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Adaptive Hybrid Iterative Linearization Algorithms for IM/DD Optical Transmission Systems

Shaohua Hu, Jing Zhang, Jianming Tang, *Member, IEEE*, Taowei Jin, Hong Lin, Wei Jin, Zhenming Yu, Roger Giddings, *Member IEEE*, Kun Qiu

***Abstract*— For optical field recovery and linear dispersion compensation, we propose a performance-enhanced linearization algorithm, termed adaptive hybrid multi-constraint iteration algorithm (MCIA), which does not require any physical modifications to standard configurations of intensity-modulation and direct-detection (IM/DD) transmission systems. To improve the sensitivity to the residual inter-symbol interference (ISI) effect, we introduce, after fiber backward-propagation, a linear feed-forward equalizer (FFE) pair into the proposed algorithm. To improve the sensitivity to fiber dispersion estimation errors, we utilize a two-stage dispersion estimator coupled with the G-S iteration. After 100-Gb/s PAM-4 signal transmissions over 400-km fibers, the simulation results show that the MCIA offers a 1.5-dB optical signal-to-noise ratio (OSNR) gain and a 1-dB optical power budget improvement compared with the decision-directed data-aided iterative algorithm (DD-DIA), for highly dispersive IM/DD transmissions. By performing adaptive dispersion estimation, the MCIA has higher tolerance to estimation errors in fiber length. Moreover, for cases subject to large dispersion, the usage of the embedded FFE pair not only desensitizes the MCIA on the limited bandwidth effect, but also accelerates the convergence performance for reaching lower BERs. We experimentally demonstrate that the proposed algorithm can support 150-Gb/s PAM-4 transmissions over 25-km standard single mode fibers (SSMF), where just a 7-tap FFE-pair is required. For 150 Gb/s transmissions, the tolerance to fiber length estimation error is increased from 0.9 km to 20 km.**

***Index Terms*—Optical communication, digital signal processing, IM/DD system, field reconstruction.**

I. INTRODUCTION

Owing to its system simplicity and relatively high cost-effectiveness, intensity-modulation and direct-detection (IM/DD) is widely deployed in short-reach communication systems and data-center interconnects [1]. For such cost-sensitive application scenarios, to further increase their signal transmission capacity versus reach performances, various techniques have been reported, which includes single sideband modulation [2], Kramers-Kronig reception [3, 4] and optical fiber-based dispersion compensation [5]. In these techniques, the data-bearing optical fields are manipulated, this requires significant modifications to the already installed IM/DD transmission links. To increase the signal transmission capacity without modifying the installed IMDD transmission links, alternative techniques exploiting digital signal processing (DSP) only have been published which include pre-coding [6, 7], nonlinear equalization [8-10] and high spectral efficiency modulation [11, 12]. However, their corresponding transmission performance ceilings start to appear, mainly because these DSP algorithms do not have sufficiently strong capabilities of overcoming the fiber chromatic dispersion (CD)-induced signal-to-signal beating interference (SSBI) effect, such an effect causes sever frequency selective power fading to occur in the signal spectral region. In addition, their DSP complexity also rapidly increases with the accumulated fiber CD effect.

The Gerchberg-Saxton (G-S) algorithm retrieves, in an iterative manner, a complex-valued optical field by utilizing multiple real-valued intensity image planes [13], thus enabling the linear reception of optical signals transmitted over the IM/DD transmission systems. To implement the G-S algorithm in the IM/DD transmission systems, additional dispersive devices were, however, introduced in [13] to construct the multiple real-valued 1-D image planes. From the practical application point of view, DSP techniques that require neither any modifications to existing IM/DD physical system infrastructures nor high receiver DSP complexity are highly preferable. For an IM/DD transmission system, there are two planes, i.e., the transmitter-side phase-intensity relationship and the receiver-side detected optical intensity [14, 15]. As a result, due to the poor global optimum performance, the conventional G-S algorithm fails to recover intensity-modulated signals when their data rates and transmission distances are above certain values. Alternatively, the introduction of G-S

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pre-compensation algorithms [16, 17] is effective, to some extent, in compensating channel distortions.

