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Multilevel Signaling Technology for Increasing Transmission Capacity in High-Speed Short-Distance Optical Fiber Communication

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SUMMARY The needs for ultra-high speed short- to medium-reach optical fiber links beyond 100-Gbit/s is becoming larger and larger especially for intra and inter-data center applications. In recent intensity-modulated/direct-detection (IM/DD) high-speed optical transceivers with the channel bit rate of 50 and/or 100 Gbit/s, multilevel pulse amplitude modulation (PAM) is finally adopted to lower the signaling speed. To further increase the transmission capacity for the next-generation optical transceivers, various signaling techniques have been studied, especially thanks to advanced digital signal processing (DSP). In this paper, we review various signaling technologies proposed so far for short-to-medium reach applications.

key words: *optical fiber communication, short reach, multilevel modulation, pulse amplitude modulation, digital signal processing*

1. Introduction

By the wide spread use of various network applications like SNS, IoT and cloud computing, on PC, smart-phones and various devices, continuous growth of intra- and inter-data center traffic produces significant demand in short-reach optical fiber links in near future [1], and the development of higher and higher capacity short-to-medium reach optical transceivers are in serious needs.

Conventionally, “Binary intensity modulation with direct detection (IM/DD)” is an almost single modulation format covering wide area of applications in high-speed short-to-medium reach optical fiber links for high-speed LAN, passive optical network (PON), intra- and inter-DC interconnection and so on since the introduction of fiber optic communication due to its simplicity and cost-effectiveness. However, further increase of its capacity is hindered mainly by the limited bandwidth of electrical and optical components.

To overcome it and realize the next-generation high-speed optical transcivers, four level pulse-amplitude modulation (PAM4) is investigated [2], and adopted for the first time in the 400GbE standardization in IEEE 802.3bs Task Force with the modulation speed of 26.6-GBaud and 53.2-GBaud in eight and four channel configurations [3], [4]), respectively. The latter one achieves very high-signaling speed of 100 Gbit/s per channel.

On the other hand, PAM signals have quite small vertical and horizontal eye-openings compared with the binary signal, and are subjective to noise and various waveform distortions induced by channel bandwidth limitation, channel non-linearity, fiber chromatic dispersion, multi-path interference (MPI), and so on. Therefore, the increase of tolerance to such degradations are indispensable for their practical implementations and also for future performance enhancement. One of key techniques to overcome such limitations is the use of advanced signaling techniques based on digital signal processig (DSP), such as modulation, demodulation, filtering, equalization, and so on.

In this paper, we review various DSP-based signaling techniques for short-to-medium reach direct-detection optical links. In Sect. 2, we focus on DSP-based signal bandwidth reduction technique such as higher-order multilevel modulation, Nyquist modulation and faster-than Nyquist (FTN) signaling. In Sect. 3, we review the configuration and applications of single-sideband (SSB) transmitter and receiver, especially in terms of recently proposed Kramers-Kronig receiver. In Sect. 4, non-linearity compensation and non-linaear equaualization schemes are introduced, such as Volterra-series equalizers, MLSE and Tomlinson-Harashima precoding.

2. Bandwidth Reduction

2.1 Higher-Order Multilevel Modulation

The number of information bits carried by a single multilevel symbol is $\log_2 N$ bits, where N is the number of signal levels. Therefore, higher-order modulation with larger N value results in higher signal capacity, and several higher-order PAM signaling experiments such as PAM6 (Ex. [5]) and PAM8 (Ex. [6]–[8]) have been reported. However, further increase of PAM signal levels is significantly difficult, since PAM is one-dimensional base-band modulation utilizing only the signal amplitude for signal modulation, and increase of signal level quickly reduces its eye-openings. Optical sub-carrier modulations can utilize two-dimensions, in-phase and quadrature-phase components, and have some more margin to increase signal levels, and up to 64 level modulation is demonstrated, for example, in discrete multi-tone signaling (DMT) [9] and half-cycle Nyquist

