100 Gb/s DQPSK Field Trial: Live Video Transmission Over an Operating LambdaXtreme® Network


Successful transmission of live (real time) video traffic is demonstrated using a prototype 100 Gb/s single-polarization differential quadrature phase shift keying (DQPSK) transmitter and receiver over an in-service 504 km link of the LambdaXtreme® optical transport platform. Teaming with Verizon Business, we demonstrate the feasibility of upgrading an existing, live traffic bearing network to 100 Gb/s per wavelength without any changes to the current hardware or software. The 107 Gb/s signal is added at a reconfigurable optical add/drop multiplexer (ROADM) at a network node in Tampa, Florida, and dropped at a ROADM in Miami, Florida, where both live video and pseudorandom test sequences are received. In addition, we discuss the steps leading up to this field trial that included several important precursor laboratory experiments. We detail the generation, detection, coding, and long-haul transmission of single-polarization DQPSK at a line rate of 53.5 Gbaud to support a net information bit rate of 100 Gb/s. © 2010 Alcatel-Lucent.

Introduction

The traffic growth in today’s communication networks has been fueled by the increase in applications such as video transport, peer-to-peer networking, and high speed computing. In Figure 1, we display measured data from one of the many available sources that underline this increase in data traffic. At the Amsterdam Internet exchange point (AMS-IX), where Internet providers can exchange traffic, the growth in average traffic throughput over the six months from August 2008 through January 2009 increased by 60 percent to a total of 400 Gb/s [1], as shown in Figure 1a. Every day, the traffic flow fluctuates from a low of 200 Gb/s to peak values as high as 600 Gb/s as shown in Figure 1b. This growth, however, flattened out between January 2009 and March 2009 perhaps due to the economic downturn or a...
saturation of new Internet connections. Despite the temporary slowdown at AMS-IX, various other sources indicate that the traffic demand continues to grow, and thus there will be increasing pressure on all parts of the network from local area to long haul to upgrade their capacity in order to handle the traffic flow. Today, most of the systems carrying data in the long haul network use 10 Gb/s per wavelength, and 40 Gb/s is being installed to handle the demand in high traffic routes. The next targeted data rate is 100 Gb/s, and standards bodies such as the Institute of Electrical and Electronics Engineers (IEEE), the International Telecommunications Union Telecommunication Standardization Sector (ITU-T), and the Optical Internetworking Forum (OIF) are working on standards for this next generation of data transport systems [20, 21, 27].

In the long-haul network, service providers desire to re-use their existing infrastructure and thus look for upgrade scenarios to 100 Gb/s and above on their
legacy networks. The goal is to be able to use the existing and widely deployed channel plans for a given system and aggregate the 10 Gb/s channels to 100 Gb/s. To achieve this, it is typically necessary for the 100 Gb/s signal to occupy the same optical bandwidth as the 10 or 40 Gb/s channels. In addition, the upgraded 100 Gb/s channel is required to have a reasonable transmission reach close to that of current 40 Gb/s offerings. Generally, when the data rate is increased for binary modulation formats such as non-return-to-zero on-off keying (NRZ-OOK), the corresponding optical bandwidth increases and the reach is reduced. Recent research and development of advanced modulation formats with differential phase demodulation as well as with coherent detection have paved the way for potential upgrade paths to 100 Gb/s (see for example [15, 16] and [57]).

High bit rate transmission experiments have historically been achieved using optical time division multiplexing (OTDM) in laboratory demonstrations [42]. Bit rates as high as 1.28 Tb/s and 2.56 Tb/s on a single wavelength have been reported by optically interleaving, in time, copies of a 10 Gb/s modulated signal [25, 44]. The short pulses typically required for OTDM systems, however, are accompanied by large optical bandwidths and are thus not suitable for systems with tight wavelength channel spacing (i.e., a high spectral efficiency). Transmission at 107 Gb/s using OOK was first reported using electronic multiplexing up to 107 Gb/s [31]. Ten channels were transmitted over 400 km with a spectral efficiency (SE) of 0.7 b/s/Hz (143 GHz channel spacing). Currently, the availability of mature high-speed electronics and optoelectronics is limited and thus most binary 100 Gb/s demonstrations have occurred in research labs [8, 32, 36, 37, 39, 50]. In an effort to improve the spectral efficiency and reach, more advanced modulation formats are being explored [12, 47]. At 107 Gb/s, the system reach was increased to 2,000 km by using differential quadrature phase shift keying (DQPSK) [49], and the spectral efficiency was improved to 1.0 b/s/Hz in a separate experiment that included transmission through reconfigurable optical add/drop multiplexers (ROADMs) [48]. In DQPSK modulation, the data is encoded onto four optical
phase levels ("symbols"). Hence, each symbol carries 2 bits of information, and one can reduce the required electrical modulation speed by a factor of 2 compared to binary modulation (i.e., from 107 Gbaud to 53.5 Gbaud). Phase-encoded signals can also be detected using a simple optical phase demodulator followed by (balanced) direct detection. The reduction in the required electrical rate to 53.5 Gb/s allows for the use of components that have already been developed for 40 Gb/s systems, thus enabling system demonstrations in more rigorous environments outside the research laboratory.

Another factor of 2 in spectral efficiency can be obtained through the use of polarization division multiplexing. Polarization-division multiplexed (PDM) (D)QPSK has been reported in several 100 Gb/s system demonstrations using both direct and coherent detection [4, 5, 15, 56]. By using PDM, the symbol rate is reduced to ~25 Gbaud, and the highest required electronic and optoelectronic bandwidths are now on the order of 20 GHz. In most applications, digital coherent (“intradyne”) receivers are used in order to separate the two polarization states without the need for fast optical polarization tracking. Digital coherent reception is paired with electronic signal processing that enables powerful algorithms for mitigating the effects of linear, and to some extent also of nonlinear, impairments incurred during signal transmission. However, the required analog-to-digital converters (ADCs) and digital signal processing (DSP) hardware ask for dedicated application-specific integrated circuit (ASIC) designs. Coherent ASICs have been demonstrated for operation at 10 Gbaud [41], and existing complementary metal-oxide semiconductor (CMOS) processes are expected to support 112 Gb/s designs operating at 28 Gbaud. Modulation formats going beyond 4 levels per polarization have also been reported for 100 Gb/s operation [16, 57]. Importantly, however, the lack of ASICs in research and development environments forces researchers to either experiment at lower symbol rates using Field Programmable Gate Arrays (FPGAs) or characterize their systems and determine bit error ratios (BERs) using offline signal processing on a personal computer. This is in contrast to the real time transmission performance characterizations that are possible for direct-detection receivers.

