3-4　光アクセスネットワークやデータセンタ間ネットワークの延伸化を実現する光電融合信号処理技術

3-4　Joint Optoelectronic Signal Processing Technology for Reach Extension in Access/ Datacenter Networks

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高速の光強度変調―直接検波 (IM-DD) 方式は、光アクセス網、モバイルフロントホール、データセンタ間相互接続など、近中距離の光ファイバ通信システムに今日広く用いられており、Beyond 5G (B5G) ネットワークにおいても重要な役割を果たすと考えられる。B5G においては、毎秒 100 ギガビットを超えるような高速・広帯域の IM-DD 伝送が求められることから、ファイバ中の波長分散の影響が顕著となり、信号品質や伝送距離などの制限要因となると考えられる。本稿では、光信号処理とデジタル信号処理を組み合わせた、光 IM-DD 方式のための新たなファイバ分散補償技術について最新の研究成果を紹介する。

High-speed intensity-modulation direct-detection (IM-DD) fiber optical transmission system is of great interest to the applications of access networks, mobile fronthaul and datacenter networks, which are essential for NICT's major R&D direction of Beyond 5G (B5G) networks. However, with the increasing signal bandwidth and optical fiber distance, fiber dispersion poses a major challenge in maintaining high-quality data transmission with low system complexity/cost. This paper presents an efficient yet low-power/complexity reach extension technology for fiber-dispersion-constrained high-speed IM-DD system, based on joint optoelectronic signal processing. It is a promising technology for energy-efficient reach extension in sustainable Beyond 5G networks.

1 Introduction

With the ever-increasing network traffic demands in Japan, Beyond 5G networks become essential and a major R&D topic of NICT, which will continue to pursue high-speed and high-quality data delivery to end subscribers [1]. In particular, R&D of high-speed datacenter (DC) and access networks are important to facilitate Beyond 5G networks, driven by the rapid growth of fixed and wireless traffic, edge computing and futuristic applications like extended reality (XR). Optical fiber communication technology is necessary in these scenarios. Multi-lane intensity-modulation direct-detection (IM-DD) scheme, e.g., with N-ary pulse amplitude modulation (PAM-N, e.g., N=4), is promising owing to the balance between the capacity and link cost [2].

In Institute of Electrical and Electronics Engineers (IEEE) standardization projects, there are at least 2 sub-projects related to access and DC networks. One is P802.3dj Task Force discussing up to 1.6 Tb/s Ethernet-based short-reach communications using either multi-lane IM-DD or coherent architecture [3]. The other is P802.3dk Task Force which discusses greater-than-50 Gb/s bidirectional point-to-point (PTP) optical access with a focus on simultane-

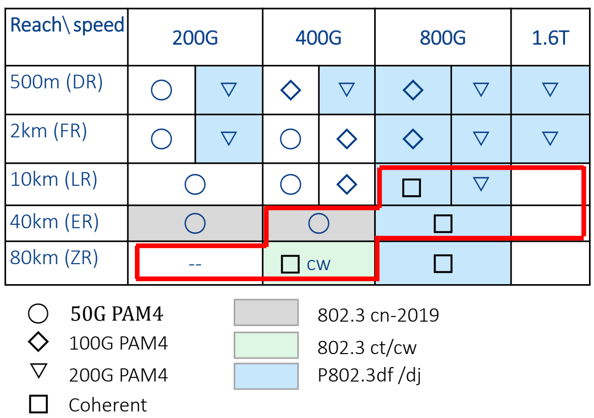

Fig. 1 Optical transmission technologies discussed in IEEE standardization process [2]. The bold red range indicates possible application range of the OE-FFE technique.

ously 100 Gb/s-and-beyond data rate and different loss budgets [4]. Figure 1 shows the current status of P802.3dj discussion.

With higher bit rate (e.g., 100 Gb/s-and-beyond) and/or longer fiber reach (such as 40 km or "ER" [2]), IM-DD fiber transmissions in C-band and even edge wavelengths of O-band would suffer severely from the power fading issue induced by fiber chromatic dispersion (CD) and DD. Due to this limitation, it can be seen from Fig. 1 that IM-DD (e.g., with PAM4) is no longer the central of discussion for distances of above 10 km for 800 G and beyond, although IM-DD still has cost and complexity merits. There are 2 main solutions for the CD limitation: one is to supplant IM-DD with coherent detection technology that can detect not only intensity/amplitude but also phase of the signals and fully remove the impact of fiber CD, as appears in Fig. 1. On the other hand, the second path, namely keeping the IM-DD architecture but adding certain "anti-CD" techniques, would also be a laudable goal considering the potential cost and complexity advantages over a full coherent system. Overall, reach extension and CD compensation technologies for high-speed IM-DD systems are highly desirable.