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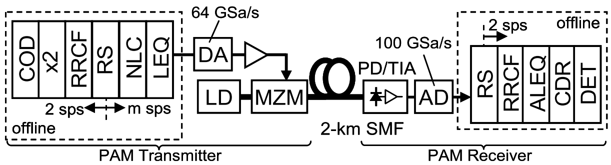


Fig. 1 Configuration of experimental Nyquist-PAM transceiver [5]. COD: PAM encoder, x2: twice up-sampling, RRCF: root-raised-Cosine filter (root Nyquist filter), RS: re-sampling, NLC: modulator non-linear compensator, LEQ: linear equalizer, DA: DA converter, LD: laser diode (λ = 1550.1 nm), MZM: Mach-Zehnder modulator, ALEQ: adaptive linear-equalizer, CDR: clock and data recovery, DET: PAM detector.

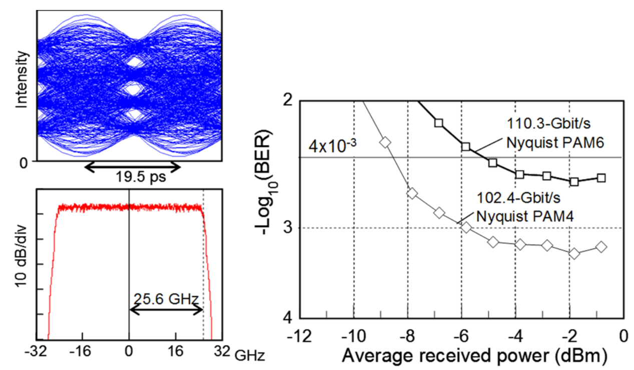


Fig. 2 Experimental eye-pattern and spectrum of received 102.4-Gbit/s Nyquist-PAM4 signal and BER performances of 102.4-Gbit/s Nyquist-PAM4 and 110.3-Gbit/s Nyquist-PAM6 signals [5].

modulation [10] experiments.

However, increase of signal levels results in thinner eye-opening or shorter symbol-to-symbol distance, which severely degrade receiver sensitivity and tolerance to signal inter-symbol interference (ISI), induced via channel imperfection, MPI, fiber chromatic dispersion and so on. They can be alleviated by the use of strong feed-forward error correction (FEC) and/or advanced ISI mitigation technique such as soft-decision FEC and MLSE, but their use in short-to-medium reach IM/DD systems is currently very limited due to their power consumption and increase of signal latency.

Another approach is to use optical phase and/or polarization to significantly increase dimensions of modulation. For example, optical phase and amplitude modulation with delay detection [11], [12], and Stokes vector modulation [13], [14] have been reported. However, these schemes tend to require significantly complex receiver structure and has the issues of cost, size, and power consumption. On the other hand, the use of simplified and detuned coherent transceiver for short to medium reach application is under serious consideration, and the Optical Internet Forum (OIF) has defined a standard called 400ZR, for single-channel 400GbE transmission up to 100 km by using 16QAM modulation.

2.2 Nyquist Modulation

Since the signal baud rate of high-speed IM/DD systems already exceed 50 GBaud and further increase of signal baud rate will face various optical and electrical device bandwidth limitation, therefore signal bandwidth reduction can be an important technique in future.

Nyquist modulation is well-known techniques for signal bandwidth reduction, which utilize "Nyquist pulses" with no ISI for signal modulation and rectify signal spectrum to reduce its bandwidth to nearly half of the signal baud rate. In principle, Nyquist modulation does not cause any ISI, that is no waveform degradation, it is especially useful for maximize signal capacity in strongly band-limited condition. Since Nyquist pulses becomes negative, its application in IM/DD links requires some DC offset.

