Experimental Demonstration of FTN-NRZ, PAM-4, and Duobinary Based on 10-Gbps Optics in 100G-EPON

Volume 10, Number 5, October 2018

Hong-Bo Zhang
Ning Jiang
Zhi Zheng, Member, IEEE
Wen-Qin Wang, Senior Member, IEEE

DOI: 10.1109/JPHOT.2018.2858804
1943-0655 © 2018
Experimental Demonstration of FTN-NRZ, PAM-4, and Duobinary Based on 10-Gbps Optics in 100G-EPON

Hong-Bo Zhang ©, Ning Jiang ©, Zhi Zheng ©, Member, IEEE, and Wen-Qin Wang ©, Senior Member, IEEE

School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

DOI: 10.1109/JPHOT.2018.2858804

Abstract: This paper presents an experimental demonstration of 100-Gbps time- and wavelength-division multiplexed passive optical network (TWDM-PON) with 4 × 25-Gbps downstream transmission. We take a comparison of faster-than-Nyquist nonreturn-to-zero (FTN-NRZ), four-level pulse amplitude modulation (PAM-4), electrical duobinary (EDB), and optical duobinary (ODB) on the same transmission link. The use of low-cost 10-Gbps optics in combination with digital signal processing (DSP) makes it feasible for a 25-Gb/s per wavelength transmission over 20-km standard single-mode fiber (SSMF) in a cost-effective way. The spectra efficiency and ISI robustness by going to the higher rate are analyzed theoretically. We achieve link budgets of 33.18 dB for FTN-NRZ, and less than 30 dB budgets for PAM-4, ODB, and EDB in downstream transmission. FTN combination with feedforward equalization (FFE) allows FTN-NRZ to have a 4.18 dB margin in power requirement of PR(30) of 10G-EPON, whereas PAM-4 and ODB with FFE also meet PR(30) with 0.25 dB margin. The results indicate that FTN-NRZ, PAM-4, and ODB can be used for 100G-EPON with 10-Gbps optics, and FTN-NRZ has better performance than other modulations, which is more suitable for next-generation 100G-EPON transmission technique with low cost.

Index Terms: 4-level pulse amplitude modulation (PAM-4), 100G-EPON, duo-binary modulation, faster-than-Nyquist NRZ (FTN-NRZ).

1. Introduction

Internet of things (IoT), cloud services, web scale ecosystem, mobile front-haul (MFH) in the 5th generation mobile era (5G) [1], [2], and 4K/HD video are dramatically driving the increasing of bandwidth demand in broadband access networks. Cisco has reported that the internet traffic is expected to continue growing, whose speed is more than twice between 2016 and 2021, which means that the global internet traffic will be beyond 100 Tb/s in 2021 [3]. To satisfy these enormous bandwidth demanding, the international standardized organizations, Full Services Access Networks (FSAN) and Institute of Electrical and Electronics Engineers (IEEE), have recently initiated to investigate the roadmap for future passive optical network (PON) [4], [5]. The IEEE P802.3ca 100G Ethernet PON Task Force has started to specify the physical layer (PHY) parameters since 2016 for next-generation 25/50/100-Gb/s Ethernet PONs (NG-EPONs). Currently, IEEE 100G-EPON

Vol. 10, No. 5, October 2018 7905813
IEEE Photonics Journal Demonstration of FTN-NRZ, PAM-4, and Duobinary

discuss the 100-Gb/s based PON by exploiting 4 pairs of wavelength division multiplexing (WDM) channels on each with 25-Gb/s transmission. Recently, Derek reported the PON roadmap and introduced technologies for the evolution of PON systems [6]. Vincent also reported the recent progress on the standardization of next generation 100G-EPON [7]. Considering the cost and power consumption, intensity modulation and directly detection (IMDD) transmission systems are preferred in NG-PONs, rather than the coherent detection scenarios [8]–[11]. In IEEE P802.3ca 100G Ethernet PON Task Force, 25-Gbps optics are employed to transmit the 25-Gb/s/wavelength signal. This could reduce the digital signal processing (DSP) complexity of transceiver, while the 25-Gbps optics cost high currently. At present, the 10-Gbps optics is a good candidate for the achievement of 100G-EPON for its technically high volume mature and effective cost. This is helpful to upgrade 10-Gb/s PONs to the next generation of 100G-PONs without additional costs. Consequently, 25-Gb/s per wavelength transmission system has been recommended employing 10-Gbps optics to achieve low-cost high-capacity PON transmissions.