In this work, single-polarization DQPSK at 53.5 Gbaud with direct detection for real time measurement is chosen. At the time of the experiments, this format represented the best trade-off between performance and technological feasibility in order to achieve transmission of a single wavelength at 100 Gb/s. Also, DQPSK with direct detection was the best option for the demonstration of single-wavelength transport of live data traffic in an optical networking environment with SE > 1 b/s/Hz. In this paper, which complements a similar summary reported in reference [51], we first summarize the various field experiments and field trials that have been demonstrated at 100 Gb/s by other groups. Then, we detail our transmitter and receiver configurations and show back-to-back performance as well as transmission performance though ROADMs. We describe pre-trial transmission testing over 2,000 km in a research re-circulating loop and over 700 km in a straight-line engineering testbed [33]. Next, we report the first phase of the field trial where pseudo-random sequences were transmitted using an alien wavelength over the installed LambdaXtreme® optical transport platform between Tampa and Miami, Florida, that is part of the Verizon Business* network [53]. Finally, we detail the field programmable gate array (FPGA)-based real-time encoding and decoding that is required to carry the live video signals using DQPSK. We demonstrate successful implementation through the transmission of high-definition television channels over the system carrying live traffic [46, 51].

Review of Reported 100 Gb/s Field Experiments and Field Trials

Several “100 Gb/s field trials” have been reported in the peer reviewed literature and also in corporate releases to the media. Generally, there are two types of “100 Gb/s demonstrations,” depending on whether serial or parallel transmission is being used. In a parallel transport architecture, a logical 100 Gb/s bit stream is split among N parallel lanes using either N optical fibers or N parallel wavelengths. The more typical application uses multiple wavelengths in the same optical fiber [45]. This splitting of a logical data stream is also referred to as “inverse multiplexing” and choices of N between 4 and 10 are presently being
discussed [20]. The advantage of parallel transport lies in the use of technologically more mature, lower-speed (~1/N) electronic and opto-electronic components. However, an inversely multiplexed wavelength division multiplexing (WDM) stream typically has a lower spectral efficiency than a single-wavelength signal, unless coherent WDM [11, 34] or orthogonal frequency division multiplexing (OFDM) [23, 24] is employed. As a result, the aggregate capacity of a system using regular WDM parallel transport will typically be lower than when using a single wavelength per 100 Gb/s communication channel. In addition, transporting parallel wavelengths poses more difficult issues for optically routed transport networks when compared to single-wavelength systems.

The second type of 100 Gb/s field demonstrations (as well as the focus of this work) is the serial transport scheme where a logical 100 Gb/s data stream is carried on a single optical wavelength and in a single optical fiber, with WDM as an option to carry multiple 100 Gb/s data streams. In this context, the term “serial transport” should not be confused with “binary modulation.” A serial transport signal may contain two (i.e., binary) or more levels in amplitude, phase, and polarization. While parallel transport options are expected to dominate short-reach (native Ethernet) applications in the access and interconnect space in the near future, serial transport is viewed as the most cost effective choice for 100 Gb/s transport in long haul service provider networks.

Parallel 100 Gb/s field trials have been predominantly reported via corporate media releases and as a result, details of the experiments are incomplete. These trials have mainly involved the use of 10 wavelengths modulated at 10 Gb/s each. One of the key technological difficulties with inverse multiplexing and WDM transmission is the handling of the time delay between wavelength channels caused by the fiber chromatic dispersion. For example, a 10-channel system with 50 GHz wavelength spacing will have a relative delay between adjacent channels of 6.8 ps/km in standard single mode fiber (D = 17 ps/nm/km). For an uncompensated link of only 100 km, the delay between the outermost wavelengths would be 6 ns or ~60 bits (6.8 ps/km × 9 × 100 km). The situation is exacerbated in optically routed networks, where additional differential delays may occur at ROADM nodes or through unintentional wavelength routing along different paths. The slipping of bits has to be accounted for in order for the data to be re-assembled into their original form. Infinera demonstrated a successful 40 Gb/s trial over a transoceanic distance totaling 8,477 km using four 10 Gb/s channels [2]. In this trial, each wavelength was passed through a “latency compensation module” (LCM), which is a channelized dispersion compensation module that trims the relative delay of each wavelength. In the trial, the LCM trimmed the relative delays to within the tolerance of the receiver electronics to complete de-skewing by means of properly designed electronic buffers. Infinera also teamed with several carriers to demonstrate 100 Gb/s Ethernet transport of test data over live networks in the United States (4,000 km) [17] and Japan (1,200 km) [19]. In the most recent trial, pre-standard Ethernet test signals based on the IEEE 802.3ba standard were transmitted over a live carrier network [18].

Another inverse multiplexing approach has been recently trialed by two carriers. In a two-wavelength system, sometimes referred to as a dual subcarrier (DS) system, 46 Gb/s were carried on two wavelengths spaced by approximately 20 GHz [28, 55]. This approach provides a 92 Gb/s line rate within a typical 50 GHz channel bandwidth. The 46 Gb/s carriers were using polarization division multiplexed quadrature phase shift keying (PDM-QPSK) at 11.7 Gbaud. Coherent detection and subsequent digital signal processing were utilized to recover the encoded data in real time using the ASICs described in [41]. Verizon and Nortel demonstrated transmission over 73 km of field-installed spare fiber with 10 Gb/s and 40 Gb/s channels on a 50 GHz grid [55]. The experiment demonstrated the power of coherent detection and digital signal processing for combating very high values of polarization mode dispersion (PMD) on this spare fiber system. The same technique was trialed between Nortel and Comcast over a live network [26] covering 240 km between McLean, Virginia, and Philadelphia, Pennsylvania; however few details are available. As the speed of the ADCs and DSPs evolves, this technique can be improved to carry rates up to 112 Gb/s. The second type of 100 Gb/s field demonstrations including

Serial transmission trials have been demonstrated by several system vendors using various modulation formats and fiber transmission installations. Two field experiments employing binary OOK at 100 Gb/s were demonstrated over field-installed fiber that was neither part of a commercial system installation nor carrying live commercial traffic. In a collaborative effort between AT&T Labs and Siemens, 100 Gb/s transmission over 160 km was demonstrated in the U.S. between Asbury Park and Little Egg Harbor, New Jersey [22]. The system consisted of two 80 km links of nonzero dispersion-shifted fiber (NZDSF) fiber connected in a loop-back manner; transmitter and receiver were collocated. The loss of the fibers was compensated using erbium doped fiber amplifiers (EDFAs) only, and standard dispersion compensation modules (DCMs) were used for compensation of chromatic dispersion. Vestigial sideband (VSB) OOK, which has a narrower spectral width than standard dual-sideband NRZ-OOK, was employed in this field experiment. To achieve this performance, optical equalization was required to mitigate distortions from the limited bandwidth performance of both the transmitter and receiver. VSB-OOK was also employed in a similar field experiment over field-installed fiber (again not carrying live traffic) in Germany between Darmstadt and Stuttgart [35]. This time, 8 wavelengths spaced by 100 GHz were transmitted in a point-to-point link (no ROADMs), demonstrating the advantage of VSB-OOK for a higher spectral efficiency compared to dual-sideband OOK. Here the fiber system was a single-mode fiber (SMF) link installed as part of a Deutsche Telekom network with a total length of 500 km. The experiment was also carried out by looping back the signal to Stuttgart, where the receiver and transmitter were collocated. Unlike the AT&T trial, the fiber in this trial had high loss and large polarization mode dispersion. Active compensation of the PMD at the receiver was required.