Given the fact that the use of post-compensation in the G-S algorithm is easier to apply more constraints to both systems and signals in order to achieve the global optimum performance of the algorithm, we have proposed a data-aided iterative algorithm (DIA) and an advanced variant known as decision-directed DIA (DD-DIA), in which the local optimization problem of the G-S algorithm is successfully addressed by using pseudo-pilot symbols and randomly allocated decision symbols [18, 19]. Numerical simulations have shown that both the DIA and DD-DIA have the potential of supporting >100-Gb/s signal transmissions. In addition to the SSBI effect, the effects associated with limited bandwidths of low-cost components involved the IM/DD transmission systems also cause significant signal distortions in high-speed IM/DD systems. As the conventional G-S algorithms only recover the optical field without effectively minimizing the limited bandwidth effect, the conventional G-S-class algorithms may still fail because of its intrinsic model-basing property [22]. Furthermore, the estimation error in fiber dispersion may also exert unwanted negative impacts on achievable overall linearization performances.

In this paper, we propose an adaptive hybrid G-S multi-constraint iterative algorithm (MCIA), where pseudo-pilot symbols, decided symbols and channel coding-associated redundant bits are fully utilized to reinforce the fast convergence performance. In the newly proposed algorithm, linear equalization is combined in each MCIA iteration to desensitize performance degradations caused by the limited bandwidth effect. The hybrid MCIA also includes a two-stage adaptive dispersion estimator to further alleviate its sensitivity against initial dispersion estimation errors. Therefore, this paper is a significant extension of our previously published papers, where the MCIA [20] and the hybrid MCIA [20,22] have been reported, by proposing and subsequently verifying the novel adaptive hybrid iterative linearization algorithm, which has a considerably enhanced performance tolerance to both CD estimation errors and the ISI effect. In order to gain an in-depth understanding of the newly proposed algorithm, in this paper, detailed discussions are made of the algorithm's design structure and its operating principles as well as numerical and experimental verifications of the algorithm. In numerical simulations, we conduct C-band 100-Gb/s PAM-4 signal transmissions over 400-km SSMF fibers to verify the convergence performance improvement, the contribution of the iteration-filter combination, and the ISI tolerance sensitivity improvement of the adaptive hybrid adaptive MCIA. It is shown that the MCIA performs best among the candidate algorithms at ideal dispersive IM/DD channels. Specifically, it is shown that the MCIA offers a 1.5-dB OSNR gain, a 1.0-dB optical power budget improvement, and a 50% reduction in the required number of iterations, compared with the DD-DIA. In addition, the introduction of an FFE pair in the MCIA not only desensitizes the MCIA performance against the limited bandwidth effect, but also accelerates the convergence process, this gives rise to lower BERs for larger dispersion cases. In regard to the sensitivity against dispersion estimation errors, we find that the hybrid MCIA, with a 2.2-km dynamic range of the initial error, performs better than any of other algorithms. After performing the adaptive dispersion estimation, we observe 39.3-km and 14.5-km dynamic ranges in the first and second stage of the estimators that totally requires no more than 20-cycles renewal of estimated fiber lengths. In experiments, we demonstrate a 112-Gb/s PAM-4 transmission over 100-km standard single mode fiber (SSMF) transmission and realize the 10-tap linear-equalizer-only SSBI cancellation using the proposed algorithms. Furthermore, considerably improved experiment demonstrations of 150 Gb/s PAM-4 signal transmissions over 25-km SSMFs are reported. We find the adaptive hybrid MCIA significantly reduces the required number of iterations compared with the DD-DIA. The CD estimation error tolerance is also improved by a factor of 22. Our work shows that the newly proposed algorithm is capable of addressing the challenges associated with the conventional G-S algorithm, implying that the algorithm is suitable for applications in high-speed IM/DD transmission systems subject to severer SSBI effects and dispersion estimation errors.

The paper is organized as follows: The principles of the adaptive hybrid MCIA are described in Section II, which includes the principle of the MCIA, the FFE-MCIA combination and the adaptive dispersion estimator. In Section III, we verify the performance improvements for the following cases: a) the MCIA in an ideal dispersive IM/DD channel, b) the hybrid MCIA in the bandwidth-limited dispersive IM/DD channel, and c) the adaptive dispersion estimator in the presence of dispersion estimation errors. In Section IV, we conduct experimental explorations of the adaptive hybrid MCIA.