Increasing the spectral efficiency (SE) is one effective method for high-capacity transmission based on band-limited optical devices. Recently, several alternative spectrally efficient modulations, such as discrete multi-tone (DMT) quadrature amplitude modulation (QAM) [12]–[14], four-level pulse amplitude modulation (PAM-4), and duo-binary (DB) [15]–[18], have been investigated in NG-PON2. DMT is considered suitable for WDM-PON thanks to its high spectrum efficiency, flexible bandwidth configuration, robustness against fiber chromatic dispersion (CD), and orthogonality for convergent multi-band orthogonals frequency division multiplexing (OFDM). However, DMT is much more complex than traditional NRZ, PAM-4, and duo-binary. Moreover, a return-transmission channel is commonly necessary for taking full advantage of bit loading and power loading techniques for DMT in reality implementation. Consequently, this will take more complexity and cost in system design. PAM-4 requires quite good linearity of optical devices and has more optical modulation amplitude (OMA) penalty. The penalty of PAM-4 compared to NRZ is about 4.77 dB. This penalty is evaluated by $10 \times \log_{10} (M - 1)$ called vertical eye closure penalty (VECP) [19], where $M$ is the levels. Electrical duo-binary (EDB), with a precoding component and an equivalent digital low-pass filter (LPF) at the transmitter to get a three-level signal, has a halved bandwidth of NRZ. Similar to PAM-4, EDB has a 3 dB OMA penalty compared to NRZ. Optical duo-binary (ODB), which is another duo-binary modulation, employed in GPON can be configured at transmitter optical sub-assembly (TOSA) to enhance CD robustness, while it needs an expensive dual-drive Mach-Zehnder modulator (DD-MZM) at the transmitter. Although there are drawbacks for PAM-4 and duo-binary, such as VECP or the use of external modulator, they are alternatives for 25-Gb/s transmission based on 10-Gbps optics for band-limited transmission scenarios due to their high spectral efficiency. Besides, there is another problem should be considered in 25-Gbps PON using directly detection based on 10-Gbps optics, which is the inter-symbol interference (ISI) caused by bandwidth limitation and fiber chromatic dispersion. To deal with the ISI, some DSP technologies such as Tomlinson-Harashima precoding (THP) [20], linear pre-emphasis equalization, nonlinear digital pre-distortion (DPD), feedforward equalization (FFE), decision feedback equalization (DFE), and maximum likelihood sequence estimation (MLSE) are adopted at transmitter and receiver DSP components.

25-Gb/s per wavelength ODB transmission of 4-wavelengths with 16-GHz APD was investigated in [21]. With the rewarding of post-equalization, the receiver sensitivity of $-27$ dBm after 20-km standard single-mode fiber (SSMF) transmission was achieved. A real time PON downstream 4 × 25-Gb/s NRZ-OOK was also conducted to perform its transmission power budget. A single delay interferometer (DI) was employed to combat the chromatic dispersion [22]. Jun-qi Xia et al. compared the requirements of FFE/DFE for NRZ and duo-binary in 10G-optics based 25G-EPON [23]. They achieved a receiver sensitivity of $-23.45$ dBm over SMF 25-km transmission with 17-tap FFE and 5-tap DFE. Since NRZ is utilized in 1-Gb/s and 10-Gb/s PON scenarios, its transceiver is very mature. Hence, NRZ is able to compatible with existing optical access network easily by traditional NRZ transceiver without additional optoelectronic devices. Also it is helpful for upgrading the smooth transition of next generation higher capacity PONs. Thanks to the DSP technologies, 25-Gb/s NRZ transmission based on 10-Gbps optics is available using faster-than-Nyquist (FTN)
algorithm, namely FTN-NRZ technique [24]–[26]. FTN signal can achieve higher SE compared to Nyquist signal using the same bandwidth and transmit power. Therefore, FTN-NRZ is a potential scheme for 25-Gb/s transmission based on commercial mature 10-Gbps optics.