Figure 1 shows an experimental set up for our first 100-Gbit/s class PAM4 and PAM6 signaling experiments [5] with Nyquist modulation. In this experiment, the signal baud rates are 51.2 GBaud for PAM4 case and 42.67 GBaud for PAM6 case and the signal bit rates are 102.4 Gbit/s and 110.3 Gbit/s, respectively. In conventional PAM signaling, the required channel bandwidth is typically more than 70% of signal baud rate (30 to 36 GHz), but the bandwidth of the experimental transceiver is severely limited to less than 14-GHz mainly by a DA converter (DAC). Therefore, we utilize two digital root-raised cosine filters (RRCF) as a Nyquist filter with the roll-off factor of 0.1 (determined to optimize receiver sensitivity). They are realized by 101-tap fixed feed-forward equalizers (FFE) and are placed separately in the transmitter and the receiver DSP sections. The Nyquist filter limits the signal bandwidth to nearly half the baud rate, that is, 25.6 and 21.3 GHz in PAM4 and PAM6 cases, and the resultant channel frequency response is equalized by the transmitter and receiver side fixed and adaptive linear equalizers. The Experimental eye-pattern and spectrum of received 102.4-Gbit/s Nyquist-PAM4 signal is shown in Fig. 2, in which three vertical eye-openings of the received PAM4 signal are clearly observed and its spectrum is rectified and limited to 25.6GHz. The bit-error ratio (BER) curves of 102.4-Gbit/s Nyquist-PAM4 and 110.3-Gbit/s Nyquist-PAM6 signals are shown in Fig. 2. They achieve enough low BER than the BER threshold of super-FEC (4E-3), but that of PAM6 shows higher BER due to increased signal levels. To show the applicability of cost-effective band-limited devices for 100Gbit/s/channel high-speed PAM signaling, we have demonstrated the use of commercial electro-absorptive modulator (EAM, Bandwidth 28 GHz)) intended for 100-GbE (25GBaud/channel) [15], which prove the effectiveness of the bandwidth reduction by the Nyquist modulation.

Although the Nyquist modulation does not induce any signal ISI, it also have some practical implementation issues: One of them is the reduced optical modulation amplitude (OMA) due to signal peaking. As shown in the eye-pattern in Fig. 2, the Nyquist waveform has upward and downward peaking at the timing of symbol boundaries, which reduces vertical eye-openings and results in 1- to 2-dB power budget loss, in IM/DD systems without optical amplifiers. Nyquist modulation is also susceptible to various linear and non-linear channel impairments, since it requires exact waveform or spectrum shape to satisfy ISI-free condition. They can be somewhat alleviated by the use of precise linear and non-linear adaptive digital filters, but typically with the sacrifice of significant computational power.

2.3 Duo-Binary and Faster-Than Nyquist Modulation

Partial response signaling is the technique to intentionally introduce known ISI to reduce signal bandwidth. Duo-binary modulation is the simplest partial-response signaling, which applies 1+D (D: symbol delay) function to the transmitted signal and reduces its 3-dB bandwidth to half. Its application to high-speed IM/DD PAM system is demonstrated in many papers, such as [16]–[18]. Since partial response filters introduce strong frequency dips (zeroes) in signal bandwidth, simple receiver side linear equalization for signal decoding will greatly reduce receiver sensitivity by noise enhancement. Therefore non-linear equalization techniques, such as most-likelihood sequence estimation (MLSE) described later is typically used to decode it.

It is also possible to tighten signal bandwidth further to less than that of the signal Nyquist bandwidth (half of its baud rate) by allowing some amount of ISI. This technique is called Faster-than-Nyquist (FTN) signaling. For example, 100 Gbit/s FTN-PAM4 signaling over 20-GHz brick-like bandwidth [19], and a 145 Gbit/s IM/DD Transmission With FTN-PAM4 signaling has been demonstrated [20]. FTN also requires non-linear decoding, and it induces some sensitivity penalties.

