4 × 40-Gb/s TWDM PON downstream transmission over 42 km and 64-way power split using optical duobinary signals and an APD-based receiver

A. Gnauck,[1,*] P. Iannone,[2] D. van Veen,[2] and V. Houtsma[2]

[1]*Bell-Labs, Alcatel Lucent, 791 Holmdel-Keyport Road, Holmdel, New Jersey,07733 USA*
[2]*Bell-Labs, Alcatel-Lucent, 600-700 Mountain Avenue, Murray Hill, New Jersey, 07974 USA*
[*]*alan.gnauck@alcatel-lucent.com*

Abstract: We demonstrate downstream transmission of a four-channel 40-Gb/s-per-channel time- and wavelength-division-multiplexed PON over a 42-km, 64-split fiber plant using optical duobinary modulation. At 1550 nm, we obtain a reach of 0-26 km or 16-42 km using two dispersion-precompensation values.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4230) Multiplexing.

References and links

1. ITU-T G.989.1, "40-Gigabit-capable passive optical networks (NG-PON2): General requirements."
2. D. van Veen, V. Houtsma, A. Gnauck, and P. Iannone, "40-Gb/s TDM-PON over 42 km with 64-way power split using a binary direct detection receiver," in *Proceedings of ECOC 2014*, Postdeadline Paper PD.1.4.
3. A. J. Price and N. Le Mercier, "Reduced bandwidth optical digital intensity modulation with improved chromatic dispersion tolerance," Electron. Lett. **31**(1), 58–59 (1995).
4. M. Nada, Y. Muramoto, H. Yokoyama, T. Ishibashi, and S. Kodama, "InAlAs APD with high multiplied responsivity-bandwidth product (MR-bandwidth product) of 168 A/W.GHz for 25 Gbit/s high-speed operations," Electron. Lett. **48**(7), 397–399 (2012).
5. IEEE Std 802.3av (2009).
6. D. van Veen, V. Houtsma, P. Winzer, and P. Vetter, "26-Gbps PON transmission over 40-km using duobinary detection with a low cost 7-GHz APD-based receiver," in *Proceedings of ECOC 2012.* Paper Tu.3.B.1 (2012).
7. V. Houtsma, D. van Veen, A. Gnauck, and P. Iannone, "APD-based duobinary direct detection receivers for 40 Gbps TDM-PON," in *Proceedings of OFC 2015*, Paper Th4H.1 (2015).
8. A. Lender, "Correlative Digital Communication Techniques," IEEE Trans. Commun. Technol. **12**(4), 128–135 (1964).
9. IEEE Std 802.3ba, clause 88 (2010).
10. D. van Veen, V. Houtsma, A. Gnauck, and P. Iannone, "Demonstration of 40-Gb/s TDM-PON over 42-km with 31 dB optical power budget using an APD-based receiver," J. Lightwave Technol. **33**(8), 1675–1680 (2015).

1. Introduction

Although optical access systems and core transport systems have distinct attributes and requirements, the historical evolution of commercial core transport can inform the current evolution of access. Early commercial transport systems were single-wavelength systems that relied solely on increases in line rate to increase capacity. The advent of cost-effective wavelength-division multiplexing (WDM), coupled with the development of the erbium-doped fiber amplifier (EDFA), allowed for an economical expansion in wavelength, thus reducing cost-per-bit while maximizing total capacity, the key drivers in transport. However, subsequent transport systems continued to expand in both wavelength and bit rate, leveraging cost and capacity improvements in each dimension.