The power budgets of 25-Gb/s transmission are discussed in IEEE P802.3ca 100G Ethernet PON Task Force, and PR30 with 29 dB of power budget is required [27]. In this paper, we systematically investigate the performance of the 10-Gbps optics based 25-Gb/s downstream transmission system adopting FTN-NRZ, PAM-4, EDB, and ODB. A 20-km SSMF transmission link is used without inline optical amplifier and dispersion compensation fiber (DCF). It is demonstrated that FTN-NRZ, PAM-4, and ODB with FFE equalization meet 10G-EPON PR(x) 30 power budget requirement. Especially, FTN-NRZ with the beneficial of FFE and FTN technologies can achieve a receiver sensitivity of $-27.18$ dBm and a link budget of 33.18 dB, while PAM-4 and ODB with FFE equalization achieved a sensitivity of $-23.25$ dBm. The results show that the FTN-NRZ has a superior performance than PAM-4 and duo-binary modulations.

2. Principles and Theoretical Analysis

2.1 Principle of Faster-Than-Nyquist Signal

The FTN-NRZ transceiver consists of FTN precoding with transmission at a higher rate than the Nyquist, matched filter, FFE equalizer, whitening filter, and FTN decoder. The FTN signal transmitted in the optical fiber communication system can be expressed as:

$$s_a(t) = \sqrt{E_s} \sum_n a[n] h(t - n\tau T),$$  

where $E_s$ is the energy per symbol for Nyquist signal, $a[n]$ is the information symbol, $T$ is the symbol period, and pulse shaping $h(t)$ which is the FTN precoding filter, generates $T$-orthogonal pulses at a rate $1/T' = 1/(\tau T)$, wherein $\tau \leq 1$ is the acceleration constant. $E_{FTN}^s = E_s \tau$ is the energy per symbol in an FTN system. Particularly, the form of FTN signal will be the same as Nyquist signal as $\tau = 1$. Here the transmission signal is propagated through an additive white Gaussian noise (AWGN) channel and a matched filter at the signal rate of $\tau T$ is employed at the receiver, then the output of matched filter can be written as:

$$y[n] = \int_{-\infty}^{+\infty} r(t) h(t - n\tau T) \, dt = \sqrt{E_s \tau} \sum_m a[m] g[n - m] + \tilde{z}[n],$$  

$$g(n - m) = \int_{-\infty}^{+\infty} h(t - m\tau T) h(t - n\tau T) \, dt$$

$$\tilde{z}[n] = \int_{-\infty}^{+\infty} z(t) h(t - n\tau T) \, dt.$$  

Subsequently, the correlation of the noise sequence is

$$E(\tilde{z}[n] \tilde{z}[m]) = N_0 g[n - m].$$

This means the output noise samples of FTN signal are correlated. Furthermore, filters and equalizers, such as matched filter, FFE and DFE, are employed on the sampling signal, they also would generate the additional correlated noise. Because the FTN decoder based on MLSE has been developed under the assumption of white Gaussian noise, we need to whiten the noise before FTN decoder. In our work, root raised cosine (RRC) filters with roll-off factor of 0.12 and acceleration constant of 0.8 are adopted as precoding filter and matched filter. The matched filter is employed to match the transmission pulse with sampling at the FTN rate. To get a better FTN performance, a whitening post-filter based on Levinson-Durbin (LD) recursion [28] is designed before FTN decoder.
2.2 Principles of EDB and Differential Phase ODB Signal

EDB and ODB are two common duo-binary modulation technologies in optical fiber transmissions corresponding to intensity modulation and field modulation, respectively. An EDB signal generated by the sum of two neighboring symbols has a halved bandwidth of NRZ with the same bitrate, which can be represented as follows [29]:

\[ c_k = a_k + a_{k-1} \]  

where \( a_k \) is the NRZ symbol and \( c_k \) is the coded EDB symbol. Generally, to avoid error propagation, precoding with exclusive-or (XOR) operation is conducted before the EDB coding,

\[ b_k = a_k \oplus b_{k-1} \]  

where \( b_k \) is the output of EDB precoding. Thus, the process of EDB coding with precoding can be written as:

\[ c_k = b_k + b_{k-1} \]  