3. Optical Single-Sideband (SSB) Modulation and Dispersion Compensation

3.1 Optical SSB Transmitter

Optical SSB modulation is the method to remove one of the optical signal side-band, which carries redundant information in terms of intensity modulation. The optical SSB signal can be generated by optical field modulation using an IQ modulator as in Fig 3 (a), in which the real part of the optical field is modulated by the incoming signal S, and its imaginary part is modulated by the Hilbert transformation of S. Figure 4 (a) and (b) show the spectra of optical dual-side band (DSB) and SSB signals, respectively, and by using SSB modulation, the signal lower sideband (LSB) (or upper sideband (USB)) can be removed as in Fig. 4 (b). Even though it utilizes an optical field modulation, but we still classified it as an IM/DD schemes, since signal information is carried and detected solely by its intensity component. Instead, a sharp optical high-pass (or low-pass) filter can also be used to remove one of the side band of IM signal as in Fig. 3 (b), which is called optical vestigial side-band (VSB) modulation.

A straightforward application of optical SSB is to double the number of wavelength channels packed in limited optical amplifier bandwidth to achieve very-high-capacity short-to-medium reach dense WDM (DWDM) links, for example, for emerging inter data-center applications. For example, we have performed DWDM transmission experiments of four-channel 81.92-Gbit/s IM/DD SSB-Nyquist-PAM4 signals over 20-km standard single-mode fiber (SSMF) [22]. Schematic configuration of a SSB-Nyquist PAM transmitter is shown in Fig. 5, in which Nyquist pulse-shaping and SSB modulation is done by a single bandpass raised-cosine filter (RCF) extracting only upper-sideband component. In order to simplify the receiver-side optical field reconstruction described later, we introduce transmitter-side SSB-induced ISI compensator (SIC) and chromatic dispersion pre-compensation. In our scheme, the Nyquist PAM signal is coded on signal power $|E_s(t)|^2$, and the SSB conversion, that is, the Hilbert conversion of $E_s(t)$ adds an extra imaginary component $E_i(t)$ to the original PAM signal (real component) as in Eq. (1), where ω is the angular optical frequency.

$$E(t) = E_s(t)\cos\omega t + E_i(t)\sin\omega t \quad (1)$$

$$I_r(t) = |E_s(t)|^2 + |E_i(t)|^2 \quad (2)$$

The $I_r(t)$ in Eq. (2) is the low-frequency direct detection output of SSB signal in Eq. (1) and it shows that the power of

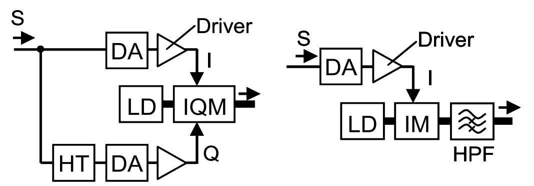


Fig. 3 Configuration of optical SSB and VSB transmitter. DA: DA converter, LD: Laser diode, HT: Hilbert transform, IQM: optical IQ modulator, IM: Optical intensity modulator, HPF: Optical high-pass filter

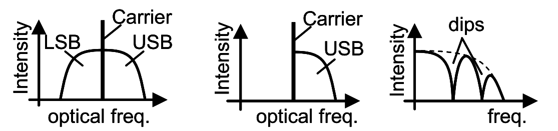


Fig. 4 Spectrums of optical DSB and SSB signals.

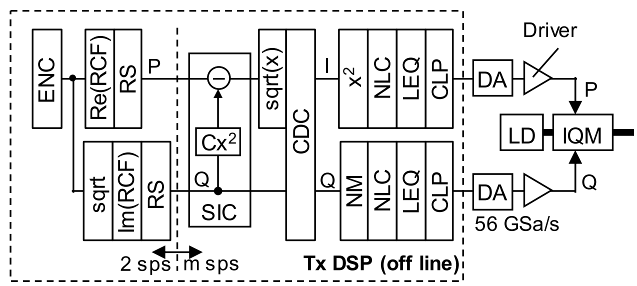
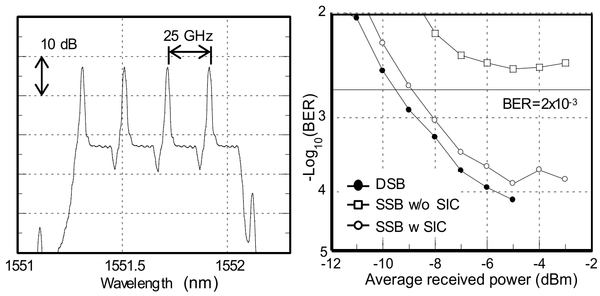