The use of higher-level modulation formats began to dominate reports on 100 Gb/s transmission with the first direct-detection [7, 49] and coherent [15] QPSK laboratory demonstrations in 2006. In addition to the trial reported here, two recent serial format trials have been reported using a single wavelength carrying 100 Gb/s polarization division multiplexed QPSK at 28 Gbaud. Employing these techniques, higher spectral efficiencies can be achieved in today’s WDM systems and one can take advantage of presently deployed optical networking platforms to upgrade systems to higher bit rates without changing fiber infrastructure or WDM system. The approach described in the main part of this paper used 53.5 Gbaud single-polarization DQPSK with delay demodulation and direct detection to support live

Table I. 100 Gb/s parallel transport field experiments/trials.

<table>
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<tr>
<th>Year</th>
<th>Distance</th>
<th>Modulation format</th>
<th>Symbol rate</th>
<th>WDM</th>
<th>Real time</th>
<th>Live network</th>
<th>Receiver</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>4,000 km</td>
<td>10 × 10G OOK</td>
<td>10 Gbaud</td>
<td>10 × 10G</td>
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<td>✓</td>
<td>PIC-DD</td>
<td>2006</td>
</tr>
<tr>
<td>2009</td>
<td>1,200 km</td>
<td>10 × 10G OOK</td>
<td>10 Gbaud</td>
<td>10 × 10G</td>
<td>✓</td>
<td>✓</td>
<td>PIC-DD</td>
<td>2009</td>
</tr>
<tr>
<td>2008</td>
<td>~ 240 km</td>
<td>2 × 46G PDM-QPSK</td>
<td>11.5 Gbaud</td>
<td>10/40/100G</td>
<td>✓</td>
<td>✓</td>
<td>Coherent</td>
<td>2008</td>
</tr>
<tr>
<td>2009</td>
<td>73 km</td>
<td>2 × 46G PDM-QPSK</td>
<td>11.5 Gbaud</td>
<td>10/40/100G</td>
<td>✓</td>
<td>X</td>
<td>Coherent</td>
<td>2009</td>
</tr>
</tbody>
</table>

DD—Direct detection  
PDM—Polarization division multiplexing  
PIC—Photonic integrated circuit  
QPSK—Quadrature phase shift keying  
WDM—Wavelength division multiplexing  
OOK—On-off keying
Similarly, 112 Gb/s PDM-DQPSK over 80 km of field fiber was demonstrated by Ciena and the California Institute of Technology, who combined 10 10 Gb/s Ethernet channels in real time into one 112 Gb/s framed payload that included forward error correction (FEC) [6]. Automatic polarization tracking combined with direct detection in the receiver enabled real time characterization [38]. In contrast to these real time trials, Verizon and Nokia Siemens Networks also transmitted a 111 Gb/s signal with two co-propagating 43 Gb/s and eight 10 Gb/s signals over 1,040 km of field-deployed fiber. The experiment used coherent detection and offline processing to determine the BER performance of the system using standard 50 GHz channel spacing [54].

Table II compares results from serial transport 100 Gb/s field experiments and trials including those of Siemens, AT&T, and others [22]; Ciena and CalTech [6]; Nokia Siemens and Verizon [54]; and Alcatel-Lucent and Verizon [51] in the United States, and Alcatel-Lucent and Deutsch Telecom in Germany [35].

At the time of the trial reported here, direct detection of DQPSK was the preferred method to achieve real time transmission of video signals in a system designed for 100 GHz as well as asymmetrically allocated 50 GHz channel spacings. This was made possible by leveraging available and mature components typically used for 40 Gb/s systems. The trial reported here, which took place between two distinct locations, Tampa and Miami, Florida, approximately 500 km apart, was not completed in a loop-back transmission mode. Instead, this was a point-to-point demonstration that presented the added difficulty of requiring clock recovery at the receive side and preventing back-to-back performance monitoring in the field.

**DQPSK Transmitter**

A schematic and photograph of the 107 Gb/s return-to-zero (RZ)-DQPSK transmitter is shown in Figure 2. The transmitter uses two LiNbO$_3$ modulators. The first modulator is a fully packaged nested Mach-Zehnder (MZ) device that consists of two sub-MZ modulators to provide the phase-coded data modulation [7, 47] while the second modulator is used optionally to carve pulses from the DQPSK data turning NRZ-DQPSK format into RZ-DQPSK [43, 47]. The data modulator is driven in a push-pull manner with two independent 53.5 Gb/s electrical signals which are generated by electronically multiplexing four 13.375 Gb/s data signals. The original data is derived from either a pseudo-random bit sequence (PRBS) generator or a live video signal multiplexed in an FPGA-based encoder; the latter process will be

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**Table II. 100 Gb/s serial transport field experiments/trials.**

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Distance</strong></td>
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<td>500 km</td>
<td>80 km</td>
<td>1,040 km</td>
<td>504 km</td>
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<tr>
<td><strong>Modulation format</strong></td>
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<td>107G VSB-OOK</td>
<td>112G PDM-QPSK</td>
<td>111G PDM-QPSK</td>
<td>107G DQPSK</td>
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<tr>
<td><strong>Symbol rate</strong></td>
<td>107 Gb/s</td>
<td>107 Gb/s</td>
<td>28 Gb/s</td>
<td>28 Gb/s</td>
<td>53.5 Gb/s</td>
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<td><strong>WDM</strong></td>
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<td>10/40/100G</td>
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<td>10/100G</td>
<td></td>
</tr>
<tr>
<td><strong>Real time</strong></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
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<tr>
<td><strong>Live network</strong></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
<td>DD</td>
<td>DD w/ pol tracking</td>
<td>Coherent</td>
<td>DD</td>
<td></td>
</tr>
<tr>
<td><strong>Year</strong></td>
<td>2007</td>
<td>2008</td>
<td>2008</td>
<td>2007</td>
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</tr>
</tbody>
</table>