The process of EDB coding is depicted in Fig. 1. The NRZ 2-level real value signal transmits into the precoding and EDB coding modules. Through these two coding circuits, the original 2-level real value signal converts to 3-level value real signal. As a result of this, EDB signal is possible to be modulated on optical signal by intensity modulation using directly modulated lasers (DMLs), electro-absorption modulated lasers (EML), or low power consumption vertical cavity surface emitting lasers (VCSEL). A 3-level hard decision device and modulus 2 operation are necessary at the receiver, which is different from traditional NRZ receiver. The decoder of 3-level EDB signal can be expressed as:

\[ \text{mod}(c_k, 2) = \text{mod}(b_k + b_{k-1}, 2) = b_k \oplus b_{k-1} = a_k \oplus b_{k-1} \oplus b_{k-2} = a_k \]  

ODB is another typical duo-binary modulation method, which employs DD-MZM to realize filed modulation. The generation of ODB signal is similar to that of EDB, a precoding module is also needed. While different from the EDB, the duo-binary coder is replaced by a DD-MZM. In our experiment, we adopt the ODB coding with differential phase in [30], and a linear equalizer is adopted to compensate the ISI impairment introduced by the bandwidth limitation. The ODB coding schematic is shown in Fig. 2. After the NRZ precoding, the coded sequence \( b_k \) and its one symbol delay sequence \( b_{k-1} \) are used as the dual-drive inputs of a DD-MZM to realize optical up-conversion. With the field modulation of DD-MZM, the precoding signal is converted to an ODB signal.

To present the differential phase ODB generation process explicitly, assuming the bit stream \( a_k \) is \([1, 0, 0, 1, 0, 1, 1, 0] \), we will get a new bit stream \( b_k \) after the precoding: \([0, 1, 1, 1, 0, 0, 1, 0, 0] \), and its delayed stream \( b_{k-1} \): \([0, 0, 1, 1, 1, 0, 0, 1, 0] \). The two signals are used to drive the
up-branch and low-branch of DD-MZM, respectively. When the DD-MZM works at the null point, its output is \( c'_k = b_k - b_{k-1} \). In such a case, the generated ODB signal in optical field is \([0, +1, 0, 0, -1, 0, +1, 0, -1, 0]\), as depicted in Fig. 2. There is a phase difference of \( \pi \) between the adjacent positive signal and negative signal. In optical fiber transmission, as the two opposite optical field pulses broadening by chromatic dispersion, the positive and negative parts will weaken the impairment rather than strengthen the ISI as the non-differential phase signals do.

In optical field, the amplitude of ODB signal \( c'_k \) presents three levels: \([-1, 0, +1]\). The ODB signal received by photodiode (PD) can be presented as follows:

\[
d_k = |c'_k| \\
= \text{mod}(c'_k + 2, 2) \\
= \text{mod}(b_k - b_{k-1} + 2, 2) \\
= b_k \oplus \text{mod}(2 - b_{k-1}, 2), \quad b_{k-1} \in \{0, 1\} \\
= a_k \oplus b_{k-1} \\
= a_k \\
(9)
\]

where \( d_k \) is the PD output, and \( b_{k-1} \in \{0, 1\} \). In ideal scenarios, \( d_k \) would equal to the original bit stream \( a_k \). Therefore, the detected ODB signal is compatible with the traditional NRZ receiver.

### 2.3 Spectra Comparison

In previous discussions, we have briefly introduced the principle of FTN-NRZ, EDB and ODB. To make a clear comparison of the transmission bandwidths for these signals, we show their spectra and eyediagrams in Fig. 3 with the same line bit rate of 28-Gb/s. As a high spectra efficiency multi-level modulation, the spectrum of PAM-4 is also depicted in Fig. 3. The results indicate that NRZ signal has the widest bandwidth, PAM-4 and EDB signals have a halved bandwidth of NRZ. FTN-NRZ has almost a halved bandwidth of NRZ with a roll-off factor of 0.12 of RRC.

