# Adaptive and DSP-Compatible Optical Multipath Interference Mitigation Scheme for 60Gbps PAM8-CRAN

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**Abstract:** We proposed an adaptive DSP-compatible time-varying multipath interference noise mitigation algorithm based on probability distribution over 15.5km SSMF at 56/60Gbps PAM4/8. The signal-to-interference ratio tolerance improvement of 3dB PAM8 shows its potentiality for high-order PAM. © 2024 The Author(s)

## 1. Introduction

Nowadays, intensity modulation and direct detection (IMDD) still dominate the solution for short-reach optical access networks considering low cost, power consumption, and complexity. With the augment in C-RAN transmission distance, the increased number of connections leads to severe multiple reflections imported by dirty fiber connectors in optical access link. Consequently, the transmitted optical signal and its delayed copies are detected by the receiver jointly, introducing optical multipath interference (MPI). NRZ has been substituted by PAM4 to promote transmission efficiency and capacity since IEEE 802.3bs. Higher-order formats such as PAM6 and PAM8 are successively put on the agenda. Because of the decrease in the level distance, high-order PAM is more vulnerable to MPI noise, and MPI constitutes a major limitation for high-speed and high-order IMDD systems [1]. MPI noise can be significantly reduced by adding a Gaussian dither signal with a phase modulator, which isn't compatible with the existing IMDD access network [2]. In [3], a hybrid code division multiplexing (CDM) coding and digital filtering method is proposed to address MPI in point-to-point links. Strictly synchronization is required and spread spectrum coding will decline transmission efficiency. In [4], a high pass filter (HPF) is used to remove MPI-induced noise at low-frequency. To realize the steep edge, a large order is needed while structuring the filter, resulting in high complexity and the transmission performance degradation at a low MPI level. Reconstructing MPI noise from error signal is first proposed conceptually [5]. In [6], the A2 scheme based on the mean filter experimentally demonstrates its effectiveness. Nevertheless, A2 which requires manual optimization of four parameters is difficult to apply in practice or adapt to higher modulation formats. In [7], an adaptive decision threshold (ADT) is proposed and simulated, which requires a training sequence. In practical applications, this dynamic change scheme puts forward high requirements on the device in high-speed scenarios. Above, MPI construction is considered a potential method, avoiding changing existing system architecture, affecting performance, or demanding high complexity. However, existing schemes are either not adaptive to channel changes or difficult to implement in high-speed transmission. The generalized adaptive MPI mitigation algorithm for high-speed and high-order signals requires further research.

This paper proposes an adaptive MPI mitigation algorithm based on a probability distribution function (PDF) with the cost of only one divider and dozens of adders in existing DSP. The proposed PDF scheme estimates the MPI noise of fallible points between levels by subtracting the mean error of the two adjacent levels, which eliminates the need for product factors and reduces error deviation. The 56Gbps PAM4 transmission over 15.5km standard single-mode fiber (SSMF) under different laser linewidth and reflection scenarios at the signal-to-interference ratio (SIR) of 23dB is successfully validated, which shows that the bit error rate (BER) performance of the adaptive PDF algorithm can even surpass that of the optimized A2. Notably, MPI mitigation for 60Gbps PAM8 signal is demonstrated for the first time over 15.5km SSMF, achieving logarithm BER optimization beyond 0.4 and SIR improvement of 3dB compared to the A2 algorithm, suggesting the advantages in high-speed and high-order access systems.

## 2. Principle of the proposed PDF scheme

For an optical access fiber link suffering from MPI, we first consider only one MPI reflection from two reflectance points to simplify the analysis. We assume the signal and MPI have aligned polarization as the worst case. Then the MPI-impaired optical signal can be expressed as: $e'(t) = e_i(t) + R_p e_i(t-\tau)$, where $e_i(t)$ is the output light of the laser, $A(t)$ is the amplitude of the signal, $\omega$ is the center angular frequency of the laser, $\phi(t)$ is the laser phase noise, $R_p$ represents the reflectance of the delayed light, and $\tau$ is the path delay for the MPI reflected signal. After photo-detection, ignoring the small beating term, the photocurrent of the MPI-impaired signal can be described as

$$I(t) = \left|A(t)\right|^2 + 2R_p A(t)A(t-\tau)\cos\left[\omega\tau + \Phi(t,\tau)\right]. \quad (1)$$