DD—Direct detection  
OOK—On-off keying  
PDM—Polarization division multiplexing  
QPSK—Quadrature phase shift keying  
VSB—Vestigial sideband  
WDM—Wavelength division multiplexing
described in the field trial section below. For PRBS testing, copies of a $2^{15} - 1$ PRBS at 13.375 Gb/s are delayed between 12 and 55 bits relative to each other to provide de-correlation for the multiplexed 53.5 Gb/s signal. Also, the pattern length chosen is the longest tractable sequence for programming our BER test set (BERT) at the receiver for the expected pattern. The data rates are chosen to account for the 7 percent overhead required for forward error correction while providing the full 100 Gb/s payload information. (The FEC is actually implemented in the live video phase of the field trial.) Four high-speed driver amplifiers boost the data signals to 5.5 Vpp in order to achieve a full, $2 \times V_{p-p}$ swing within the data modulator. Measurements of the frequency response ($S_{21}$) of the two sub-MZMs reveals a 3 dB bandwidth of approximately 30 GHz and the low-frequency switching voltage is $V_{p-p} = 5$ V. The second MZM, a standard 40 Gb/s dual-drive modulator, is sinusoidally dual-driven at 53.5 GHz to provide a 50 percent duty cycle pulse train with a repetition rate of 53.5 GHz [47, 51]. The optical spectra for RZ- and NRZ-DQPSK signals are shown in Figure 3 measured with 0.1 nm resolution bandwidth (RES BW). The RZ spectrum that corresponds to the 9.3 ps pulse width is much wider than the NRZ spectrum.
The schematic of the 107 Gb/s DQPSK receiver is shown in Figure 4. The wavelength carrying the 107 Gb/s signal that is to be measured is demultiplexed from the dense wavelength division multiplexing (DWDM) line system using the drop port of the ROADM. The signal is input to a standard optical pre-amplifier stage consisting of two L-band EDFAs and a single wavelength interference filter (OF) with a 3 dB bandwidth of 2 nm. Any residual chromatic dispersion is compensated using a commercially available fiber Bragg grating based tunable dispersion compensator (TDC) that has a tuning range ±400 ps/nm and an operating bandwidth of 80 GHz [29]. Then the signal is optionally passed through an optical equalizer (OEQ) to mitigate distortions arising from limited modulator and driver bandwidths and/or from narrowband optical filters. The OEQ is a 2-tap feed-forward filter made in Si:SiO₂ technology, with a tap delay of 10 ps (i.e., with a 100 GHz frequency periodicity) [9]. The benefit from using the OEQ is observed mostly for NRZ-DQPSK, which is expected due to the stronger impact from inter-symbol interference (ISI) on NRZ formats [47]. For most of our RZ-DQPSK experiments, the OEQ was bypassed with little or no effect on performance. After equalization, the signal enters a delay interferometer (DI) to convert the optical phase modulation into intensity modulation amenable to direct detection [47]. While a commercial receiver would have to incorporate two differently biased DIs to simultaneously receive both DQPSK quadratures, our experimental setup only incorporates a single DI. We access the other quadrature by tuning the DI through a voltage control that thermo-optically changes the delay by π/2. The DI is a commercial bulk-optics DI with a differential delay of 15 ps (66.7 GHz free spectral range [FSR]) and a polarization-dependent frequency shift (PDF) of less than 150 MHz. Optical demodulation is followed by balanced detection, using an integrated pair of photodiodes with a bandwidth of approximately 40 GHz. To demultiplex the resulting 53.5 Gb/s bit stream down to rates where error measurements can be made, a fully integrated electronic 1:2 clock and data recovery (CDR) demultiplexing module [8, 10] converts the signal to 26.75 Gb/s. This is followed by a 1:4 demultiplexing stage to arrive at 6.6875 Gb/s.
for real time error measurement or further FPGA processing, as required for the live video transmission. The first stage demultiplexer also includes clock recovery that is based on a phase locked-loop (PLL) that uses a voltage controlled oscillator (VCO) operating at 26.75 GHz. The clock is divided down to 6.6875 GHz to drive a second stage 1:4 demultiplexer. All BER results reported in this paper are obtained by sequentially measuring and averaging the BER of all four 13.375 Gb/s tributaries within each of the two DQPSK quadratures (4 × 1 and 4 × Q). The electronic tributaries were accessed by phase-shifting the corresponding clock signals to the respective demultiplexing stages while leaving constant all other experimental parameters. The eye diagrams are also shown for RZ- and NRZ-DQPSK both for the input to the receiver and after optical demodulation. The input eyes are measured on a 50 GHz photodiode and a 70 GHz sampling oscilloscope while the demodulated eyes are observed at the output of the balanced photodiode.

**Back-to-Back Performance**

Figure 5 shows the back-to-back BER performance of the DQPSK transmitters and receivers as measured in the laboratory. The optical signal-to-noise ratio (OSNR) is referenced to a 0.1 nm noise bandwidth and includes both polarizations of the amplified spontaneous emission (ASE). In the development of the equipment to be used in the field trial, we strived to produce the best transmitter and receiver pair that could be built with the components available at the time. Our initial transmitter/receiver pair required an OSNR of 18.5 dB for BER = 10^-3 using RZ-DQPSK. Using NRZ-DQPSK without the OEQ, we saw an error floor at ~10^-3. The OEQ mitigated residual ISI in the NRZ-DQPSK waveform to yield error-free performance with a required OSNR of 21 dB at BER = 10^-3. We subsequently improved our transponder hardware (open symbols in Figure 4) to arrive at a required OSNR of 17 dB for RZ-DQPSK and 19 dB for NRZ-DQPSK. Table III summarizes our required OSNR values at BER = 10^-3 and compares them to various other modulation options, including 100 Gb/s measurements and idealized simulation results. Requirements are presented for NRZ-OOK [50], VSB-NRZ-OOK [37], NRZ-DQPSK [33, 53], RZ-DQPSK [33, 53], PDM RZ-DQPSK using both direct detection [4] and coherent detection [15], and PDM 16-QAM [16].

**Summary of Experiments Leading Up to the Field Trial**

Several important experiments were carried out in the laboratory and development labs that ensured a successful field trial. First, as discussed in the previous section, the transmit and receive hardware was developed to provide a low required OSNR that could enable long-haul transmission. Second, transmission testing was completed both in a recirculating loop testbed and in a straight-line testbed to assess the potential reach of 100 Gb/s DQPSK and to observe effects which may limit the transmission reach such as chromatic dispersion, polarization mode dispersion, and fiber nonlinearities. Third, it is important to understand the effects of optical filtering on the system and how ROADMs can limit the system performance, and measurements were made...
to examine this effect. All of these experiments are conducted in a typical research mode where BER performance is assessed using a PRBS as a test bit pattern. The final and very important step was the design and testing of the FPGA-based hardware that would take a live video signal encapsulated in a synchronous optical network (SONET) OC-192 signal, encode it, and multiplex it up to 107 Gb/s for transmission, including a real-time implementation of FEC.

### 2,000 km RZ-DQPSK Transmission Testing in a Recirculating Loop Testbed

The recirculating loop testbed that is similar to the LambdaXtreme system described later in the paper is used for initial laboratory transmission experiments. There are, however, a few notable differences. In the lab, the fiber spans are NZDSF fiber (TrueWave® RS) with an average dispersion of 4.5 ps/nm/km. Typically one can expect to see a mix of fiber types in the field. The amplification scheme also differs from the commercial system. The lab system uses a mix of single-pump Raman amplification and erbium-doped fiber amplifiers, thus limiting the available bandwidth for transmission. LambdaXtreme provides up to 54 nm of usable bandwidth from 1,554 to 1,608 nm.