Fig. 5 Experimental SSB Nyquist-PAM4 Transmitter with digitlal SSB-induced ISI compensator (SIC) and CD pre-compensation (CDC) [22]. RCF: Raised-cosine filter extracting upper side band, NM: normalization, NLC: modulator non-linearity compensator, LEQ: linear equalizer, CLP: clipping.



(a) DWMD spectrum (b) BER performances

Fig. 6 Experimental DWDM spectrum of four-channel 81.92-Gbit/s SSB Nyquist-PAM4 signals and BER performance [22].

imaginary component $|E_i(t)|^2$ causes ISI in the detection of $|E_s(t)|^2$. The proposed SIC estimates it with a weight factor C at the transmitter side, and subtract it from the original PAM signal in advance to reduce ISI. Experimental DWDM spectrum of four-channel 81.92-Gbit/s SSB Nyquist-PAM4 signals with 25-GHz spacing is shown in Fig. 6 (a), which results in net spectral efficiency (SE) of 3.03 considering the super-FEC overhead. As shown in Fig. 6 (b), the BER of SSB signal is greatly improved by the use of the proposed SIC.

Further high net-SE of 3.3 is reported in [23], in which 108-Gbit/s 64QAM SSB half-cycle Nyquist-SCM signals are multiplexed with 27-GHz-spacing. These SE values exceeds that of 100-Gbit/s DP-QPSK coherent systems with 50-GHz frequency spacing (2.0), and has a potential of realizing Tbit/s class DWDM transmission with simple IM/DD techniques.

SSB signaling is also used to suppress the generation of frequency dips (zeros) in received signal spectrum induced by fiber chromatic dispersion (CD): When dual-sideband (DSB) IM optical signal is transmitted over optical fiber, the phase of each spectral components at signal baseband frequency f_s are rotated by fiber transfer function $C(f)$ in Eq. (3),

$$C(f) = exp\left(-j\frac{\pi\lambda^2}{c}{f_s}^2 D\right) \tag{3}$$

where λ is the signal wavelength, c is the speed of light, and D is the total fiber chromatic dispersion. It causes frequency dips in received signal spectrum as in Fig. 4 (c), since the upper and the lower side band frequency components at the frequency $+f_s$ and $-f_s$ cancel out each other, and significantly degrades received signal [21]. Therefore, various high-speed IM/DD transmission experiments with sub-carrier modulations utilizes SSB-signaling to prolong transmission distance over dispersive fiber (Ex. [23]–[25]).

3.2 Optical SSB Receiver

As previously described, direct-detection of SSB signal causes superfluous signal component called signal-signal beat interference (SSBI). Assuming $E_s(t)$ as optical field

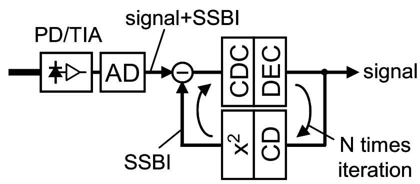


Fig. 7 Schematic configuration of iterative SSBI rejection in optical SSB and VSB receiver. CDC: chromatic dispersion compensation, CD: chromatic dispersion, DEC: decision circuit.

component of the modulated single-sideband signal (actually degraded by CD) and E_0 as that of CW carrier, the received optical field $E(t)$ is expressed as Eqs. (4), and the output signal $I_r(t)$ obtained by the direct-detection of $E(t)$ leads to Eqs. (5).