II. PRINCIPLES OF THE ADAPTIVE HYBRID MCIA

To realize the improved linearization performance, the adaptive hybrid MCIA has to deliver two goals, i.e., better global optimum and improved performance robustness. In this section, special attention is thus given to approaches, which are adopted in the adaptive hybrid MCIA to deliver the desirable goals.

A. Approaching the Global Optimum: the MCIA

The signal recovery process of the G-S algorithm can be regarded as solving an optimization problem, where the objective is to reconstruct an optical field that minimizes the mean square error between the detected optical current $I_o(m)$ and the intensity of the reconstructed optical field $R_1(m)$ as shown Eq. (1),

$$\min \quad e(R_1) = \mathbf{E}\left[\left|\left\|R_1(m)\right\|^2 - I_o(m)\right|^2\right] \tag{1}$$

Eq. (1) belongs to a non-convex optimization problem due to the complicated nature of $I_o(m)$ [21], thus the existence of insufficient constraints cannot enable the cost function to achieve its global optimum and reach the lowest BER.

To address the challenge, depending upon the features of the transmitted signals, three constraints can be introduced into Eq. (1), including pilot symbols, pseudo-pilot and coding redundancy, known as the DIA [18], the DD-DIA [19] and the MCIA [20], as shown in the red boxes of Fig. 1, which can be mathematically expressed as Eq. (2).

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$$\begin{aligned} \mathrm{G}[x(n),k] &= \mu_{M,L}(n,k)d_{pilot}(n) + \\ &[1-\mu_{M,L}(n,k)]\left\{\theta(n,k)x'(n)+\left[1-\theta(n,k)\right]x(n)\right\} \end{aligned} \tag{2}$$

where $x(n)$ is the down-sampled sequence, $\mu_{M,L}(n,k)$ represents the training symbol allocation strategy at the n-th symbol and the k-th iteration. $d_{pilot}(n)$ is the pilot symbol inserted before fiber transmission. $\theta(n,k)$ is a random signal that follows the Bernoulli distribution at the n-th symbol and the k-th iteration to determine whether a pseudo-pilot is used. The pseudo-pilot signal that are ready to replace the back-propagated sequence is defined as $x'(n)=\mathrm{T}\{\Xi[x(n)]\}$, where T and Ξ represent the operators of the FEC and the maximum likelihood decision.

To realize a desired linearization performance improvement, the residual ISI and the estimation error of the dispersion parameter are the key hurdles for the MCIA to overcome model mismatches in practical transmission systems, thus we present the solutions in the following subsections.

B ISI Desensitization: Principle of the Hybrid MCIA

Since equalization prior to the G-S iteration would destroy the response of fiber dispersion, this may result in non-convergence of the G-S algorithm. To combat the bandwidth limitation, we insert an inner FFE pair into the MCIA iteration [22], as shown in Fig. 1. To mitigate the residual ISI induced by bandwidth limitations, the first FFE estimates the residual ISI that is not compensated by the MCIA and then transforms the backpropagated signal into the transmitted signal. This FFE avoids the under-fitting of the MCIA for bandwidth limitation and improves the accuracy of the pilot insertion and the pseudo-pilot substitution. The cost function can be expressed as

$$\min_{h_{FFE1}} \quad J(h_{FFE1}) = \mathbf{E}\left[\left\{d_{TS}(n)-\left[\left|T_1(n)\right|^2-A\right]\otimes h_{FFE1}(n)\right\}^2\right]. \tag{3}$$

The second FFE re-introduces the estimated residual ISI into the updated version of the transmitted signal to make the residual effects transparent to the MCIA. The cost function can be expressed as

$$\min_{h_{FFE2}} \quad J(h_{FFE2}) = \mathbf{E}\left[\left\{d_{TS}(n)\otimes h_{FFE2}(n)-\left[\left|T_1(n)\right|^2-A\right]\right\}^2\right], \tag{4}$$

where A, $d_{TS}(n)$, $h_{FFE1}(n)$, $h_{FFE2}(n)$ and $\otimes$ represent for the bias current, the training sequence, the kernels of FFE_1 and FFE_2, and the convolution operation. The introduction of two FFEs within an iteration cycle makes the MCIA work well for practical cases and improves the adaptivity of the MCIA. The output of FFE_1 can be directly sent to the following blocks. After the hybrid MCIA, we can cascade another simple outer FFE with a longer memory length for further equalization. It should be noted that pre-equalization is also necessary to compensate for the transceiver's ISI effect for optical back-to-back (B2B) cases.