The baud rate of PAM-4 with total line rate of 28-Gb/s is 14-Gbaud, which means that it occupied a bandwidth of 7-GHz. So that the bandwidth of PAM-4 is not limited by the 10-Gbps class experimental setup. Nevertheless, as we previously mentioned that PAM-4 has a penalty with respect to the NRZ for its multi-level decision and VECP. In addition, PAM-4 always has nonlinearity impairment in intensity modulation for its high linear requirement. Which means that the receiver would have a sensitivity reduction although it is a non-band-limited transmission system.
For the other three band-limited transmission systems, as aforementioned that the detected ODB signal \( d_k \) (in electric domain) at receiver end is an NRZ signal, and then its spectrum is the same as normal NRZ. As a digital LPF with taps \([1, 1]\) is used for EDB coding, EDB has a halved bandwidth of NRZ. So that the transmission bit rate of EDB is two times that of NRZ with the same bandwidth. FTN-NRZ introduces a controllable ISI and achieves a much smaller bandwidth than NRZ. Its bandwidth, as depicted in Fig. 3, is almost the half of conventional NRZ, which is very similar to that of EDB. Hence, transmission of 25-Gb/s using FTN-NRZ is feasible by employing 10-Gbps optics.

According to the spectra analysis and comparison, with the help of duo-binary and FTN techniques, FTN-NRZ, PAM-4, and EDB almost have the halved bandwidth of traditional NRZ. Therefore, it is possible that upgrading line bit rate from 10-Gb/s to 25-Gb/s based on existing 10G-PON transmissions with 10-Gbps optics.

### 2.4 ISI Robustness Analysis of CD

As we analyzed in previous subsection, there are enough bandwidth for FTN, PAM-4, and EDB transmission with 25-Gb/s based on 10-Gbps optics because of their narrow spectra. Therefore, the ISI impairment introduced by transmission channel is decreased; and the controllable ISI introduced by precoding can be compensated at the receiver. While for ODB signal, as aforementioned, its received pulse is similar to NRZ and consequently its bandwidth is limited. The ISI impairment introduced by bandwidth limitation and chromatic dispersion should be considered. We have analyzed the ISI robustness of ODB signal in fiber channel by broadening its pulse introduced by ISI.

To demonstrate this ODB ISI robustness, we take a comparison between NRZ and ODB transmission. Both of the two chromatic dispersion impairment demonstrations are depicted in Fig. 4. Fig. 4(a) shows that there is 1-bit error as two adjacent high-level pulses broadened in red dash lines. The wrong decision will occur at center symbol “0”. The decision result is \([1, 1, 1]\). While in Fig. 4(b), as the pulses broadened, plotting in red and blue dash lines, the two ODB signals with inverse phase will be cancelled each other at symbol “0” as plotting in black solid line. So that the decision result is still \([1, 0, 1]\) without any bit error.

To mathematically analyze the ISI robustness of ODB, assuming the original NRZ pattern \( a_k \) is \([1, 0, 1]\) with initial index \( n + 1 \), i.e., \( a_{n+1} = 1, \ a_{n+2} = 0, \ a_{n+3} = 1 \). The corresponding values of precoding stream \( b_k \) and ODB sequence \( c_k \) are listed in Table 1. We noticed that both values of \( a_{n+1} \) and \( a_{n+3} \) are symbol “1” before precoding. After ODB coding, they have the same absolute value of “1” while with a phase difference \( \pi \). Thereby the differential phase enhance the ISI robustness as the two pulses broadening along with the fiber propagation.

On the basis of the preceding analysis, the ISI robustness of ODB outperforms NRZ signal and other multi-level intensity modulation signals, such as PAM-4 and EDB. It is because of that PAM-4 and EDB with multi-level signal have the same modulation method with NRZ and have the same
Fig. 4. Schematic of ISI robustness introduced by fiber chromatic dispersion for NRZ and ODB signal: (a) ISI illustration of NRZ, (b) ISI illustration of ODB.

