# On the Spatial Resolution of Location-Resolved Performance Monitoring by Correlation Method

**Choloong Hahn[(1)], and Zhiping Jiang[(1)*]**
[(1)] *Huawei Technologies Canada, 303 Terry Fox Drive, Ottawa, Canada*
*zhiping.jiang@huawei.com*

**Abstract:** We show that the spatial resolution of correlation method for location-resolved performance monitoring is as good as the MMSE by applying deconvolution. Also, we propose a digital block filtering method to improve the spatial resolution under given signal and link condition.


## 1. Introduction

Location-resolved performance monitoring which utilized optical nonlinearity has recently attracted great attention due to its impairment localization capability. During the light propagation along a transmission link, various impairments can exist, such as chromatic dispersion, polarization dependent loss (PDL), nonlinear noise, multi-path interference (MPI), and optical filter misalignments. At the receiver, those impairment may be detected, but the detection is usually limited to the total accumulated amount of those impairments. It is important to detect such impairments at the receiver side, but sometimes the detection of exact location is more critical to resolve and recover the transmission line from those failures.

There are two main streams in location-resolved monitoring which are correlation method (CM) [1-3] and minimum mean square error (MMSE) method [4,5]. They are sharing one primary concept that the unique signal waveform at each location generated by dispersion is recorded in the nonlinear distortion. However, such longitudinal monitoring method suffers from spatial resolution and consequent estimation accuracy because the uniqueness of the nonlinear distortion is limited by the dispersion correlation width [6]. Recently, it is claimed in [6] that the MMSE method does not suffer from the spatial resolution because the MMSE naturally includes deconvolution process while CM does. However, the deconvolution can be directly applied to the result of CM, and it can provide the same spatial resolution as MMSE in noise-less and distortion-less condition. CM and MMSE are two different technique, thus they can have different applications. For example, CM can easily do MPI localization [3] by preparing a special correlation template, while MMSE may need further efforts.

In this paper, we propose to use digital block filtering (DBF) to improve spatial resolution without deconvolution by narrowing down the dispersion correlation width. Also, we show that the CM can provide same spatial resolution as MMSE with deconvolution or DBF. This method can be applied to other location-resolved performance monitoring methods which utilize the uniqueness of nonlinear distortions.

## 2. Basic Principle of Location-Resolved Performance Monitoring

The location-resolved performance monitoring can be performed by utilizing nonlinear distortions. As schematically shown in Fig. 1(a), the light propagation in optical fiber can be considered as repeated dispersion operations ($\widehat{D}$) followed by nonlinearity operations ($\widehat{N}$). The dispersion generates unique signal waveform at each location, and then the followed nonlinear operation records the waveform into nonlinear distortion, which is also unique. Those two operations are in a non-permutable relationship, therefore the local nonlinear distortion can be retrieved at Rx. Also,

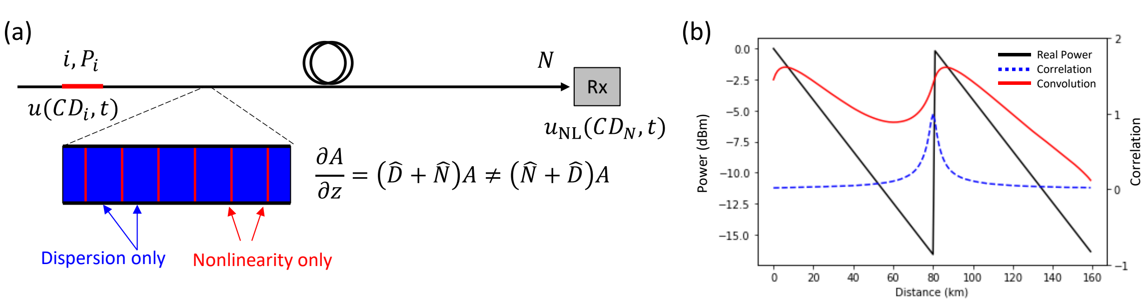


Fig. 1: (a) A schematic picture of nonlinear distortion generation under signal propagation along a fiber link. (b) Degradation of longitudinal power profile estimation due to dispersion correlation.

accumulated dispersion is uniquely linked to a distance in a dispersion uncompensated link, therefore the location of each nonlinear distortion can be detected at the receiver.