C CD Desensitization: The Adaptive Hybrid MCIA

The conventional G-S linearization algorithm is sensitive to fiber dispersion estimation error. The multiple constraints can improve the error tolerance, however, their capabilities in this regard are not robust enough, because the fiber dispersion estimation error causes the accumulation of the signal estimation errors during the forward and backward digital propagations. To address such a challenge for practical dispersion-varying transmission links, we introduce a two-stage adaptive method into the hybrid MCIA, called adaptive hybrid MCIA, for dispersion estimation, as illustrated in Fig. 2. It is assumed that the fiber dispersion coefficient is fixed, the fiber dispersion estimation process is thus equivalent to the optimization of fiber length according to the frequency-domain transfer function of the CD effect [21]. For the first stage, the dispersion is coarsely determined by the cost function as,

$$\min_{L_{\text{test}}} \; J(L) = \mathbf{E}\left[\left\{\left|\sqrt{d_{TS}(m)+A}\otimes h_{CD}(m,L_{\text{test}})\right|^2-\left[I_{\mathrm{O}}(m)+A\right]\right\}^2\right]. \tag{5}$$

To search for the optimum fiber length, an equally-spaced testing vector of the fiber length is input to the optimization equation of Eq. (5), where the step width of the testing fiber length L_{test} is dependent on the tracking extreme of the second stage.

For the second stage, the cost function is defined by

$$\min_{L_{\text{test}}} \; J(L) = \mathbf{E}\left[\left\{\left|\sqrt{T(m)+A}\otimes h_{CD}(m,L_{\text{test}})\right|^2-\left[I_{\mathrm{O}}(m)+A\right]\right\}^2\right]. \tag{6}$$

In this stage, the estimated fiber length converges to the true fiber length, which can be accurately adjusted and tracked by an early-late gate without any training sequence. The estimator minimizes the MSE between the detected and calculated intensity signals after forward digital propagation. Hence, the dispersion parameter can be updated continuously along the MCIA iteration. If, at the first stage, the attempted range of the fiber length is large enough and the testing step are within the error tolerance of the second stage, coarse estimation at the first stage can guarantee the correct initialization of the second stage. We summarize the above-described technique in Fig. 3, where the solved problem and key operations are also shown clearly.

III. SIMULATIONS AND DISCUSSIONS

To verify the performance improvement of the proposed adaptive hybrid MCIA in double-sideband (DSB) IM/DD optical transmission systems, we conduct numerical simulations using VPI, where a single carrier PAM-4 signal is

TABLE 1. SIMULATION PARAMETERS [18]

System parameter	Modulation format	PAM4
	SRRC rolling factor	0.1
	Dispersion parameter	16 ps/nm/km
	Central wavelength	1550 nm
Modulator: MZM	V_π	10 V
	Bias voltage	2.5 V
	Driving amplitude	0.4 V
PD: PIN	Dark current	0 A
	Thermal noise	10×10^{-12} A/Hz$^{1/2}$
	Responsivity	1 A/W

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transmitted. Table 1 shows the corresponding device parameters of the considered PAM-4 DSB IM/DD transmission system.

At the transmitter, a pseudo random bit sequence (PRBS) is encoded (Hamming block code with an overhead of 16.13%), which is then mapped into a PAM-4 symbol sequence. After that, the symbol sequence is up-sampled by a factor of 2. The square-root raised cosine (SRRC) filter with a roll-off factor of 0.1 is applied to the up-sampled symbol sequence to improve the spectral efficiency and partially eliminate CD-induced signal distortions. Electrical-to-optical (E/O) conversion is realized by a Mach-Zander modulator (MZM) biased at $V_{\pi}/4$, where an input continuous optical waveform operates at a wavelength of 1550.00 nm and has a linewidth of 100 kHz. The driving voltage amplitude of the RF input to the MZM is 0.4 V. An ideal optical power-controlled EDFA is deployed after the MZM to ensure that an optical launch power is fixed at -2 dBm. The chromatic dispersion parameter is taken to be 16 ps/nm/km, which is identical to that corresponding to a commercial G. 652 fiber. An optical AWGN source loads noise to the optical signal transmitted through the system in order to adjust optical signal's OSNRs in a dynamic range from 34 to 43 dB, where the noise power is calculated within a spectral resolution of 0.1 nm. At the receiver, to control the received optical power, a pre-amplifier is employed before the PIN photodiode where thermal noise and shot noise is considered. After optical-to-electrical (O/E) conversion in the receiver, the electrical current is sampled at 2 samples per symbol. It should be noted that for cases where the dark current and thermal noise of a PD are higher than those used in the simulations, the extra channel noises just give rise to the increment of SERs at the low received optical power (ROP) ends, and their impacts on the SSBI cancellation performance degradations are negligible.