$$E(t) = (E_0 + E_s(t))\, cos\,\omega t + E_i(t)\, sin\,\omega t \tag{4}$$

$$I_r(t) = |E_0|^2 + Re(E_s(t))E_0 + |E_s(t)|^2 + |E_i(t)|^2 \tag{5}$$

The first term of Eqs. (5) is a constant, and the second term is the required receiver output, and the third and fourth term is the SSBI component. The effect of SSBI can be alleviated by increasing the carrier power, that is, with high carrier-to-signal power ratio (CSPR), but it severely degrade receiver sensitivity due to smaller modulated component. Therefore, various cancellation techniques of SSBI have been reported so far (Ex. [10], [23], [24]), which is also necessary for receiver-side chromatic dispersion compensation. As an example, one of the precise digital iterative rejection scheme of SSBI is shown in Fig. 7: The digitized signal from the receiver front end, that is signal field with SSBI, is input to a decision circuit after CD compensation (CDC), then it is squared after applying CD to estimate SSBI component. The estimated SSBI is subtracted from the original received signal in order to improve accuracy of signal decision. By iteratively-repeating SSBI estimation and rejection, it is possible to have very precise signals with CD compensation. But this scheme requires very high computational power.

3.3 Kramers–Kronig Receiver

Kramers–Kronig (KK) receiver, recently proposed by Meccozi [26], [27], is a sophisticated alternative of iterative receiver-side SSBI rejection scheme, which analytically reconstruct phase component of optical field from the intensity information of the received SSB signal. To do so, the incoming signal should satisfy the minimum phase condition [26], the signal should be SSB (or VSB) and its field trajectory does not encircle the origin. In such a case, the received optical field $E(t)$ can be reconstructed from the received intensity $I(t)$ as in Eqs. (6) and (7) [28],

$$E_s(t) = \left(\sqrt{I(t)}\, exp(j\varphi_E(t)) - E_0\right) exp(j\pi Bt) \tag{6}$$

$$\varphi_E(t) = H(log\, I(t)) \tag{7}$$

where E_0 is the carrier component, B is the signal bandwidth, $\phi_E(t)$ is the estimated phase of the received field.

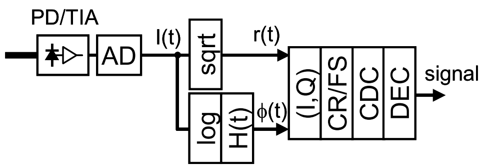


Fig. 8 Schematic configuration of Kramers-Kronig receiver. H(t): Hilbert Transformation, (I,Q): Cartesian coordinate conversion, CR/FS: Carrier removal and frequency shift

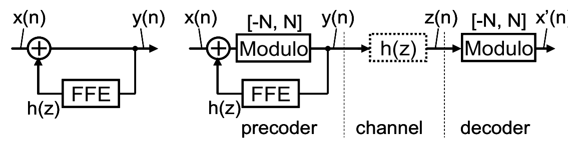


Fig. 9 Schematic configurations of IIR preequalizer and THP encoder/decoder.

Typical schematic configuration of KK receiver is shown in Fig. 8.

With the KK receiver, it is possible to accurately reconstruct optical field of received SSB signal without iterative calculation. Its various experimental demonstrations are reported so far: For example, a 16×112Gb/s SSB-PAM4 WDM Transmission over 80km SSMF [29], 400-Gbit/s transmission with a single photo-diode [30], and direct detection of 480-Gbit/s signal with two polarization-diversity KK receivers after 80km SSMF [14] have been demonstrated.

Although the KK receiver is attractive in its straight forward implementation than iterative scheme, it still requires substantial computational power, since non-linear calculation in Eqs. (3) and (4) requires twice to four-times signal upsampling. It also requires very high CSPR to satisfy the minimum phase condition especially when high chromatic dispersion is applied, which may degrade its BER performance: In [28], it is reported that the optimum CSPR for the KK receiver is 6 dB at the back-to-back and it increases to 8 dB after 400-km SSMF transmission, and its required OSNR is higher than that of iterative receiver by about 0.3 to 2 dB after 400-km transmission.