For commercial passive optical network (PON) evolution, the key drivers are reducing cost-per-subscriber, while increasing bandwidth-per-subscriber to meet demand. Today, commercial PONs are at a similar evolutionary crossroads as the one previously faced by core

#241447 Received 20 May 2015; revised 28 Aug 2015; accepted 2 Sep 2015; published 8 Sep 2015

systems: After several PON generations of increased bit rates on an identical single-wavelength time-division-multiplexed (TDM) architecture, the Full Service Access Network (FSAN) group has proposed NGPON2, a time- and wavelength-division multiplexed (TWDM) PON that multiplies the bit rate by stacking 4 or 8 wavelengths with 10 Gb/s each [1]. FSAN abandoned the single-wavelength evolutionary path, not because WDM provided a steep cost reduction as was the case for core transport, but due to technical challenges associated with increasing the serial bit rate, including meeting the optical power budget and the decreased dispersion tolerance at 40 Gb/s.

Yet history has shown that continued serial bit rate increases are likely, as innovations and volumes bring down cost. We have previously demonstrated [2] a single-wavelength 40-Gb/s downstream bitrate using optical duobinary modulation [3] and a 25-Gb/s receiver [4] based on an avalanche photodiode combined with a transimpendance amplifier (APD-TIA). We obtained 31 dB of optical power budget and a 26-km differential reach at 1550 nm over an outside plant consisting of up to 42 km of standard single-mode fiber (SSMF) and a 64-way power split. In this paper we explore a four-channel wavelength-division-multiplexed (WDM) version of this system that can serve as a downstream upgrade to the 4 x 10-Gb/s NGPON2 system. We achieve a total 160-Gb/s downstream bit rate, and again obtain a 26-km differential reach at 1550 nm over an outside plant consisting of up to 42 km of SSMF and a 64-way power split.

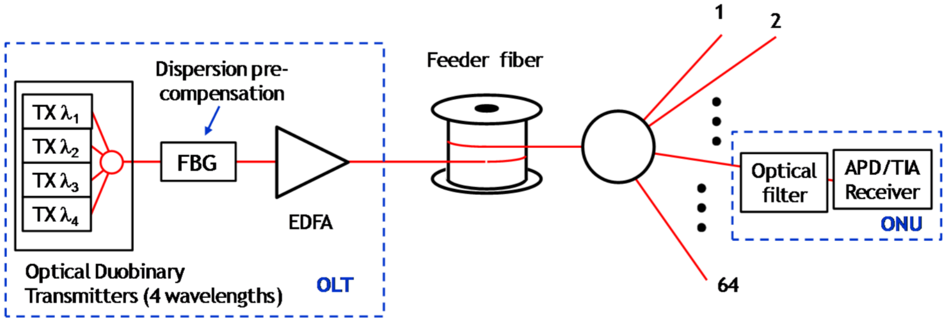

Fig. 1. Simplified diagram of the 160-Gb/s TWDM PON concept.

2. 4 × 40 Gb/s TWDM-PON experiment

The concept for our TWDM PON downlink is shown in Fig. 1. The optical line terminal (OLT) contains 40-Gb/s WDM optical duobinary (ODB) transmitters, whose outputs are combined and passed through a dispersion precompensator based on a fiber Bragg grating (FBG). The signals are amplified and transmitted through up to 42 km of standard single-mode fiber (SSMF) to a 1:64 splitter. Each output of the splitter serves an optical network unit (ONU), with the wavelength assigned to a particular ONU selected by an optical filter. In a commercial system, this would be a low-cost tunable filter, in keeping with the NGPON2 recommendation. For this experimental demonstration, we use an arrayed-waveguide grating (AWG) as the receiver's optical filter. This work focuses on demonstrating 40-Gb/s WDM downstream performance. The uplink can take advantage of existing 10-Gb/s TDMA technology [5]. For a symmetric system, the uplink would probably require a more cost-effective approach than the one we propose for downstream.