TABLE 1
ISI Robustness of ODB for Pattern: [1, 0, 1]

<table>
<thead>
<tr>
<th>index</th>
<th>n</th>
<th>n+1</th>
<th>n+2</th>
<th>n+3</th>
<th>n+4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_k$</td>
<td>$\cdots$</td>
<td>$\alpha$</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$b_k$</td>
<td>$b$</td>
<td>$a \oplus b$</td>
<td>$1 \oplus a \oplus b$</td>
<td>$0 \oplus a \oplus b$</td>
<td>$1 \oplus a \oplus b$</td>
</tr>
<tr>
<td>$c_k$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$A$</td>
<td>0</td>
<td>$-A$</td>
</tr>
</tbody>
</table>

modulation characteristic. So that the ODB could achieve a better performance than the other three modulations with the same ISI.

3. Experimental Setup
To take a fair comparison in experiments, all these modulations of FTN-NRZ, PAM-4, EDB, and ODB are evaluated on the same optical fiber transmission link. Fig. 5 presents the experimental setup to evaluate the IMDD-based FTN-NRZ, EDB, and PAM-4 transmission system. They almost have the same transceiver except the symbol coder and decoder parts, which are described in previous section. For the ODB transmission system, it needs an extra DD-MZM. We depicted its
experimental setup in Fig. 6. EDFA was not adopted in both of the two schemes to investigate the cost-effective transmissions. In Fig. 5, the bit stream is firstly mapping into NRZ or PAM-4 symbols then followed a configurable coding filter (CCF). CCF is a filter array, which can be configured by a software controller. This software defined modulation (SDM) method is useful in system upgrade and for backward compatible to lower down the costs. This CCF includes two filters: a band-limited pulse shaping filter (FTN pre-coding) and an EDB coder filter. If the two filters are bypassed, the output of the CCF is NRZ or PAM-4 signal, which should be determined by previous symbol mapping module. A pre-emphasis equalization is used to compensate the high frequency attenuation by the narrow-band devices. The pre-emphasis equalization employs a 7-taps linear FIR filter, and its taps is configurable. In our experiments, we conducted two times pre-emphasis over the transmission. For the first time, we downloaded the system S21 parameters to the pre-emphasis equalization taps. For the second time, the response of normal signal transmission was evaluated and calculated. With this calculated normal signal response, we modified the original S21 parameters and conducted the transmission again. To achieve a net rate with 100-Gb/s transmission based on 10-Gbps class optical devices, four EMLs were used as WDM light sources. Each EML modulated on 25-Gb/s net line bit rate. The system transmitted 100-Gb/s net line rate over 20-km SSMF in C-band without in-line optical amplifier. After the fiber transmission, an optical band-pass filter (OBPF) was adopted to emulate a WDM de-multiplexer. An APD with 3-dB bandwidth of 7.5-GHz (Oclaro AT10EC) directly detected the filtered optical signal. Then a digital storage oscilloscope (DSO) with sampling rate of 80-GSamples/s and 20-GHz analog bandwidth was used to emulate the ADC and captured the received signals. The quantification bits of the ADC is 8. These captured signals were demodulated by off-line program. In our off-line DSP program, the signals were first re-sampled at a sample rate of $2 \times R_s$. Which means that our followed DSP algorithms work at two samples per symbol (2-SPS). An automatic gain controller (AGC) circuit controlled the input signals power for DSP. Then
the power-stable signals were filtered by a matched filter and followed a digital timing recovery (TR). Simple Mueller-Muller phase detector detected the clock phase error. With this phase error, a digital interpolation filter could recover the timing from the filtered signals. For all the signals, FTN-NRZ, PAM-4, EDB and ODB, a linear FFE with 17-tap \( T_s/2 \)-spaced equalized the ISI introduced by narrowband limitation and fiber chromatic dispersion. In addition, to improve the performance of FTN-NRZ band-limited signal, a FTN-NRZ unit with components of post filter and MLSE, was adopted at the last part of the DSP. The MLSE module has 3-tap and 4-state in our experimental processing. Finally, we measured the performance of received optical power (ROP) versus BER by counting the number of error bits. The variation of ROP controlled through a variable optical attenuator (VOA) in the fiber link before OBPF.