To help understand the fiber CD-induced power fading in IM-DD systems, we provide (small-signal approximated) theoretical frequency response of IM-DD systems in Eq.(1):

$$H_{\mathrm{CD}}^{(\mathrm{IMDD})}(\omega) = \cos(2\pi^2 f^2 \beta_2 L) \tag{1}$$

Where $\beta_2 = -D\lambda^2/2\pi c$ is a group velocity dispersion (GVD) parameter (D: dispersion coefficient, λ: optical wavelength, c: speed of light), and L is the fiber length. We can see that, due to fiber CD and DD, the amplitude of the channel response approaches zeros (or "deep spectral notches" occur) at frequencies f satisfying $2\pi^2 f^2 \beta_2 L = (2p-1)\pi/2$ $(p = 1,2,\ldots)$, i.e., information can barely pass these frequency bins, namely "power fading". To achieve acceptable performance, the complexity of DSP needs to be high to compensate for these deep notches that quickly become more as signal bandwidth or distance increases. Figure 2 depicts examples of theoretical frequency response of 50 Gigabaud (GBd) signal transmitted over 30 km and 60 km single-mode fiber (SMF), and 100 GBd over 30 km in C-band.

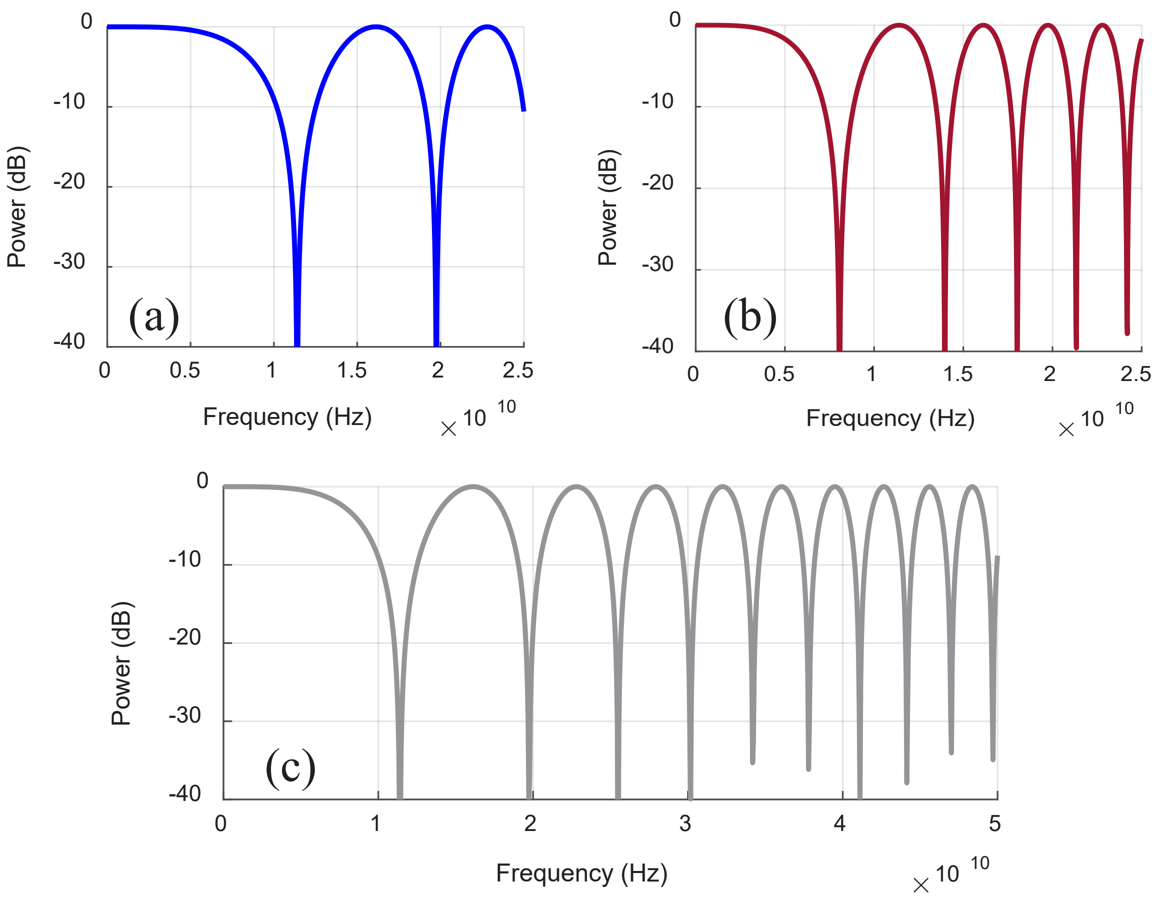

Fig. 2 Theoretical frequency response of (a) 50 GBd signal over 30 km, (b) 50 GBd signal over 60 km and (c) 100 GBd signal over 30 km SMF in C-band.