It is shown that the level value will affect the MPI noise and indicates that MPI has a more significant impact on high-level PAM signals. If the power of the signal and additive white Gaussian noise (AWGN) is expressed as

$Psig(t)$ and $n(t)$ (having zero mean and variance $\sigma_N^2$), Eq. (1) can be modified as

$$I(t) = Psig(t) + n(t) + 2R_p\sqrt{Psig(t)Psig(t-\tau)}\cos\left[\omega\tau + \Phi(t,\tau)\right]. \tag{2}$$

Concerned with two or more MPI reflection signals, the PDF of the electrical signal will quickly converge to the Gaussian distribution. This means there are thresholds $th_m$ (m = 0, 1, …, M-1) where few judgment errors occur when an error intensively occurs when $(I(t) - D(t)) > th_m$, where $D(t)$ is the decision level. Given the analysis from Eq. (1), $th_m$ decreases as the signal level rises.

According to the analysis above, we propose the PDF scheme to suppress MPI noise, and the schematic diagram is shown in Fig. 1. Taking the PAM4 signal for example, the MPI noise interfered signal is sent to DSP to acquire the probability distribution function about signal level. According to the distribution, six threshold levels are identified in conformity with the threshold determination rules, dividing the input signal into the trusted points that are considered correct for each level and the desultory points that are likely misjudged between levels. For trusted points, the corresponding original signal can be obtained by directly deciding and exporting. For desultory points at different level intervals, the MPI noise of the point is estimated by the mean error of the trusted points belonging to its two adjacent levels. Desultory points are compensated by subtracting calculated MPI noise and then recovered to the original signal by decision so that the MPI noise can be mitigated adaptively contrasting to different channel environments. The threshold determination rules are as follows: According to the probability distribution function, the PAM4 signal is divided into multiple groups and presented with three valleys each determining two threshold levels on both sides as the upper and lower boundaries for desultory points. For each threshold level, we initially consider levels corresponding to 3 groups near the valley and on the same side as possible value. For the lower side, the level corresponding to the group that includes 25% more data points than the valley can be determined as the threshold level. For the upper side, besides 25% of data points more than the valley, the target group must also have more data points than the lower side threshold group. The above process can be completed in the existing DSP.

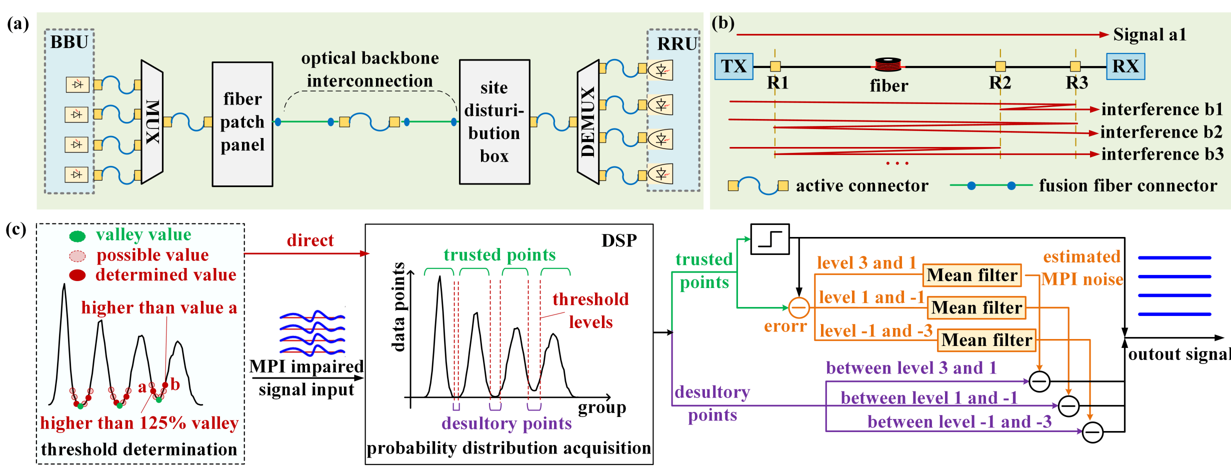


Fig. 1. (a) Experimental setup of IMDD CRAN fronthaul system, (b) MPI schematic, (c) The schematic diagram of proposed PDF scheme.