Due to the optical field modulation, ODB needs an extra DD-MZM and works at its null point. Hence, there are some differences for the experimental setup of ODB from intensity modulation setup. The experimental setup of ODB shows in Fig. 6. At the transmitter, two electrical signals with \( 1-T_s \) time delay differential drive the DD-MZM, and they are up-converted to optical signal. While at the receiver, the detected signal by APD are normal NRZ signal. Therefore, we re-used the previous FTN-NRZ receiver excluding the FTN-NRZ unit.

The adopted key parameter values of transmitter optical sub-assembly (TOSA) and receiver optical sub-assembly (ROSA) in our experiment are listed in Table 2. The pattern length of the bits is \( 2^{17} \). The bandwidths of the optical devices are measured at 3-dB attenuation.

### 4. Experimental Results

Firstly, the transmission performance of the 25-Gb/s FTN-NRZ signal for optical back-to-back (oBtB) and over 20-km SSMF transmission distance was experimentally investigated. Fig. 7 presents the measured BER curves as a function of ROP. The minimum required received optical power (rROP) for oBtB is \(-28.3 \) dBm at the FEC limit (25% overhead hard-decision FEC with pre-FEC BER of \( 1 \times 10^{-3} \)). While the minimum rROP is \(-27.18 \) dBm at the FEC limit for 20-km SSMF fiber transmission. There is 1.12 dB power penalty for 20-km SSMF transmission. To improve the rROP performance, more FFE and PF taps of FTN can be configured, while that will increase the DSP complexity and take more power consumption.

Fig. 8(a) shows the received power penalty of 20-km SSMF transmission for PAM-4. In these experimental results, the required ROPs of oBtB and 20-km SSMF at FEC limit are \(-23.91 \) dBm and \(-23.25 \) dBm, respectively. Therefore, this penalty is 0.66 dB at FEC limit. Its penalty is almost
Fig. 7. Experimental results of FTN-NRZ for optical back-to-back vs. single-mode fiber over 20-km transmission.

Fig. 8. Experimental results of PAM-4 and EDB for optical back-to-back vs. single-mode fiber over 20-km transmission: (a) ROP versus BER of PAM-4, and (b) ROP versus BER of EDB.

the half of FTN-NRZ. Because PAM-4 has a higher modulation order, its baud rate is half of NRZ. The impairment from pulse broadening of PAM-4 introduced by fiber chromatic dispersion is lower than high baud rate NRZ signal. For EDB signal experimental results, represents in Fig. 8(b), although EDB reduces its bandwidth by introducing controllable ISI, its baud rate is not reduced with the same baud rate as NRZ. So that the penalty is 3.21 dB, it is higher than PAM-4. Parts of the
Fig. 9. rROP comparison of NRZ, EDB, and PAM-4: (a) ROP versus BER for oBtB, and (b) ROP versus BER for 20-km SSMF transmission.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Configure</th>
<th>Sensitivity</th>
<th>Link budget</th>
<th>PR(x) 30:margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTN-NRZ</td>
<td>pre/post-FTN FFE</td>
<td>-27.18</td>
<td>33.18</td>
<td>4.18</td>
</tr>
<tr>
<td>PAM-4</td>
<td>FFE</td>
<td>-23.25</td>
<td>29.25</td>
<td>0.25</td>
</tr>
<tr>
<td>EDB</td>
<td>FFE</td>
<td>-21.73</td>
<td>27.23</td>
<td>-1.27</td>
</tr>
<tr>
<td>ODB</td>
<td>FFE</td>
<td>-23.25</td>
<td>29.25</td>
<td>0.25</td>
</tr>
<tr>
<td>ODB</td>
<td>w/o FFE</td>
<td>-22.38</td>
<td>28.38</td>
<td>-0.62</td>
</tr>
</tbody>
</table>

penalty come from ISI and VECP. If we employed complex equalizations to equalize EDB signal, such as FTN technologies, both of the penalty and rROP at the FEC limit will decreased. However, employing these complicated equalizations to EDB, there will be no any advantage compare with FTN-NRZ. Thus, we just use linear FFE as the receiver equalizer to compensate the ISI and chromatic dispersion impairments.