The wavelengths from 10 co-polarized C-band distributed feedback (DFB) lasers were multiplexed prior to entering the RZ-DQPSK modulator [49]. After amplification and −254-ps/nm dispersion precompensation, which also decorrelates adjacent WDM channels by 16 symbols, the signals enter a recirculating loop composed of 4 spans of 100 km nonzero dispersion fiber (21 dB span loss). Chromatic dispersion is compensated every 100 km using dispersion compensating fiber (DCF), leaving +21 ps/nm of residual dispersion per span at 1,550 nm. The span loss is compensated using hybrid EDFA/Raman amplification with counterpropagating, depolarized Raman pumps at 1,455 nm (15 dB average Raman gain per span). A dynamic gain equalizer filter (DGEE, ~6 dB loss) compensates for amplifier gain ripple and Raman gain tilt. Dispersion post-compensation is adjusted for best BER after transmission for each channel. The average differential group delay for a one loop roundtrip is less than 2 ps. No noticeable BER variations were observed by manually varying launch and/or loop polarization and re-adjusting the polarization controller at the receiver. The signal power launched into the loop is about 0 dBm per channel, with a 1.5 dB spread across the WDM channels. This launch power is close to optimum, as determined in a single-channel 2,000 km transmission experiment (see inset to Figure 6). As the single-channel launch power is increased above +1 dBm, the BER penalty grows due to nonlinear interactions in the fiber [13]. Measurements of the WDM spectrum after 2,000 km transmission reveal a 3 dB spread in channel power that results in a delivered OSNR that varies between 22.5 and 24 dB across the band. The variation is mostly due to the uncontrolled amplification scheme and limitations in the resolution of the DGEE employed in the loop experiment. A comparison with the corresponding back-to-back numbers yields an estimated

<table>
<thead>
<tr>
<th>Modulation format</th>
<th>NRZ-OOK</th>
<th>VSB-NRZ-OOK</th>
<th>NRZ-DQPSK</th>
<th>RZ-DQPSK</th>
<th>PDM RZ-DQPSK</th>
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<tbody>
<tr>
<td>Symbol rate</td>
<td>107 Gbaud</td>
<td>107 Gbaud</td>
<td>53.5 Gbaud</td>
<td>53.5 Gbaud</td>
<td>26.75 Gbaud</td>
</tr>
<tr>
<td>Theoretically ideal OSNR req</td>
<td>17.3 dB</td>
<td>17.3 dB</td>
<td>15.5 dB</td>
<td>15.5 dB</td>
<td>15.5 dB</td>
</tr>
<tr>
<td>Measured OSNR req</td>
<td>21 dB</td>
<td>23 dB</td>
<td>19 dB</td>
<td>17 dB</td>
<td>17.5 dB</td>
</tr>
</tbody>
</table>

1OTDM–based receiver  2Off-line ADC and DSP processing

DQPSK—Differential quadrature phase shift keying  PDM—Polarization division multiplexing

NRZ—Non-return-to-zero  QAM—Quadrature amplitude modulation

OOK—On-off keying  RZ—Return-to-zero

OSNR—Optical signal-to-noise ratio  WDM—Wavelength division multiplexing

Table III. OSNR requirements for various 100 Gb/s modulation formats.
transmission penalty of approximately 2 dB to 3 dB. Figure 6 shows the BER performance of all 10 channels after 2,000 km transmission. Open triangles denote the individual tributaries of the I/Q components, and solid circles denote the average channel BER. The dashed line represents the $2 \times 10^{-3}$ BER correction threshold of enhanced 7 percent overhead FEC, theoretically enabling a post-FEC BER $<10^{-16}$. All channels perform well below the FEC threshold.

**DWDM and ROADMs**

The optical architecture of the ROADM in the LambdaXtreme optical transport system is based on an asymmetric interleaver to support both 10 Gb/s and 40 Gb/s binary modulation formats as shown in the simplified drawing in Figure 7 [14]. Channels are interleaved onto a 50 GHz grid using the asymmetric interleaver to combine even and odd sets of channels that are spaced by 100 GHz. The optical bandwidth of the adjacent channels is asymmetric with the narrow channel having a 3 dB width of 35 GHz and the wide channel having a width of 65 GHz. The transmission characteristic of the interleaver is illustrated in the inset of Figure 7. Individual wavelength channels are dropped by de-interleaving the 100 GHz spaced channels to two sets of 200 GHz spaced channels that are subsequently accessed through a $1 \times 32$ arrayed waveguide grating (AWG) router. Similar functionality is achieved on the even channels but is not shown in the figure. Wavelength channels that either pass through the add/drop ports or are expressed through the ROADM node will experience the filtering effects of these components. The 50/100 GHz interleavers have the narrowest bandwidth and thus are the
limiting filters in the system. Many studies have been reported that examine the effects of filter concatenation on high-speed optical signals (see, e.g., [3] and [30]). Thus it is important to understand these limitations when specifying an upgrade to higher speed signals that may have larger optical bandwidths.

We examined the effect of optical filtering (without fiber transmission) for both NRZ- and RZ-DQPSK at 107 Gb/s in the LambdaXtreme ROADM architecture. In contrast to typical laboratory studies where a single device is placed in a short recirculating loop to emulate filter concatenation [3], we included up to six different, non pre-selected interleavers for these concatenation experiments. Hence, our measurements also capture typical variations in center frequency, bandwidth, and filter dispersion. Figure 8 shows the OSNR penalty at BER = 10^-3 for different numbers of concatenated interleavers. Since there are two interleavers per ROADM, data is measured at 2, 4, and 6 interleavers. The filtering effect produced by two interleavers causes nearly a 4 dB penalty for both NRZ- and RZ-DQPSK. For more concatenations, RZ-DQPSK proves more robust to filtering than NRZ-DQPSK, with an 8 dB penalty measured after six interleavers (3 ROADMs).

**Field Trial Emulation in the LambdaXtreme Transport System**

Straight-line transmission testing was performed on a laboratory installation of the LambdaXtreme optical transport system [33]. Testing was initiated on two different system configurations designed to emulate actual deployed systems. Originally, the route chosen for the field trial was in the United States, in Texas, between Dallas and San Antonio with an intermediate ROADM node in Austin. This route covers approximately 700 km with the intermediate ROADM after 500 km. Eventually, and unrelated to any laboratory test results, a second route became the choice for the actual field trial in Florida between Tampa and Miami. This is a 500 km system between ROADM nodes similar to the Texas-Austin route. Thus, both routes were adequately emulated by the laboratory setup.

LambdaXtreme employs backward and forward Raman pumping to provide both large optical bandwidth and low noise leading to improved OSNR margins compared to EDFA-based systems. It also uses a singly periodic dispersion map where the dispersion of each span is nominally compensated for a residual dispersion of 15 to 20 ps/nm per span, and dispersion pre-compensation of approximately −300 ps/nm is used. DCM modules are placed at the in-line amplifier (ILA) nodes and can also be Raman-pumped to reduce the loss and increase transparency. This type of dispersion map has been shown to provide transmission in a solitonic regime for 10 Gb/s signals where the interplay of self-phase modulation and dispersion reduces nonlinear interactions and enhances transmission reach [13]. At 40 Gb/s and higher, the signals propagate in a pseudo-linear regime where nonlinear penalties are also reduced due to an averaging effect [13]. For phase-coded formats, research continues to examine the nonlinear propagation effects. The signal quality may degrade in these systems due to non-linear phase noise interactions. However, recent experiments at symbol rates above 25 Gbaud have demonstrated similar performance to their binary modulated counterparts [49]. The typical launched optical signal power is −4 dBm per channel, controlled and stabilized by

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**Figure 8.**

OSNR penalty as a function of passes through LambdaXtreme® ROADMs (2 interleavers per ROADM) for 107 Gb/s RZ- and NRZ-DQPSK formats.
LambdaXtreme’s automatic management and control system.