2 Related Works

Previous CD compensation solutions for IM-DD systems may be categorized into "optical approaches" and "electronic / digital signal processing (DSP) approaches". For the former, several optical infinite impulse response (IIR) and finite impulse response (FIR) filters have been discussed for IM-DD systems with around 40 Gb/s bit-rates [5][6]. However, for 100 Gb/s-and-beyond systems with multi-level signaling, it is very challenging to achieve error-free performance without using DSP. On the other hand, the latter approach has been widely discussed in recent years [7]–[9] with the advances of high-end analog-to-digital converters (ADC) and application-specific integrated circuits (ASIC). Some examples include Tomlinson-Harashima precoding (THP), decision-feedback equalizer (DFE) and maximum likelihood sequence estimator (MLSE). However, currently the DSP complexity achieved is still much higher than that of industry's interest (i.e., 10~30tap FFE, optionally few-tap DFE, optionally low-power MLSE) [10].

3 The OE-FFE Technique

In this section, we will introduce our joint optoelectronic signal processing technique named "optoelectronic feedforward equalization" or "OE-FFE" in short, which can overcome the challenges of reach extension or CD compensation with low complexity [11].

The concept of OE-FFE for CD compensation in IM-DD transmission is illustrated in Fig. 2(a). One example of theoretical frequency response is shown by the dashed curve in Fig. 2(c): 4 deep notches can be seen in the first Nyquist zone (0~25 GHz) for a 50 GBd signal after transmitting over 50 km in C-band. In OE-FFE-based IM-DD system, the optical signal after fiber transmission is firstly processed by a simple optical circuit. The design objective is to avoid all deep spectral notches by this optical circuit and to drastically reduce the complexity of the post-DD DSP from complicated and implementation-challenging DFE or MLSE; residual shallow notches are allowed and left for low-complexity, hardware-friendly all-feedforward equalizer (FFE) to handle without notable effect on the recovered signal quality.

The optical circuit should be simple, low-cost, and hopefully consuming negligible energy. One of the simplest realizations of the optical circuit is a 1-tap optical delay line (ODL) as illustrated in Fig. 2(b). It consists of a 50:50 power splitter, a delayed path with φ phase shift and delay T, and a 50:50 power coupler. It is integrable and considerably simpler than an optical FIR filter. If the φ and T are properly optimized, such 1-tap ODL will remove all the deep notches. As an example, when φ and T of the 1-tap ODL are -0.65π and 8 ps, the corresponding theoretical frequency response is shown by the dotted dashed curve in Fig. 2(c). The attenuation of residual notches are less than 10 dB, which will be compensated by the post-DD digital equalizer. In practice, the parameters of OE-FFE such as φ, T and number of digital FFE taps would be coordinately designed according to the target CD range.

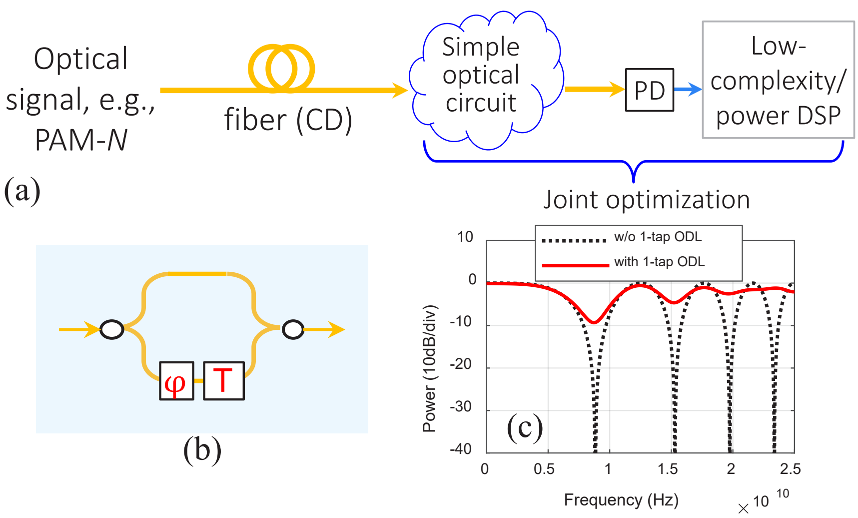

Fig. 3 (a) illustration of IM-DD system with OE-FFE. (b) One of the simplest optical circuit, namely 1-tap optical delay line (ODL). (c) Theoretical frequency response (0~25 GHz) of 50 GBd PAM4 transmission over 50 km in C-band.