Our choice of ODB modulation permits both long reach and a high link budget, but at the cost of a somewhat more complex transmitter. Electrical duobinary (EDB) [6] and ODB have been proposed as chromatic dispersion-tolerant alternatives to non-return-to-zero (NRZ) modulation for use in high-speed PON downlinks. Both EDB and ODB use an inexpensive binary direct detection receiver at the ONU, but EDB is simpler and therefore less costly to implement at the transmitter, since the launched waveform is identical to NRZ. Comparing

#241447 Received 20 May 2015; revised 28 Aug 2015; accepted 2 Sep 2015; published 8 Sep 2015

the three formats [7], ODB has the highest chromatic dispersion tolerance, exceeding the reach of NRZ modulation by about a factor of two and that of EDB by about 1.3. Furthermore, stimulated Brillouin scattering (SBS) is effectively suppressed by ODB due to the absence of an optical carrier, enabling higher optical launched power for achieving a larger optical power budget. Since ODB modulation requires modulating both optical amplitude and phase, we use Mach-Zehnder modulators (MZMs) to modulate the light from continuous-wave lasers. However, because the MZM is a shared component it is less cost sensitive as compared to components in the ONUs.

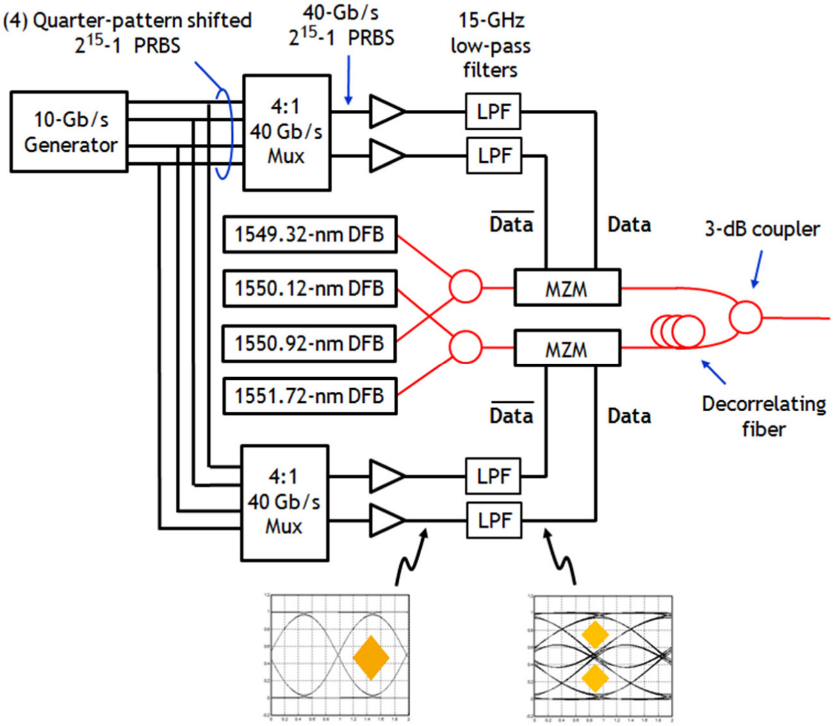

Fig. 2. Experimental implementation of the ODB transmitters. Insets show simulated (noise-free) electrical drive signals before and after low-pass filtering. The yellow regions represent the eye openings.

Figure 2 shows the detailed experimental setup of the ODB transmitters. The four laser sources are distributed-feedback (DFB) lasers operating on a 100-GHz grid from 193.5 THz to 193.2 THz (1549.32 nm to 1551.72 nm). Two transmitters are used, one for the two odd channels and one for the two even channels. Four 10-Gbps pseudo-random bit sequences (PRBSs) of length 2^{15}-1 are multiplexed together to form differential 40-Gbps 2^{15}-1 PRBS signals. These signals are then low-pass filtered with 15-GHz filters to generate three-level signals which differentially drive a MZM having 35 GHz 3-dB bandwidth. The noise-free simulated eye diagrams included as insets in Fig. 2 show the shape of the electronic drive signals before and after low-pass filtering. In a commercial system, a lower speed 15-GHz MZM could have been used in place of the high-speed modulator and low-pass filter. Biasing the MZM at the null generates the ODB signal. Although the ODB eye has two intensity levels, resembling an NRZ eye, it is characterized by 3 distinct states: a zero state and two ones states separated by pi phase shift. To avoid error propagation and to simplify the receiver circuitry when using real data, a precoder would be employed at the transmitter when using duobinary modulation [8]. In the case of a pseudorandom binary sequence (PRBS) pattern, as in our experiments, it is not needed. A length of fiber is used to decorrelate the data from the two transmitters. Manual polarization controllers and a polarizing beamsplitter (not shown) are used to assure that the signals are co-polarized when they are combined in a 3-dB optical coupler, resulting in the worst case for linear-crosstalk and fiber-nonlinearity penalties.