## 3. Experimental Setup and Results

Fig. 2 shows the experimental setup of MPI impaired IMDD system. We generate a 56Gbps PAM4 signal and a 60Gbps PAM8 signal to validate the effectiveness of the PDF scheme for different modulation formats, respectively. After upsampling at 2sps, the signal is then pulse-shaped using a root-raised cosine filter with a roll-off factor of 0.1 and then loaded into the arbitrary waveform generator (AWG) with a sampling rate of 64 GSa/s. The output of AWG is enhanced by an electrical amplifier (EA) and then drives the Mach-Zehnder modulator. A continuous-wave laser (CWL) with narrow linewidth (CoBrite DX2, linewidth <25 kHz) acts as the laser source, with center wavelength and output power of 1550m and 15.5 dBm, respectively. To compare PDF scheme performance at large linewidth, a DFB laser with wavelength at 1550nm and linewidth of 4MHz is also adapted. The modulated optical signal is then injected into the MPI fiber link consisting of a signal branch of 15.5km SSMF and an interferer branch, which cascades with a variable attenuator (VOA) to adjust the SIR. For one MPI reflection scenario, the interferer branch is constituted only by a delay path of 3.3km SSMF, as shown in Fig. 2(b). For two reflection scenarios, the interferer branch is composed of two delay paths of 0.5km and 1.1km SSMF, respectively, as shown in Fig. 2(c). There is a polarization controller (PC) for each delay path to match the polarization states. The coupled optical signal from the signal branch and interferer branch passes through a VOA which is used to adjust the received optical power (ROP), sent to the photodetector, and finally is sampled by a digital sampling oscilloscope (DSO) at 100 GSa/s to offline signal process.

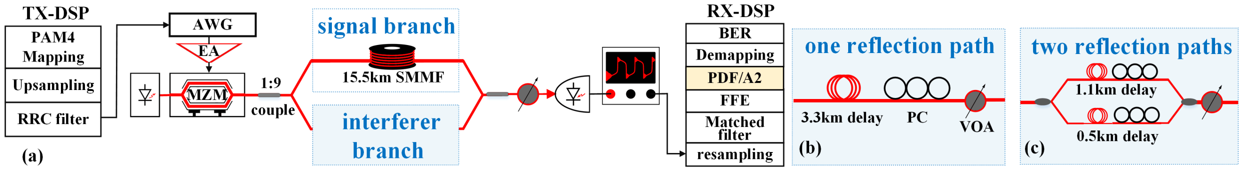


Fig. 2. (a) Experimental setup of MPI impaired IMDD system, (b) one reflection path, (c) two reflection paths.

For one MPI reflection scenario: Fig. 3(a)-(b) and (c)-(d) show the BER performance for 25kHz and 4MHz laser linewidth at 56Gbps PAM4, respectively. It indicates that compared with the optimized A2 scheme, the adaptive PDF algorithm can improve the BER when the laser linewidth is small. Concerning large laser linewidth, the proposed scheme can adaptively achieve the same performance with optimized A2 when the signal is too damaged to reach the 7% hard-decision forward error correction (HD-FEC) limit and begin to promote performance when impaired BER reaches 7% HD-FEC limit. For two MPI reflection scenarios: Fig. 3(f) and (g) show BER performance for 25kHz and 4MHz laser linewidth at 56Gbps PAM4 with different received optical power (ROP), respectively. It is evidenced that the PDF algorithm can bring obvious logarithm BER elevation of about 0.1-0.3 at 25KHz laser linewidth. Towards 4MHz laser linewidth, performance improvement is observed when the BER of the impaired signal reaches the 7% HD-FEC limit, which is similar to a single reflection situation. For higher modulation formats such as PAM8, the experiment is demonstrated under one reflection with 25kHz laser linewidth and 60Gbps transmission speed when the ROP is -5dBm. It can be seen that the proposed PDF scheme can mitigate the MPI of the PAM8 format effectively and significantly improve BER and an SIR tolerance rise of 3dB is achieved relative to A2. It can be seen that the proposed PDF scheme can significantly improve the logarithm BER beyond 0.4 which suggests effective MPI mitigation at PAM8, and an SIR tolerance rise of 3dB is achieved relative to A2.