4 Performance Evaluation

We evaluate the performance of the proposed OE-FFE technique by experiments, in which 50 GBd (100 Gb/s) PAM4 signal is successfully transmitted over SMF with distances up to 61.38 km in C-band.

The experimental setup is shown in Fig. 4. The 100 Gb/s electrical PAM4 signals was modulated onto an optical carrier at about 1,547 nm in C-band via a single-drive Mach-Zehnder modulator (MZM) biased around its quadrature point, thus generating an optical double-sideband (DSB) PAM4 signal. The transmission line included 50 km SMF and an Erbium-doped fiber amplifier (EDFA). In the OE-FFE-based receiver, the PAM4 signal was firstly processed by a 1-tap ODL (based on free-space components; delay T≈8ps). It was then detected by a 50 GHz PD and processed by DSP including digital FFE after RF amplification and 160 GSa/s analog-to-digital converter (ADC). The PD input power was about 2 dBm. The DSP included resampling with low-pass filtering, downsampling, synchronization, FFE, and PAM demodulation & bit error counting.

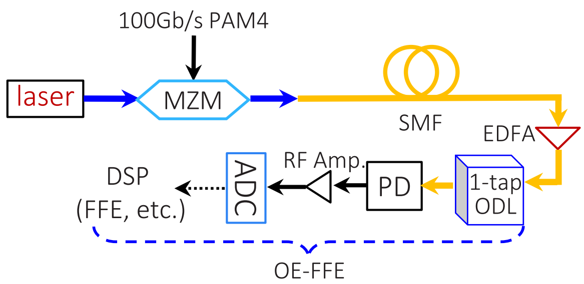

Fig. 4 Experimental setup.

Figure 5(a) shows the measured frequency response of the received 100 Gb/s electrical PAM4 signal without and with the 1-tap ODL, respectively, after 50 km transmission. It was confirmed that the optical part of OE-FFE avoids the deep spectral notches caused by CD and DD. Moreover, the experimental responses match well with theoretical ones in Fig. 3(c). Figure 5(b) shows the PAM4 bit error ratio (BER) versus SMF length. Both cases of without and with OE-FFE are depicted. In the case "without OE-FFE", the 1-tap ODL was replaced by an optical bandpass filter, while digital DFE was used. Considering the 6.25% hard-decision FEC limit (BER=4.7e-3 [12]), the achievable transmission distance was less than 6 km when the DFE with 61 feed-forward (FF) taps and 39 feedback (FB) taps was applied. In contrast, the OE-FFE enabled >61 km transmission or more than 55 km reach extension, with low-complexity DSP (using a nonlinear FFE with only about 1/3 of complexity or 35 taps).

5 Summary and Outlook

We presented an OE-FFE technique for efficient reach extension and CD compensation for high-speed IM-DD system based access/datacenter networks. OE-FFE-empowered 100 Gb/s PAM4 signal transmission over 61.38 km was verified, showing >55 km reach extension. In the future, we aim to develop joint optoelectronic signal processing techniques for more advanced IM-DD systems such as ≥200 Gb/s; we also plan to study the potential of a shared 1-tap ODL for CD compensation of multiple WDM channels for simultaneous capacity expansion and reach extension.

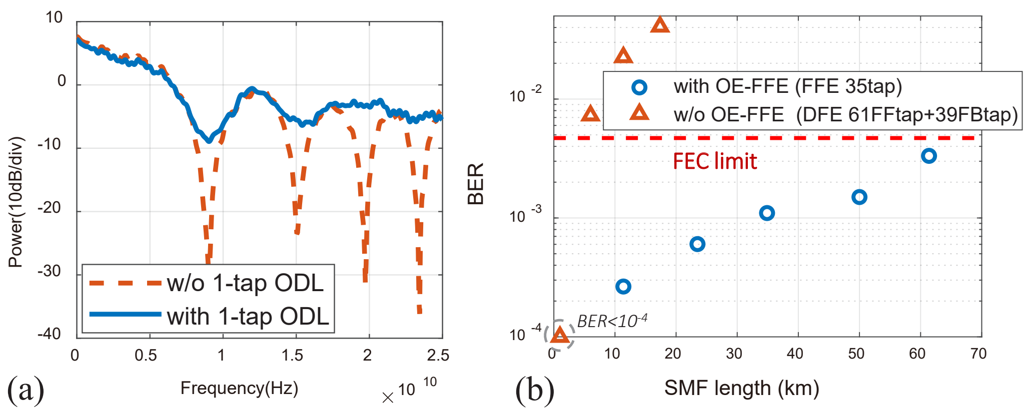

Fig. 5 Experimental results of 100Gb/s IM-DD PAM4 transmission. (a) Frequency response after 50 km. (b) BER vs. SMF length, showing remarkable >55 km reach extension.

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