4. Non-Linearity Compensation and Non-Linear Equalization

4.1 Volterra-Series Equalizer

Since multilevel signals have small eye-opening, channel non-linearity induced by for high-speed electrical and optical devices, for example, DA and AD converters, driver amplifiers and optical modulators can significantly degrade its BER performance due to uneven eye opening, timing error, or residual ISI after linear equalization, which leads to high BER floor or sensitivity degradation. One of the simplest non-linearity compensation is to introduce digital non-linear inverse function in the tranceiver; such as the Arcsin function to linearize sinusoidal modulation charctersistics of a Mach-Zehender modulator. However, it is sometimes difficult to exactly locate the soure and shape of non-linearity, and also some channel frequency responses coupled with the nonlinear device makes it impossible to fully compensate it by simple inverse function approach.

The Volterra-series non-linear compensator (NLC) is an powerful univeresal approach to adaptively compensate channel nonlinearity: Its use is proposed in [33], and it is, for example, applied to the reception of 112-Gbit/s PAM4 signals to compensate the nonlinaer behavior of directly-modulated laser. The Volterra-series NLC is a combination of N_L-tap linear FFE and non-linear FFE composed from the k-th order Volterra kernel of N_{NL} samples: For example, 3-rd order Volterra kernel (k = 3) at sample i of $N_{NL} = 5$ can be expressed as $w_{k1,k2,k3} \cdot (\mathrm{i} - k_1) \cdot (\mathrm{i} - k_2) \cdot (\mathrm{i} - k_3)$ where $\mathrm{w}_{\mathrm{k1,k2,k3}}$ is the tap coefficient and k_1, k_2, k_3 are independent indices in $[-2, 2]$. The Volttera-series NLC has very powerfull compensation capability up to k-th order non-linearity with chanel length N_{NL}, but it requires high computational power since the number of non-linear taps increase very rapidly as k and N_{NL}.

4.2 Nonlinear Equalizer

Nonlinear equalizers are the powerful equalizer utilizing non-linar signal estimation/decision process, represented by the MLSE and decision feedback equalizer (DFE).

MLSE estimates most possible received symbol sequence out of received data, to minimize the Euclid distance from it. Number of high-speed multilevel signaling experiments with MLSE have been reported so far, such as [10], [17], [18], [20]. Efficient sequence estimation algorithm such as Viterbi & Viterbi algorithm is typically used in practical implementation, but still it requires vast amount of computational power, especially for higher-order multilevel signals and longer channel memory case.

DFE is a simple and effective nonlinear equalizer utilizing symbols output from the decision circuit for the input of equalizer to erase the effect of ISI and noise. DFE is also used in some IM/DD transmission experiments such as [16], but it has the issues of error propagation and stability in practical implementation.

Tomlinson-Harashima Precoding (THP) [34], [35] is another non-linear equalization scheme of signal ISI, which does not have the problems of error propagation and stability, unlike DFE. Figure 9 shows the basic configuration of THP: The THP precoder in Fig. 9 (b) has similar configuration as IIR pre-equalizer which realize inverse function of channel transfer function of h(t) by feedback configuration, but has Modulo function to limits its output range to $[-\mathrm{N}, \mathrm{N}]$, where N is the number of PAM signal levels and the PAM signal spacing is set to 2. The modulo function folds back signal components strongly distorted by $\mathrm{h}^{-1}(\mathrm{t})$ in amplitude domain, but after the channel transmission applying h(t), they are folds back again to the original location by receiver-side Modulo decoder.