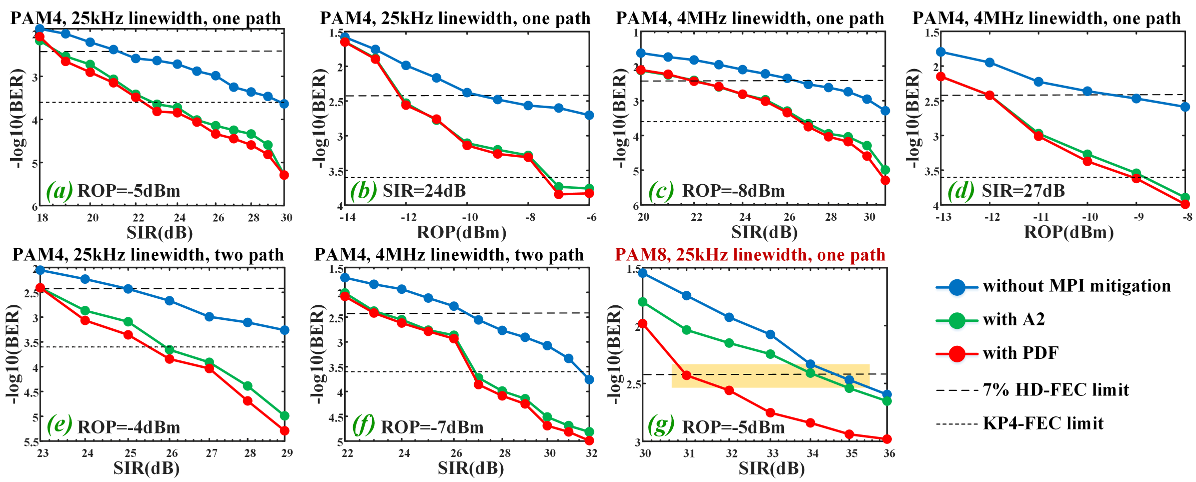


Fig. 3. Experimental results under one delay path of 25kHz laser linewidth (a) BER versus SIR at 56Gbps PAM4 with -5dBm ROP (b) BER versus ROP at 56Gbps PAM4 with 24dB SIR (c) BER versus SIR at 60Gbps PAM8 with -5dBm ROP, and results of 4 MHz laser linewidth (d) BER versus SIR at 56Gbps PAM4 with -8dBm ROP (e) BER versus ROP at 56Gbps PAM4 with 27dB SIR; results at 56Gbps PAM4 under two delay paths of 25kHz laser linewidth (f) BER versus SIR with -4dBm ROP, and results of 4 MHz laser linewidth (g) BER versus SIR with -7dBm ROP.

## 4. Conclusion

The proposed DSP-compatible PDF algorithm can adaptively determine the threshold levels and correct desultory points without manually adjusting the weight factors to deal with channel changes. Furthermore, it doesn't increase complexity compared to the A2 scheme nor demand a high processing rate like the ATD scheme. The PDF scheme effectively improves the BER of severely impaired signals above the 7%HD-FEC limit, meanwhile overcoming the local optima problem faced in the A2 algorithm at 56Gbps PAM4. In 60Gbps PAM8, the PDF algorithm improves the logarithm BER beyond 0.4 than the optimized A2 algorithm, with a 3dB tolerance increase in SIR.

## 5. Acknowledge

We thank the support of the National Nature Science Foundation of China (NSFC) (62331013, 62171190).

## 6. References

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