The line system, depicted in Figure 9, consists of a ROADM to add the 107 Gb/s signal at the ITU frequency 188.60 THz (1,589.6 nm), followed by five 100 km spans of NZDSF (LEAF® fiber in all but one span), an intermediate ROADM at 500 km, and an additional two 100 km spans before dropping the signal at a third ROADM at a total transmission distance of 700 km. Figure 10 shows the optical spectra at the input and after 700 km. To further equate the lab demonstrator to the field, the 107 Gb/s signal was co-propagating with 21 other wavelengths that were either continuous wave (CW) or modulated at 10 Gb/s, as shown in Figure 10a. At the intermediate ROADM at 500 km, the 107 Gb/s signal was either

**Figure 9.**
700 km transmission system setup in LambdaXtreme® engineering testbed emulating potential field trial routes.

**Figure 10.**
Optical spectra at the input and after 700 km, with the 107 Gb/s channel co-propagated with up to 22 other wavelengths.
dropped together with a large number of 10 Gb/s channels in the shorter wavelength range or was passed through to close the 700 km link. The WDM spectrum after 700 km transmission is shown in Figure 10b. Figure 11 shows the BER as a function of OSNR for both NRZ- and RZ-DQPSK as measured in the LambdaXtreme system testbed. The diamonds are measurements of the filtering effect through the ROADM nodes using two (solid) and four (open) asymmetric interleavers and reveal the linear filtering penalties going through add-, drop-, and intermediate ROADMs as summarized in the previous section. The squares represent the combined effect of filtering and transmission through 500 (solid) and 700 km (open). NRZ-DQPSK is not showing a noticeable fiber transmission penalty, while RZ-DQPSK accumulates ~1 dB penalty after 500 km and ~1.5 dB after 700 km in addition to the linear filtering penalty. Both formats are readily able to close the link at 500 km with an OSNR margin >4 dB for NRZ-DQPSK, and >5 dB for RZ-DQPSK, at a delivered OSNR of ~27 dB. After 700 km transmission, NRZ-DQPSK fully exhausts its margin, with a BER of $1.4 \times 10^{-3}$ at the delivered OSNR of ~25 dB. During the 107 Gb/s measurements, 10.7 Gb/s channels spaced 200 GHz from the 107 Gb/s channel were monitored using a standard SONET test set, and no errors were observed. Adding and dropping the 107 Gb/s channel also did not produce any transient SONET errors on the 10.7 Gb/s channels.

**107 Gb/s Field Trials on LambdaXtreme in the Verizon Network**

The route chosen for the 107 Gb/s field trials (in August 2007 and November 2007) was between Tampa and Miami, Florida, on the Verizon Business’ ultra long haul (ULH) network. This route is a small part of an extensive long-haul national-scale network operated by Verizon Business that includes many installations of LambdaXtreme optical transport systems. Both 10 Gb/s and 40 Gb/s wavelengths are operating on portions of the network today. The field trial route was largely chosen based on the fact that the system was lightly populated with commercial traffic to minimize possible disruption to paying customers in the event of a failure. In addition, the optical fiber used was of sufficient quality suitable for 100 Gb/s transmission and no changes were made to the existing fiber or amplifier chain for the trial. The characteristics of this route are similar to any other 500 km route in the entire nationwide network.

The 504 km route, shown in Figure 12, uses a LambdaXtreme optical transport system. Span nodes and links are illustrated. Also shown are pictures of the DQPSK transmit and receive equipment in the respective central offices. The 107 Gb/s DQPSK test channel at 1,589.6 nm (188.60 THz) was generated at the Verizon Central Office in Tampa and added to the transport network through the Tampa ROADM. In addition to the 107 Gb/s test channel, the system carried up to nine 10.7 Gb/s channels. Of the nine 10 Gb/s channels, three were providing transport services, two were 10 Gb/s modulated pilot channels, and four were new 10 Gb/s turn-ups. Three of these channels carried live Verizon customer traffic. Figure 13 shows the optical spectrum at the Miami ROADM as measured on the optical spectrum analyzer, which is also pictured. The 107 Gb/s channel has the same power as the 10.7 Gb/s channels.
but appears lower in the figure due to the low (0.1 nm) resolution bandwidth. The spectra of the two formats, RZ- and NRZ-DQPSK, are plotted on the same graph (center), and as a result of filtering, only a slight difference is observed between the two formats as expected.

The fiber spans were between 93 km and 111 km of mostly LEAF fiber, with some standard single-mode sections in between. Span losses ranged from 20 dB to 24 dB. The delivered OSNR measured in Miami was 27.5 dB for a software-stabilized nominal channel launch...
power of $-4\, \text{dBm}$. The system software required no modifications to control and monitor the 107 Gb/s channel since the optical spectrum is similar to a 40 Gb/s DPSK channel that is standard for the system. The 107 Gb/s transmitter and receiver were connected to the line system exclusively through the add/drop ports of the installed ROADMs at either end point of the route, with no additional signaling path or automatic feedback. Once the fiber was connected to the add port of the ROADM, the system software was configured to add the new wavelength to the system. Figure 14 shows the BER as a function of OSNR for the field trial, using multiplexed $2^{15}-1$ PRBS as previously described. For reference, the 500 km testbed results of Figure 11 are also plotted in Figure 14. After 504 km transmission, the field measurements yield an OSNR margin of $>5\, \text{dB}$ and $>6\, \text{dB}$ for NRZ-DQPSK and RZ-DQPSK, respectively, if FEC with a BER correction threshold of $10^{-3}$ is assumed. In these measurements, the OEQ was only used for NRZ-DQPSK but not for RZ-DQPSK, where it had no effect. Throughout the field trial, we meticulously monitored all co-propagating 10.7 Gb/s OOK channels carrying Verizon customer traffic using the standard system monitoring software. No impact due to the addition of the 107 Gb/s DQPSK channel was found.

**Live Video Transmission**

During the pre-trial testing and the first PRBS trial, the FPGA-based hardware for DQPSK precoding/decoding and client side FEC coding was developed in a parallel effort. These functions were necessary to demonstrate the transmission of live video traffic, passed to our setup as an OC-192 client signal during the field trial. Furthermore, rate adaptation was needed, since typical high-speed multiplexers only combine by factors of 2 or 4, and not 10, as is needed to get from 10.7 Gb/s to 107 Gb/s.