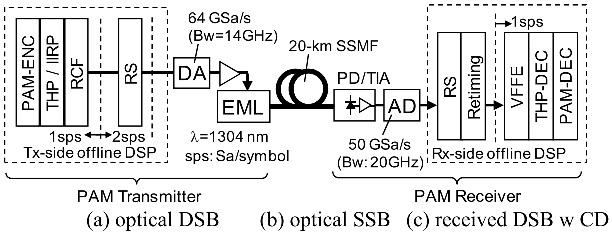


Fig. 10 Setup of experimental IM/DD Nyquist-PAM4 transceiver with IIRP or THP. ENC: encoder, DEC: decoder, RCF: raised-Cosine filter, RS: re-sampling, EML: electro-absorption modulator integrated laser, VFFE: Volterra-feed forward equalizer.

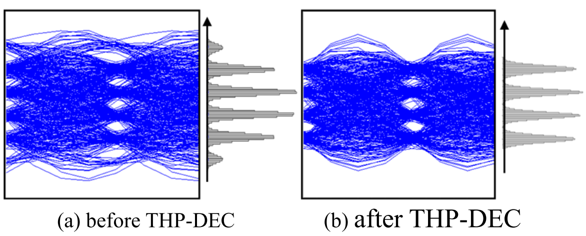


Fig. 11 Received eye-patterns and histograms of 45-GBaud IM/DD FTN-PAM4 signals with 9-tap THP.

Due to its stability and less computational requirement, application of THP to high-speed optical signaling has been also demonstrated in some papers: For example, THP is applied to coherent QAM signals for long-distance optically-amplified transmission lines [36], [37]. It is also applied to IM/DD PAM signals for short-distance systems with optical amplifiers [38], [39], in order to overcome chromatic-dispersion induced ISI and frequency dips.

On the other hand, a significant drawback of THP is the increase of signal levels, that is PAM4 to PAM6, PAM8 or more, when strong channel transfer function is applied. Therefore, its application to IM/DD PAM system in which available signal power is limited and increase of signal levels leads to the reduction of OMA and system power budget.

We propose the use of THP with Nyquist PAM and FTN-PAM signals to alleviate the effect of power budget reduction: Figure 10 shows the setup of our experimental Nyquist- and FTN-PAM transceiver. In the Tx-side offline DSP, a PAM signal sequence generated at a PAM encoder is preequalized by IIRP or THP, then, it is filtered by a raised-cosine Nyquist filter. After resampling, it is fed to a 64-GSa/s 8-bit DAC with 3-dB bandwidth of 14 GHz, which is a major bandwidth limiting device in the transmitter, and its output signal is supplied to 1.30-μm EML. The receiver-side ADC has a steep built-in aliasing filter of 20-GHz bandwidth. After the retiming, an adaptive 51-tap FFE with 7-symbol Volterra non-linearity compensator is applied to residual channel equalization. Then PAM signal is decoded for BER estimation after optional THP decoder.

The received signal before a THP decoder is shown in Fig. 11 (a), which is converted from PAM4 to PAM6. It is recovered to PAM4 again after PAM4 with the THP decoder as in Fig. 11 (b). It is also shown that the peak power of PAM6

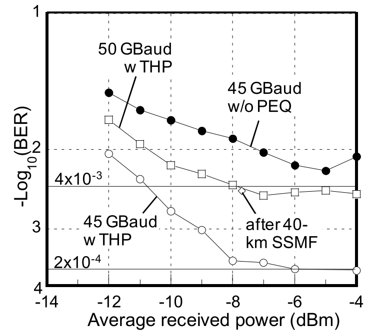


Fig. 12 45- and 50-GBaud Faster-Than-Nyquist PAM4 signaling with THP.

and PAM4 signals are almost the same, since the former has less peak power than the normal Nyquist PAM6 signal. We confirm that the THP-Nyquist PAM4 shown 1.2-dB sensitivity improvement, and also perform 90-Gbit/s and 100-Gbit/s FTN experiments as in Fig. 12 to show its superior equalizing performance.

5. Conclusions

We have reviewed signaling technologies to increase transmission capacity next-generation short-to-medium reach high-capacity IM/DD optical fiber links and transceivers.

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