The stringent link budget and reach requirements for the latest PON standards create challenges in either the C band (low loss and high chromatic dispersion) or O band (higher loss and low chromatic dispersion). For our experiment we have selected the C band for lower loss. To compensate for the accumulated chromatic dispersion (approximately 17 ps/nm/km at 1550 nm in our SSMF), we use FBG-based dispersion compensation. Had we operated in the O band, the dispersion compensation would have been unnecessary, but the link budget would have suffered slightly due to the increased fiber loss in this band. An erbium-doped fiber amplifier (EDFA) is then used to boost the total launched optical power to + 18 dBm (+ 12 dBm per channel), which was found to be the optimum power (limited by fiber nonlinearity) for the maximum reach of 42.4 km. This is significant because it is the same power that was found to be the optimum in the single-channel case [2], indicating that inter-channel nonlinear effects are negligible. We note that, as with the MZM, the FBG and EDFA are shared components, and therefore less cost-sensitive than components in the ONU.

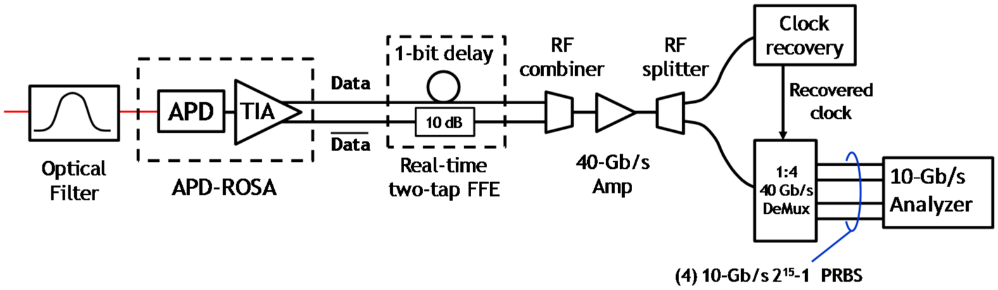

Fig. 3. Experimental implementation of the APD-based receiver.

The experimental setup of the receiver is shown in Fig. 3. Before the detector, a single wavelength is selected using a fixed optical filter. For the filter we use one channel of an arrayed waveguide grating (AWG) with 100-GHz channel spacing and 50-GHz −3-dB bandwidth. The optical filter has insertion loss of 3 dB, and the crosstalk from adjacent channels is ≤35 dB, as shown in Fig. 4. As mentioned previously, a deployed system would employ a tunable filter rather than a fixed filter at the ONU for wavelength selection. A 25-Gb/s APD-TIA receiver is used in conjunction with the transmitter's high launch power to achieve the large optical power budget typical of standardized PONs, at a lower cost and power consumption relative to an optically pre-amplified receiver. The 25-Gb/s APD-TIA receiver optical subassembly (ROSA) was developed for the 100G Ethernet standard [9], and is expected to mature and become low cost in the near future. The measured receiver −3-dB bandwidth of 15 GHz results in a receiver power penalty when used at 40 Gb/s. To reduce this penalty, a simple 2-tap feed-forward equalizer (FFE) is implemented by combining the differential receiver outputs after one output is attenuated and delayed by one bit. This simple FFE circuit has been shown to improve sensitivity by more than 1 dB [10]. After equalization, the clock is recovered and the 40-Gb/s data stream is de-multiplexed to four 10-Gb/s streams, each with virtually identical performance, for real-time bit-error-rate (BER) measurements.