The receiver side DSP procedures include different linearization algorithms for performance comparisons, match filtering, down sampling, and maximum likelihood symbol decision. The abovementioned linearization algorithms include: adaptive Volterra filtering (VF) with 100-, 11-, and 5-taps for the three-order equalizer with parameters having acceptable computational complexities; the conventional G-S iterative algorithm (Conv. IA); the data-aided iterative algorithm (DIA); the decision-directed DIA (DD-DIA); the multi-constraint iterative algorithm (MCIA); the hybrid MCIA, and the adaptive hybrid MCIA. For the DD-DIA or MCIAs, we use 120 DIA iterations with a 10% overhead for pre-convergence and 59 DD-DIA or MCIAs iterations for convergence acceleration.

We testify the performance improvement in three aspects: firstly, we show the linearization performance improvement in dispersive optical fiber channel. Secondly, we show the performance improvement after the synthesis of the MCIA with linear equalization in the band-limited dispersive channel. And finally, we show the robustness enhancement of the adaptive hybrid MCIA in the presence of the dispersion estimation error.

A. Transmission Performance Improvement for Dispersive IM/DD Channels

We conduct 100-Gb/s 400-km PAM-4 signal transmission simulations without considering bandwidth limitation and calculate corresponding BERs at different OSNRs and ROPs to show the transmission performance improvements, the results are shown in Fig. 4(a) and (b), where the ROP and OSNR are fixed to -8 dBm and 40 dB, respectively. Similar results can be found in [20] for different data rates and transmission distances. Note the MCIA in this comparison are not combined with the linear equalizer pair or adaptive dispersion estimators. As shown in Fig. 4, a large accumulated fiber CD results in a complete failure of the VF because the equalization model is under-fitted. In addition, neither the conventional IA and nor the 10% DIA can recover the signal because of the existence of the local optimization problem. In sharp contrast, the DD-DIA and the MCIA have a significantly improved capability of successfully dealing with the global optimization problems, as a direct result, compared with the DIA, the MCIA and the DD-DIA have more than one order of magnitude BER improvement. At a BER of 1×10^{-2}, the MCIA gives rise to an 1.5-dB OSNR gain and an 1-dB power budget improvement compared with the DD-DIA. As for the optimal performance, the large slopes of the OSNR(ROP)-dependent BER curves indicate the MCIA's strong system linearization capability. The MCIA is benefitted from the strictest signal constraints and the reduction in incorrectly decided pseudo-pilot symbols.

To explain how the decision errors are reduced, by taking into account a case where 100-Gb/s 400-km PAM-4 transmissions are considered at a 40-dB OSNR and an -8-dBm ROP, we show the error propagation feature for the DD-DIA and the MCIA. We depict the decision errors at different iterations for 2000 time slots after enabling the DD-DIA and the MCIA in a 2-D decision error map in Fig. 5. The map is gridded up by the iteration number and time index, where the narrow block in green represents the occurrence of decision errors. We can figure out the error occurrence as a function of iteration number for the *n*-th symbol. For the DD-DIA, most of the errors disappear after 40 iteration cycles, as expected, the residual small number of decision errors do not affect the algorithm convergence, and the error correction mechanism is still contained in the combination of the DIA and decision process. However, the rest of the uncorrected symbols with a lower percentage cannot be recovered after 59 iterations, this indicates that the local optimization problem still exists in the DD-DIA. As a comparison, after 30 iteration cycles, the remaining time slots with decision errors in the DD-DIA are almost corrected. This implies that the MCIA improves the linearization performance and reduces the computational complexity.