Next, we make the penalty comparisons of oBtB and 20-km SSMF transmissions in Fig. 9 for all the transmissions in our experiment: FTN-NRZ, PAM-4, and EDB. The oBtB and 20-km SSMF fiber transmission results are depicted in Fig. 9(a) and Fig. 9(b), respectively. The experiment of ODB is to investigate its fiber chromatic dispersion robustness compared with the other three modulations. So we presents the ODB transmission performance over 20-km SSMF in Fig. 9(b). In order to find its best performance, additional FFE is adopted at the receiver and it makes a 0.87 dB rROP gains.

Finally, we summarize the optical receiver sensitivity of all the modulation formats and equalizations in Table 3. We also calculated the link budgets of PR(x) 30 and its link margin. From Table 3, FTN-NRZ has the most complex transceiver DSP algorithms and achieves the best
performance. The link budget of FTN-NRZ is 33.18 dB. For PR(x) 30 in 10G-EPON, the power margin is 4.18 dB. The link budget and power margin meet the 10G-PON requirements. Hence, FTN-NRZ in 25-Gb/s/λ transmission system can support the backward upgrade of 10G-PONs. Besides FTN-NRZ, there are another two scenarios in Table 3 meet the 10G-PON link budget: PAM-4 and ODB with FFE equalizer. Although ODB with FFE have the same link budget with PAM-4 in Table 3, it is not recommended since its high cost of DD-MZM. Further, PAM-4 has a lower bandwidth and has the potential to transmit a higher bit rate with the same optical devices and some fiber link. Table 3 presents that FTN-NRZ would be the best alternative for current 10-Gbps class optics based 25-Gb/s PON transmission system, while PAM-4 and ODB are another two alternatives. For next generation higher line rate PON transmission, PAM-4 has a potential for its high spectrum efficiency, and maybe it will become the best choice for the next generation 40/50-Gb/s/λ or even 100-Gb/s/λ PON transmission system. In addition, we had made a rough estimation of power consumption for PAM-4 and FTN-NRZ by ASIC. The chip frequency is about 391-MHz. And assuming that 14-nm process will be adopted to implement these chips. The DSP power consumption of PAM-4 and FTN-NRZ are 0.6-W and 0.9-W, respectively. Although the power consumption of FTN-NRZ costs a little higher than that of PAM-4, it does not require quite good linearity of optics.

5. Conclusions

In this paper, we presented the experimental study of 10-Gbps class optics based $4 \times 25$-Gb/s 100G-EPON transmission for FTN-NRZ, PAM-4, EDB and ODB over 20-km SSMF transmission without in-line optical amplifier and optical dispersion compensation devices. The same experimental setup was used for FTN-NRZ, PAM-4, and EDB, while an extra DD-MZM was adopted for ODB. A 10-Gbps class APD with 3-dB bandwith of 7.5-GHz was employed to receive all of the signals. In order to compensate the ISI impairment introduced by band-limited devices and fiber chromatic dispersion, FFE is used for all of the received signals demodulation. For FTN-NRZ modulation, an additional FTN technology is adopted because of these band-limited devices. The experimental results show that the link budgets of FTN-NRZ, PAM-4, and ODB go beyond 29 dB as OLT launch power of 6 dBm and pre-FEC BER of $1 \times 10^{-3}$. FTN-NRZ has the superior performance with the link budgets of 33.18 dB and 4.18 dB power margin achieved in 10G-EPON PR(x) 30. Duo-binary transmissions, ODB and EDB, did not show more of their advantages in this experiment. Therein, EDB performs the worst receiver sensitivity and cannot meet the power requirement of PR(x) 30. PAM-4, another potential short range transmission modulation, maybe further improve on its sensitivity to suitable for next generation PON transmissions by employing more complex algorithms, such as pre-DPD at transmitter and FFE+DFE combined with MLSE at receiver. However, PAM-4 required much better linearity of optics than two-level NRZ signals. The optics with good linearity cost much. Therefore, considering the trade-off between cost of optics and performance, FTN-NRZ of 25-Gb/s/λ transmission based on 10-GHz class optical devices is superior to the others. So that FTN-NRZ is more suitable for upgrading existing 10G-EPONs to 100G-EPON with currently mature commercial 10-Gbps class optics for low-cost consideration.

References

Demonstration of FTN-NRZ, P AM-4, and Duobinary