We implemented DQPSK precoding and rate adaptation [40] on a Xilinx® Virtex® II Pro X field programmable gate array as shown in the center of

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**Figure 14.**
BER for 107 Gb/s transmission of RZ- and NRZ-DQPSK signals over 500 km from Tampa to Miami. Engineering testbed data is also plotted for comparison.
Figure 15. The FPGA has 20 multi-gigabit transceivers (MGTs), each of which supports up to 10.0 Gb/s. Since this is lower than the required 10.7 Gb/s (input) or 13.375 Gb/s (output), an additional 2:1 multiplexing stage (5.35 Gb/s input, 6.6875 Gb/s output) had to be inserted as shown. As a result, we used 16 MGTs as outputs, 2 as inputs, and 2 as reference ports for clock and trigger signals. This restricted the interface to a single 10.7 Gb/s client signal, passed to the FPGA as 2/110035.35 Gb/s. However, once on chip we immediately generated an equivalent of 10 parallel 10.7 Gb/s streams by (a) replicating the input data stream with 64-bit decorrelation delays (I-component) and (b) generating five 27/110021 PRBSs (Q-component), shifted forward by 1/8th word. Framing bytes were inserted into the I-component for comma-alignment purposes at the receive-side FPGA. Having a PRBS available on one DQPSK quadrature facilitated BER testing and parameter optimization at the (remote) receiver during the field trial. Accessing the I or Q tributary at the receiver is achieved by tuning the optical delay interferometer at the input to the receiver to choose the desired tributary. Note that the inclusion of a short PRBS on one quadrature prior to DQPSK pre-coding does not compromise the effective transmit pattern length, since the subsequent DQPSK pre-coding circuit combines the real traffic (I) with the PRBS (Q) to again yield a random transmit pattern. Through the above process, we mimic an equivalent 10× 10.7 Gb/s FPGA input. Most notably, we process a full 107 Gb/s data bus inside the FPGA core. The latest generation of FPGAs will have enough input/output (I/O) bandwidth to actually feed in 10× 10.7 Gb/s. The FPGA output is sent to 16 parallel MGTs running at 6.6875 Gb/s each, such that the mimicked input rate equals the actual output rate (10× 10.7 Gb/s = 16 × 6.6875 Gb/s = 107 Gb/s).

The live high-definition television (HDTV) video signal obtained from the Verizon FiOS* national video service network is encapsulated in a Gigabit
Ethernet (GbE) stream and tapped optically to provide an OC-192 (9.95 Gb/s) signal to the input of the 107 Gb/s transmitter in Tampa [46]. The OC-192 signal is fed to the client port for G.709-compliant enhanced FEC encoding to produce an OTU-2 framed signal at 10.7 Gb/s, as shown in Figure 15. The FEC encoded signal is then passed to the 2:1 demultiplexer to reduce the data to two streams at 5.35 Gb/s to meet the requirements of the FPGA hardware as described above. The FPGA is clocked at 167 MHz as derived from the FEC board, and the 2:1 demultiplexer is clocked by a recovered clock at 5.35 GHz using an external clock recovery (CR) unit. Due to the inherent inability of a low-speed (167 MHz) FPGA reference clock to synchronize high-speed (6.6875 Gb/s) I/Os with an accuracy corresponding to the high-speed signal, the data channels leaving the FPGA exhibit random integer-bit shifts. Each power-up or reset cycle of the FPGA alters the offsets between any two channels in an unpredictable manner. Such an offset is of minor concern on the receive side of an FPGA, where comma-alignment algorithms may be implemented to align the incoming bit streams. At the output, however, strict bit alignment is required to preserve the DQPSK precoding throughout the multiplexing hierarchy. Hence, we had to implement a dedicated channel alignment algorithm [40, 52] to ensure proper alignment of the parallel FPGA output channels.

Before applying real time video signals, we verified correct performance of pre-coding and channel alignment by accomplishing error-free detection of a PRBS fed as a client signal into the FPGA. **Figure 16** shows a photograph of the FPGA and some of the multiplexing stages as mounted into a 19-inch rack-mountable box. At the output of the FPGA board, the signals are multiplexed from 6.6875 Gb/s to 13.375 Gb/s in eight 2:1 multiplexers. These eight outputs are subsequently multiplexed in two groups (I and Q) by 4:1 multiplexers to produce two 53.5 Gb/s outputs. The multiplexers produce data and data bar outputs that are amplified using high-speed driver amplifiers (SHF 810) and applied to the nested Mach-Zehnder LiNbO₃ modulator, as also described in the DQPSK transmitter section of this paper.

The optical output is amplified and pre-filtered before the optical power is set to the requirements given by the LambdaXtreme specifications. The signal is input to the ROADM port of the LambdaXtreme node in Tampa. Only the optical spectrum and eye diagrams as observed on a single and balanced photodetector were monitored at the transmitter side. No BER information was available for fine tuning of the transmit hardware. The only feedback available was manual, enabled by voice over a cellular telephone and by a video link set up via a dedicated Ethernet service channel that is part of the LambdaXtreme node installation. As in the PRBS trial, the wavelength was set to 1,589.6 nm (188.60 THz) and the link between Tampa and Miami was carrying up to nine wavelengths, as shown previously in Figure 13. The live traffic on the 10 Gb/s channels was protected at the SONET or Internet Protocol (IP) layer during the trial, but no protection mechanisms were triggered during the entire trial period.

In Miami, the 107 Gb/s signal was retrieved from the drop port of the ROADM at the specified wavelength and was input to the 107 Gb/s receiver, as described in a previous section and as shown in Figure 4 and

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**Figure 16.** Photograph of the FPGA and electronic multiplexing packaged in a 19-inch rack mount box.
Figure 17. Now the demultiplexed 6.675 Gb/s signals are sent to the FPGA for processing or alternatively for BER monitoring of the PRBS signals. The receive-side FPGA is required to undo the rate adaptation that was done by the transmit-side FPGA by locking to the inserted framing bytes and extracting a single tributary at the encoded OC-192 rate (2/11 x 5.35 Gb/s → 5.35 Gb/s). The recovered clock is also input to a clock rate adapter module. In this module, the frequency is further divided to a low frequency (~80 MHz), where it is compared with a pre-scaled VCO frequency in a commercial synthesizer chip to lock the VCO to the new frequency for clocking the output multiplexer (5.35 GHz). High-quality clock recovery was one of the most crucial elements to the success of the trial, considering that the transmitter and receiver were located in separate locations.

This resulting 10.7 Gb/s signal is then fed to an FEC decoding board and the OC-192 output is passed through a SONET test-set for monitoring to a standard Fujitsu FW4500 to map four of the STS-1s into a GbE channel. The GbE signal is passed to a video test set (JDSU DTS-330) to extract the HDTV signals for display on an HDTV screen as shown in Figure 12. As expected, no video signal defects were observed during the trial, and all of the co-propagating 10.7 Gb/s channels remained error-free during the entire trial period, which included both daytime (6 AM to 2 PM) and nighttime (12 AM to 6 AM) testing. In addition, the signal polarization was monitored and recorded at the receiver over the testing periods [51] using a polarimeter. Despite observed fluctuations in the polarization, we did not observe any significant performance changes that were correlated to changes in the polarization.