The above results suggest that if the DD-DIA and the MCIA have larger numbers of initial decision errors, the final BERs can be affected. Hence, appropriately selecting the DIA-based pre-convergence iteration cycles may not only accelerate the convergence progress but also reduce the SERs. The SERs of the DD-DIA and the MCIA are plotted as a function of iteration index for three different cases where the DD-DIA and the

MCIA start at the DIA-based iteration cycles of 10, 30, and 50. Fig. 6 shows that the MCIA reduces the SERs more rapidly than the DD-DIA [20]. When the total number of iterations is large enough, all the SER curves of the MCIA are approximately one order of magnitude lower than the DD-DIA. The minimum required number of iterations for the MCIA to reach a SER of 2×10^{-2} can be as low as about 30, which are just 67% of the iteration cycles required by the DD-DIA.

Furthermore, regarding the hybrid MCIA, our intention is to overcome the MCIA's high performance sensitivity against the estimation errors beyond the RF-induced ISI limit. The interesting is that the introduction of the inner FFE pair also contributes to the algorithm convergence and BER reductions at larger accumulated fiber dispersion. This is because even the MCIA also back-propagates the impacts associated with the SSBI effect through the fiber particularly for small iteration indices. As a result, the convergence is degraded by the inaccurate insertions of pilots and pseudo-pilots. The above statement is verified in Fig. 7. In this simulation, as the fast convergence performance for 100-Gb/s PAM-4 transmission over 400-km SSMF makes the contribution of FFE-pair indistinctive, we transmit a 200-Gb/s PAM-4 signal over 300-km SSMF. Since there are no bandwidth limitation deployed in the simulation links, the RF-induced ISI effect is blocked out. When the transmission capacity increases, the convergence acceleration and BER reductions are observed for the 200 Gb/s@300 km case as shown in Fig. 7. The BERs are reduced from 5×10^{-2} (for the MCIA) to 1.65×10^{-2} (for the hybrid MCIA with a 10-tap FFE). More than 10 cycles of iteration are saved at the BER of 2.5×10^{-2} when the tap count increases from 5 to 10.

The results presented above indicate that the hybrid MCIA has the best transmission performance and the fastest convergence speed over the other algorithms considered here.

B. Performance Improvement in Bandwidth-Limited Dispersive Channels

The MCIA is sensitive to the RF-induced ISI effect because the ISI effect leads to time-domain signal amplitude changes. From the phase retrieval perspective, the linearization algorithm regards the ISI-contaminated signal as the optical intensity. Reducing the difference between the normalized detected electrical signal and the optical intensity signal is the main challenge of any effective signal recovery techniques including the MCIA.

In this subsection, based on the simulation system configuration of 100 Gb/s@400km SSMFs, we deploy two low pass filters after the optical current from the photodiode being captured to simulate the ISI effect imposed to the optical current. The Z-transforms of these filters are $H_1(z)=1+0.5z^{-1}$ and $H_2(z)=1+0.5z^{-1}+0.2z^{-2}$,whose magnitude-frequency responses are shown in Fig. 8(a) and (d), which are corresponding to 2.5-dB and 5-dB fading at 25 GHz. The spectra of the signal output from the lowpass filter (LPF) are shown in Fig. 8(b) and (e). To verify the robustness of the hybrid MCIA, we compare the BER variations for individual iterations in Fig. 8(c) and (f) , in which the MCIA fails in recovering the signal, whilst the hybrid MCIA shows more than one order of magnitude BER reductions and 75% of BER reductions for the H_1 and H_2 cases, respectively. When the number of FFE taps increases, the BER of the hybrid MCIA can be further reduced.

Fig. 8 verifies the effectiveness of using the hybrid MCIA in minimizing the limited bandwidth effect. It is also worth noting that Fig. 8(f) also manifests that the hybrid MCIA is not capable of performing well for channels suffering from serious bandwidth limitations. To guarantee the signal recovery performance of such channel, a pre-equalizer should be implemented at the transmitter for the optical back-to-back (B2B) case.

On the other hand, to lower the DSP complexity, the channel estimation of the inner FFE does not have to be activated for each individual iteration. To verify such statement, we show the estimated responses of FFE_1 and FFE_2 in a 25-tap hybrid MCIA, where $H_2(z)$ is adopted as the LPF. As shown in Fig. 8(g), the difference of the estimated tap values in the FFE pair are negligible, this suggests that the adaptive FFE channel estimation can be further simplified by static estimations.