#241447 Received 20 May 2015; revised 28 Aug 2015; accepted 2 Sep 2015; published 8 Sep 2015

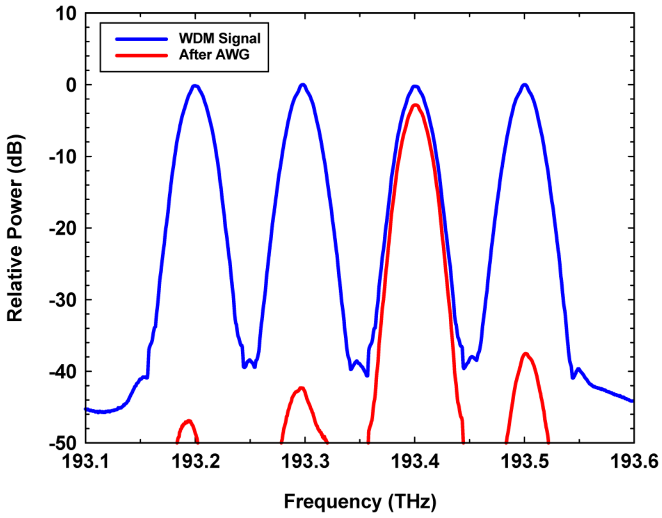

Fig. 4. Spectrum of the 4-channel ODB signal before and after filtering by the AWG. Resolution: 0.05 nm.

3. Experimental results

Figure 5 shows the back-to-back receiver performance with the 2-tap equalizer, where red squares and blue circles represent BER data for single-channel NRZ and ODB, respectively. For consistency, all powers were measured at the input of the APD (i.e. after the optical filter for the WDM case). The power needed to reach a BER of $1.0\text{x}10^{-3}$, the raw BER corresponding to a post-FEC BER of $1.0\text{x}10^{-12}$, is −23.0 dBm for NRZ, while it is −21.2 dBm for ODB due to the increased intersymbol interference of the ODB signal (see eye patterns in Fig. 4 insets). The black triangles and green inverted triangles show the BER data for ODB in WDM operation and using the AWG filter, for the inner even and odd channel, respectively. Near the FEC limit, performance of the two transmitters is very similar, and there is a small improvement relative to the single-channel case due to the optical filtering.

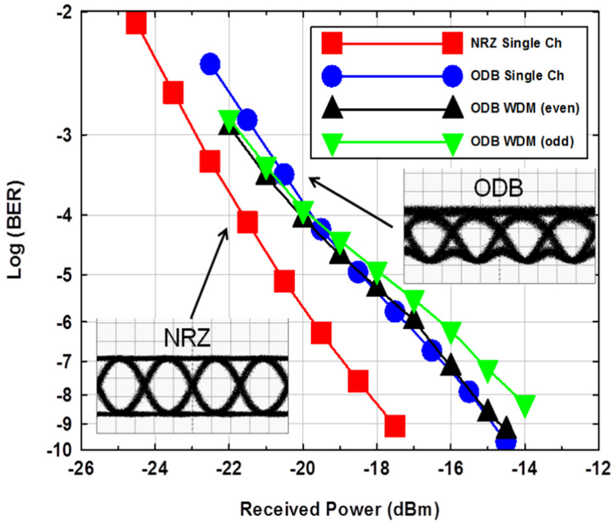

Fig. 5. Back-to-back performance for single-channel NRZ and ODB (without the AWGR), and for 4-channel WDM ODB (odd and even inner channels). Insets: transmitted eyes.