Conclusions

We have demonstrated the technological feasibility of 100 Gb/s end-to-end long-haul optical networking at high spectral efficiencies using differential quadrature phase shift keying and direct detection in a live in-service optical network. The results show that it is possible to upgrade the capacity of the
LambdaXtreme optical transport platform from 40 Gb/s to 100 Gb/s per channel, even without the use of coherent detection or polarization multiplexing. At the time of the trial, DQPSK represented the best trade-off to enable live video transport over a distance of 500 km between optical add/drop points at a serial per-channel bit rate of 100 Gb/s. Current and future advances in components and technologies will further improve the system margin, reach, and tolerance to optical filtering to enable systems to satisfy the increasing growth in traffic demand.

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References
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GLENN WELLBROCK is the director of optical transport network architecture and design at Verizon, where he is responsible for the development of new technologies for both the metro and long haul transport infrastructure. Previous positions include running the advanced technology lab, establishing evaluation criteria, and setting engineering guidelines for all backbone transport equipment. He has also held various positions within network operations units. In addition to his 20+ years at Verizon, Mr. Wellbrock was responsible for product architecture within the USA-focused optical networks group at Marconi, and product planning at Qplus Networks, with a specific focus on developing alternative modulation techniques.

WANG LEE is a distinguished member of technical staff in the Optical Transport Network Architecture and Design group with Verizon Communications. Mr. Lee began his career as a central office technician for New York Telephone Company. He took on increasingly higher positions as CO supervisor, responsible for provisioning and maintenance of toll equipment, and CO manager, overseeing POTS and special service installation and repairs. He then joined the Tier II Transport Technical Support group responsible for providing assistance to the field forces on resolving complex SONET, WDM, and DCS trouble. He was then recruited by the Verizon Technology Organization-System Integration and Testing team, where he conducted system verifications testing on pre-deployment optical transport products.

GREG LYONS is the manager of the Scheduled Activity Request team at the Verizon National Network Management Center in Reston, Virginia. The National Network Management Center (NNMC) is Verizon’s premier national surveillance center and is accountable for providing around-the-clock vigilance over the various national backbone networks that support all of Verizon’s FiOS service offerings. Mr. Lyons’s responsibilities at the NNMC include supervising, scheduling, and reporting on all of the change management activities that take place in the FiOS network on a daily basis. Prior to this Mr. Lyons held positions at Verizon Business as a senior engineer supporting the ULH transport network and at Verizon Global Network Solutions as senior staff consultant with the Long Distance Network Planning group and with the Network Build team. While serving with the engineering and planning groups, he worked extensively with VTO and SIT lab personnel to create...
real-world lab configurations with the Alcatel-Lucent LambdaXtreme® DWDM platform in direct support of the Verizon production ULH network. Mr. Lyons’s telecommunications career began 12 years ago when he started working for Bell Atlantic as a cable maintenance splicer.

PETER HOFMANN is a manager of transport planning in the Verizon Global Network Planning organization in Boston, Massachusetts. He and his team are responsible for architecture and technology planning for the Verizon optical transport network. Mr. Hofmann has 26 years of telecom experience with Verizon, all in the transport network area. He has been fortunate to be on the leading edge of new transport technology development, specifications, and deployment during that time. He started his career working with T-Carrier, then the first DS3-based multimode and single-mode optical multiplexing system, proceeding to SONET ADM and DCS, and now to DWDM/OTN and P-OTP. He has held positions in network operations, technical support, engineering, and planning.

TINA T. FISK is a principal engineer for the Verizon Services Organization. Within Verizon, her contributions extended from operations (Tier II), provisioning (Lead, ULH DWDM, and SONET) to transport planning (principal engineering) in the area of TDM, SONET, and DWDM/OTN interoperability testing and new technology research. Ms. Fisk led a team of system administrators and tactical and strategic specialists throughout Europe, Asia, and South America, and during Implementation Force (IFOR), Desert Storm, and other DOD activities. She received accolades from the DOD during IFOR as a system administrator and network controller. Her experience in satellite, RF, UNIX, networking, and VME systems assisted in the development, integration, and fielding of prototype systems for training, reconnaissance, and force protection.

E. BERT BASCH is a principal member of technical staff at Verizon Network and Technology in Waltham, Massachusetts. He received the doctoral degree of Elektrotechnisch Ingenieur from the Delft University of Technology, Delft, the Netherlands. He began his career with GTE Laboratories 40 years ago and was responsible for GTE’s pioneering research on optical communication systems, which led to deployment of the world’s first fiber optic communication system in the PSTN. He also conducted seminal studies on multi-gigabit transmission systems and coherent optical communications. He developed the technical requirements for GTE’s fiber-to-the-home trial in Cerritos, California, and directed all of GTE’s major fiber optic field trials. In 2000, after GTE’s merger with Bell Atlantic, he joined Verizon’s Network and Technology organization. His evaluation of network architectures resulted in the adoption of a ROADM infrastructure with OTN-based transport for service transparency, the integration of switching functionality in the transport platform that allows single node configurations from all-TDM to all-packet, and the use of multiple levels of tandem connection monitoring to enable performance monitoring and protection across multiple domains. He also developed the key optical specifications for the design of Verizon’s long-haul network infrastructure. More recently, he has been investigating the impact of advanced modulation techniques and nonlinearities on the performance of ultra long-haul DWDM systems, and he initiated the testing of 100 Gb/s transmission systems in Verizon’s network. He is the (co-)author of more than 200 research papers and several book chapters, is the editor of the book Optical Fiber Transmission, and holds 12 patents. He is also the recipient of two Warner Technical Achievement Awards, GTE’s highest technical award, for exceptional contributions to optical communication technology and gigabit networking. He is a member of Sigma Xi, Senior Member of the IEEE, and currently a general co-chair for OFC/INFOEC 2010.

WILLIAM J. KLUGE is a senior staff consultant working on quality of service (QoS) devices for the Verizon FiOS video service located in Basking Ridge, New Jersey. Mr. Kluge has 27 years of telecom experience with Verizon. His previous positions included managing the Transport Technical Support team for Global Network Solutions (GNS) and evaluating and accepting Element Management Systems (EMS) in the Verizon Lab, and he is a subject matter expert (SME) on SONET ADMs, DWDM/ROADM, and digital cross-connect systems (DCS) technologies.

JOHNNY R. GATEWOOD is a network manager for the Global Transport Network Management Organization in the Verizon Service Organization, located in Cary, North Carolina. He and his team are responsible for one of the largest transport networks spanning the globe providing transport data surveillance and maintenance functions for Verizon. During his 12 years at Verizon, Mr. Gatewood has held many management positions, in the Tier II Transport,
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YVES PAINCHAUD is a researcher with TeraXion in Quebec City, Quebec, Canada. He received an M.Sc. degree in physics from the University of Montreal and a Ph.D. degree in electrical engineering from Laval University. Early in his career, he worked at INO in Quebec City in different fields of optics including fiber Bragg gratings, fiber lasers, biophotonic sensors, and lidar. For the past 10 years, his work at TeraXion has been focused on the development of components based on fiber Bragg gratings for the telecommunication industry. He developed advanced fabrication techniques for complex fiber Bragg gratings and was involved in the development of fixed and tunable chromatic dispersion compensators.