C. Sensitivity to Dispersion Estimation Error

As already stated, the proposed adaptive dispersion estimation includes coarse estimation and accurate tracking stages: The first stage utilizing the training sequence has higher initial error tolerance, and the output estimated fiber length can be stored for the initialization of the second stage. If the element number of the testing vector are large enough, we can obtain an accurate estimation. This treatment, however, requires huge computational complexity. As such setting just a few equally spaced testing fiber length with a relatively large step is preferred, where we can use the fiber length with the minimum cost function value as the initialization parameter for the second stage. In the second stage, no overheads are used for the adaptive estimation, this leads to the achievement of fiber length dynamic tracking but without scarifying the data rate.

To appropriately configure the first stage, we need to know the dynamic range of the initial estimation error for the second stage. Therefore, we first conduct simulations to explore the dynamic range of the algorithms with and without the second stage adaptive fiber dispersion estimation, the corresponding results are shown in Fig. 9 (a) and (b), respectively. When the adaptive method is disabled, the DD-DIA shows an 1.6-km dynamic range while the MCIA and the hybrid MCIA show a 2.2-km dynamic range at the BER of 1×10^{-2}, the above results significantly outperform the DIA and the conventional IA. Such a dynamic range expansion for these two algorithms is due to the sequentially enhanced global optimum feature. On the other hand, when introducing the adaptive dispersion estimation into the algorithm, the conventional IA has a 12.0-km dynamic range while other algorithms have the same dynamic range of 14.5-km, which is 6.6 times larger than the hybrid MCIA without adaptive fiber length estimation. Moreover, by comparing BERs between Fig. 9(a) and (b), for each algorithm, it is found that the dynamic dispersion estimator introduces negligible performance penalties, even

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though the estimation error of the fiber length still exists in the first several iterations of the G-S-class IA. This is reasonable because, for the G-S-class IA, the detected signal is unchanged and participates in the forward and backward propagation every iteration to have the capability of algorithm re-convergence.

Then, we calculate the errors of the coarse estimation in the first stage as a function of estimation error of the initial fiber length in Fig. 10(a), where a local convex region with the dynamic range of 39.3 km is shown. By combining the dynamic range of the two stage estimations, for the adaptive hybrid MCIA, we can infer that if the initial estimation error at the first stage is lower than 19.65 km, using only three equally spaced testing fiber lengths, with a step of ~6 km, at the first stage is sufficient for the coarse dispersion estimation. The dynamic range of the estimation error in fiber length is further measured under different bit-rates and transmission distances, as shown in Fig. 10 (c). It has inversely proportional relationship with bit rate. However, the 200 Gb/s PAM-4 system still has a ~10 km dynamic range. In fact, we can always find an eligible initial fiber length for the second-stage estimator by increasing the testing range and the number of testing fiber lengths.

Finally, we show the convergence performance of the second-stage dispersion estimator. In the simulations, the initial fiber length errors are set from -5 km to +5 km. In the 100 Gb/s@400 km transmission system case, just ten estimation operations are required to reach the target fiber length. Note that we use the early-late-gate to adjust the fiber length at the second stage, and hence three candidate fiber lengths are needed for each estimation operation.

IV. EXPERIMENTAL VALIDATION

Following the MCIA-based experimental demonstration of 112-Gb/s PAM-4 signals over 100-km SSMF transmissions in [22], figure 11(a) shows the experimental setup. An encoded PAM-4 waveform is loaded to an 8-bit DAC operating at 92 GSa/s, which then passes through a broadband radio frequency amplifier (RFA, CENTELLAX OA4MVM3) and is modulated onto a 1550-nm wavelength using an MZM (Fujitsu FTM7937EZ) with a bandwidth of 35 GHz. An external cavity laser has a linewidth of ~150 kHz and an output optical power of 10 dBm. The MZM-modulated optical signal is transmitted over 100-km G.652 SSMFs with optical launch powers varying between 2 and 8 dBm. After fiber transmissions, an EDFA is introduced to compensate for the fiber loss. A variable optical attenuator (VOA) is then introduced to adjust the received optical power (ROP) by a TIA-free single-ended PD (FINISAR XPDV2120RA) with a bandwidth of 40-GHz. The detected optical current is sampled by a 59-GHz digital phosphor oscilloscope (DPO) at 200 GSa/s. The transmitter and receiver DSP flowcharts are illustrated in Fig. 11(b) and (c). To maximize the transmission performance, use is made of a 20-tap FFE for pre-distortion to compensate for the bandwidth limitation, and the FFE coefficients are calculated under a back to back (B2B) case. Note that for both the DD-DIA and the MCIA, the constraints are not applied in every iteration. We adjust the iterations for the DD-DIA (or MCIA) and the conventional IA to pursue a better global optimum and a further computational complexity reduction. After the DD-DIA and MCIA, an inner FFE (outer FFE) is utilized to compensate for the residual signal distortions associated with channel modulation imperfections.

