laperle, C., "Performance of dual-polarization QPSK for optical transport systems," *J. Lightwave Technol.* **27**(16), 3546–3559 (2009).

[26] Franz, B. et al., "A single-chip optical equalizer enabling high-fidelity 107-Gb/s optical non-return-to-zero signal generation," in [*Proc. Eur. Conf. Opt. Commun. (ECOC)*], (2005).

[27] Sieben, M., Conradi, J., and Dodds, D., "Performance of optical OFDM in ultralong-haul WDM lightware systems," *J. Lightwave Technol.* **17**(10), 1742–1749 (1999).

[28] Lowery, A. J., Du, L. B., and Armstrong, J., "Performance of optical OFDM in ultralong-haul WDM lightware systems," *J. Lightwave Technol.* **25**(1), 131–138 (2007).

[29] Li, A., Faucher, J., and Plant, D. V., "Burst-mode clock and data recovery in optical multiaccess networks using broad-band PLLs," *IEEE Photon. Technol. Lett.* **18**(1), 73–75 (2006).

[30] Zhan, J.-H. C., Duster, J. S., and Kornegay, K. T., "Full-rate injection-locked 10.3 Gb/s clock and data recovery circuit in a 45 GHz–f_T SiGe process," in [*Proc. IEEE Custom Integrated Circuits Conf. (CICC)*], 557–560 (2005).

[31] Lee, J. and Liu, M., "A 20-Gb/s burst-mode clock and data recovery circuit using injection-locking technique," *IEEE J. Solid-State Circuits* **43**(3), 619–630 (2008).

[32] Terada, J., Nishimura, K., Kimura, S., Katsurai, H., Yoshimoto, N., and Ohtomo, Y., "A 10.3 Gb/s burst-mode CDR using a $\Delta\Sigma$ DAC," *IEEE J. Solid-State Circuits* **43**(12), 2921–2928 (2008).

[33] Liang, C.-F., Hwu, S.-C., and Liu, S.-I., "A 10Gbps burst-mode CDR circuit in 0.18μm CMOS," in [*Proc. IEEE Custom Integrated Circuits Conf. (CICC)*], 599–602 (2006).

[34] Nogawa, M. et al., "A 10 Gb/s burst-mode CDR IC in 0.13 μm CMOS," in [*Proc. IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*], 228–595 (2005).

[35] Tagami, H., Kozaki, S., Nakura, K., Kohama, S., Nogami, M., and Motoshima, K., "A burst-mode bit-synchronization IC with large tolerance for pulse-width distortion for Gigabit Ethernet PON," *IEEE J. Solid-State Circuits* **41**(11), 2555–2565 (2006).

[36] Lee, S.-H. et al., "A 5-Gb/s 0.25-μm CMOS jitter-tolerant variable-interval oversampling clock/data recovery circuit," *IEEE J. Solid-State Circuits* **37**(12), 1822–1830 (2002).

[37] Shastri, B. J. and Plant, D. V., "5/10-Gb/s burst-mode clock and data recovery based on semiblind oversampling for PONs: theoretical and experimental," *IEEE J. Sel. Topics Quantum Electron.* **16**(5), 1298–1320 (2010).

[38] van Ierssel, M., Sheikholeslami, A., Tamura, H., and Walker, W. W., "A 3.2 Gb/s CDR using semi-blind oversampling to achieve high jitter tolerance," *IEEE J. Solid-State Circuits* **42**(10), 2224–2234 (2007).

[39] Shastri, B. J. and Plant, D. V., "Burst-mode clock and data recovery for optically interconnected data centers," in [*Proc. IEEE Photonics Society Summer Topicals Meeting*], 201–202 (2010).

[40] Châtelain, B. et al., "SPM-tolerant pulse shaping for 40 Gb/s and 100 Gb/s dual-polarization QPSK systems," *IEEE Photon. Technol. Lett.* **22**(22), 1641–1643 (2010).

[41] Châtelain, B., Jiang, Y., Roberts, K., Xu, X., Cartledge, J. C., and Plant, D. V., "Impact of pulse shaping on the SPM tolerance of electronically pre-compensated 10.7 Gb/s DPSK systems," in [*Proc. Opt. Fiber. Commun. (OFC) Conf.*], (2010).

[42] Pasandi, M. E. M. and Plant, D. V., "Zero-overhead phase noise compensation via decision-directed phase equalizer for coherent optical OFDM," *OSA Optics Express* **18**(20), 20651–20660 (2010).

[43] Pasandi, M. E. M. and Plant, D. V., "Data-aided adaptive weighted channel equalization for coherent optical OFDM transmission systems," *OSA Optics Express* **18**(4), 3919–3927 (2010).

[44] Pasandi, M. E. M. and Plant, D. V., "Improvement of phase noise compensation for coherent optical OFDM via data-aided equalizer," in [*Proc. Opt. Fiber. Commun. (OFC) Conf.*], (2010).

[45] Pasandi, M., Haghighat, J., and Plant, D. V., "Adaptive weighted channel equalizer for direct-detection optical OFDM transmission systems," in [*Proc. IEEE Photonics Society Summer Topicals Meeting*], 85–86 (2009).

[46] Shastri, B. J., Faucher, J., Kheder, N., Zeng, M., Zicha, N., and Plant, D. V., "Performance analysis of burst-mode receivers with clock phase alignment and forward error correction for GPON," *Analog Integrated Circuit and Signal Processing* **60**(1-2), 57–70 (2009).

[47] El-Sahn, Z. A., Shastri, B. J., Zeng, M., Kheder, N., Plant, D. V., and Rusch, L. A., "Experimental demonstration of a SAC-OCDMA PON with burst-mode reception: local versus centralized sources," *J. Lightwave Technol.* **26**(10), 1192–1203 (2008).

[48] Shastri, B. J., El-Sahn, Z. A., Zeng, M., Kheder, N., Plant, D. V., and Rusch, L. A., "A standalone burst-mode receiver with clock and data recovery, clock phase alignment, and RS(255,239) codes for SAC-OCDMA applications," *IEEE Photon. Technol. Lett.* **20**(5), 363–365 (2008).

[49] Shastri, B. J., M'Sallem, Y.-B., Zicha, N., Rusch, L. A., LaRochelle, S., and Plant, D. V., "Experimental study of burst-mode reception in a 1300 km deployed fiber link," *J. Opt. Commun. Netw.* **2**(1), 1–9 (2010).

[50] Shastri, B. J. and Plant, D. V., "Probabilistic theory for semi-blind oversampling burst-mode clock and data recovery circuits," in [*Proc. IEEE Midwest Symposium on Circuits and Systems (MWSCAS)*], 161–164 (2010).