#241447 Received 20 May 2015; revised 28 Aug 2015; accepted 2 Sep 2015; published 8 Sep 2015

Figure 6 shows the 1:64 PON transmission results for the channel at 193.4 THz. We demonstrate two different reaches (0-26.9 km and 15.7-42.4 km) by appropriately setting the dispersion precompensation: The −330-ps/nm FBG was concatenated with either a length of SSMF or dispersion-compensating fiber to obtain the required precompensation values of −224 ps/nm or −488 ps/nm, respectively. Obviously, FBGs can be designed for particular required values. Compared with our single-channel work [2], the power margin (received power minus receiver sensitivity) is lower due to the 3-dB loss of the AWG used as the receiver optical filter. However, there is little degradation from inter-channel fiber nonlinear effects. Finally, at the longest reach of 42.4 km, we confirmed that all WDM channels attained a BER of $1.0\text{x}10^{-3}$, and that their performance was the same within ± 0.1 dB.

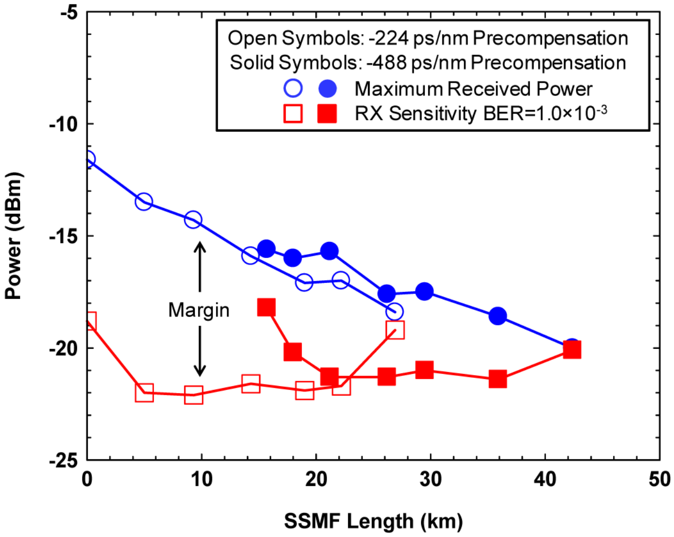

Fig. 6. Transmission results for the inner channel at 193.4 THz over the 1:64 TWDM PON for two values of dispersion precompensation (−224 ps/nm and −488 ps/nm).

4. Summary

We have demonstrated downstream transmission in a 4 × 40-Gb/s TWDM PON over a 42-km-SSMF, 64-split fiber plant, that can serve as an upgrade to the 4 x 10-Gb/s NGPON2 downstream method currently being standardized by FSAN and ITU-T. The optical duobinary modulation format provides improved chromatic dispersion and nonlinearity tolerance as compared to standard NRZ signaling, resulting in longer reach and permitting higher launched power. We use a booster EDFA to launch + 18 dBm (+ 12 dBm/ channel) into the fiber and a fiber Bragg grating to offset outside-plant fiber dispersion for operation in the C-band. Using a 25-Gb/s APD/TIA receiver we obtain a differential reach of 26 km at 1550 nm without any form of digital signal processing. Compared with our previous single-channel work, we find little degradation in performance at a per-channel launched power of + 12 dBm, other than the reduction in power margin due to the 3-dB loss of the optical filter at the receiver. An obvious constraint of this C-band system is the fact that the same PON cannot simultaneously serve the nearest (0-16 km) and farthest (26-42 km) users, due to the required choice of dispersion precompensation value. Operation in O-band would not require dispersion precompensation and thus a single PON design could operate over the full 0-40 km range addressed by the ITU-T standard, but would require higher launch power to offset the increased fiber loss.

#241447 Received 20 May 2015; revised 28 Aug 2015; accepted 2 Sep 2015; published 8 Sep 2015

Acknowledgment

The authors thank Atul Srivastava and the NTT Electronics Corp. team for their technical contribution.

#241447 Received 20 May 2015; revised 28 Aug 2015; accepted 2 Sep 2015; published 8 Sep 2015