Figure 12(a) shows the experimentally measured BER performance versus launch power for different signal recovery algorithms [22]. The figure shows that both the VF and the conventional IA fail in recovering the signals, while the DD-DIA and the MCIA can achieve BERs of well below 1×10^{-2}, corresponding to which, the DD-DIA and the MCIA have a 4-dB and >8-dB launch power dynamic range, respectively. This indicates that combining the FFE with the MCIA improves the system performance robustness against fiber nonlinearity. This also suggests that the proposed technique may have potential of supporting EDFA-free transmissions subject to high optical launch powers. To explore the memory length required by the inner and outer FEEs, we calculate the BER versus tap count, as shown in Fig. 12(b) and Fig. 12(c). The BER curves verify the necessity of combining the FFE with the MCIA for practical transmissions. The inner FFEs can improve the signal recovery performance of the MCIA with 10 to 20 taps only. The outer FFE can effectively compensate for the residual ISI effect with just 10 taps. Since the MCIA has more constraints and an improved error correction capability compared with the DD-DIA, the MCIA combined with the FFE halves the required number of FFE-taps at a BER of 1×10^{-2}. We show the BER versus iteration count in Fig. 12(d) to compare the convergence performance of the DD-DIA and the MCIA, to reach a BER of 1×10^{-2}, the MCIA just requires 130 iterations, in which 26 MCIA iteration cycles are included. This indicates that the MCIA's complexity and signal recovery performance outperform other algorithms considered in the paper.

We further increase the signal transmission bit rate to 150-Gb/s with a 25km transmission distance to verify the linearization performances at a higher data rate, as for such case, the MCIA is more sensitive to CD estimation errors. Benefitted from the proposed hybrid linearization algorithm, the deep power fading nulls are gradually upraised with increasing iteration, as shown in Fig. 13(a). By using the adaptive hybrid MCIA, for 150 Gb/s transmissions, we can still reduce the BER by more than one order of magnitude with just a 7-tap FFE, as shown in Fig. 13(c). To find out the CD estimation error tolerance improvement, we show the BER and the normalized cost function in the presence of the fiber-length estimation error. The dynamic ranges for the first- and the second-stage of the dispersion estimator are 20 km and 11.5 km, respectively, as shown in Fig. 14(a) and (c), which results in a tolerance enhancement by a factor of 22.2 compared with the hybrid MCIA (0.9 km, shown in Fig. 14(b)). Therefore, the adaptive hybrid MCIA is expected to support a robust C-band double side-band IM/DD system with a higher transmission capacity.

V. CONCLUSION

We have proposed the adaptive hybrid iterative linearization algorithm to recover PAM-4 signals after IM/DD transmissions. Through numerical simulations of 100-Gb/s 400-km signal transmissions, we have found that: (1) The MCIA offers the

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faster convergence performance and lower BERs compared with the DD-DIA; (2) The hybrid MCIA not only improves the sensitivity of the MCIA to RF-induced ISI, but also improves the convergence performance of the MCIA for large accumulated dispersion cases; (3) The adaptive dispersion estimator has a dynamic range of tens of kilometer, which can tolerate sufficiently large initial estimation errors in transmission distances. Thereafter, we have conducted experiments of C-band 112-Gb/s (150-Gb/s) PAM-4 signal transmissions over 100-km (25-km) IM/DD systems and verified the effectiveness of the proposed hybrid algorithm combining the MCIA and linear equalizer together. The proposed algorithm can compensate for the severe CD-induced SSBI effect and is robust to channel filtering and nonlinear interference with relative low complexity. The proposed linearization iteration is expected to support higher-capacity PAM transmissions at C-band with a 22 times tolerance enhancement against the CD estimation error.

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