For example, assuming a linear signal waveform at location $i$ is given as $u(CD_i, t)$, where $CD_i$ is the accumulated chromatic dispersion from Tx to location $i$, and $t$ is the time, then the nonlinear waveform at the location becomes $u_{\mathrm{NL}}(CD_i, t) = u(CD_i, t)\exp(-j\gamma|u(CD_i, t)|^2)$ due to the Kerr nonlinearity. For a small nonlinearity, it can be written as $u_{\mathrm{NL}}(CD_i, t) = u(CD_i, t) + \Delta u_{\mathrm{NL}}(CD_i, t)$ where, $\Delta u_{\mathrm{NL}}(CD_i, t) = -j\gamma u(CD_i, t)|u(CD_i, t)|^2$ is the nonlinear distortion of location $i$, $\gamma$ is the nonlinear coefficient, and $j$ is the complex number.

Since the $\Delta u_{\mathrm{NL}}(CD_i, t)$ accumulates chromatic dispersions during propagation to the location $N$ (Rx), the received nonlinear distortion generated at location $i$ becomes $\Delta u'_{\mathrm{NL}}(CD_i, t) = H_{N-i}\big(\Delta u_{\mathrm{NL}}(CD_i, t)\big)$, where $H_{N-i}$ is the function to add chromatic dispersion $CD_N - CD_i$ to the nonlinear distortion. Therefore, the received nonlinear signal is the sum of the linear signal and all accumulated nonlinear distortions as $u_{\mathrm{NL}}(CD_N, t) = u(CD_N, t) + \sum_{i=1}^{N} \Delta u'_{\mathrm{NL}}(CD_i, t)$. The accumulated nonlinear distortion has the local power and signal waveform information. Therefore, the location-resolved performance monitoring can be done by retrieving desired local information from the accumulated nonlinear distortions. In order to retrieve local information from nonlinear distortions, the uniqueness of each location is required. Thus, the spatial resolution of such performance monitoring is limited by the distance that the uniqueness is guaranteed, which is mainly determined by the dispersion correlation width.

One of the common location-resolved performance monitoring is longitudinal power profile estimation [1,2]. The power profile can be obtained by repeating the estimation of each local power for all the locations. However, the resulted power profile is a convolution between real power profile and correlation curve as shown in Fig. 1(b). The dispersion correlation is fundamental limitation of the spatial resolution in such longitudinal monitoring. Therefore, it is required to mitigated the dispersion correlation effect to improve the spatial resolution.

## 3. Digital Block Filtering

The dispersion correlation mainly depends on the dispersion coefficient of link fibre and signal baud rate [1]. It is well known that high frequency signals are rapidly changing by dispersion accumulation which leads to narrower dispersion correlation width. From similar idea, high frequency components of a signal spectrum have fast response to the dispersion while the low frequency components do not. Therefore, the basic idea of DBF is to filter out low frequency components of the signal to reduce dispersion correlation in the accumulated nonlinear distortion.

Fig. 2 shows dispersion correlation curves of local nonlinear distortions for a 68 GBaud signal. The black dashed curve is the dispersion correlation curve of nonlinear distortions without DBF, and other coloured curves are the correlation curve with brick wall shaped DBF under different filtering bandwidth (BW). The dashed arrow indicates the direction of increasing the BW up to 50 GHz with 10 GHz steps. The inset is one example of spectrum after DBF applied. The non-zero tail of the dispersion correlation curve is the main contribution to the poor spatial resolution and consequent estimation errors. The errors become critical when the local power is weak because the contribution of other location is getting higher than the target location. This can be compensated by an offset adjustment to some extent, but it cannot be completely compensated because it is location dependent. On the other hand, the DBF eliminates the contributions from neighbouring locations. Therefore, DBF can be a promising method to improve spatial resolution and estimation accuracy.

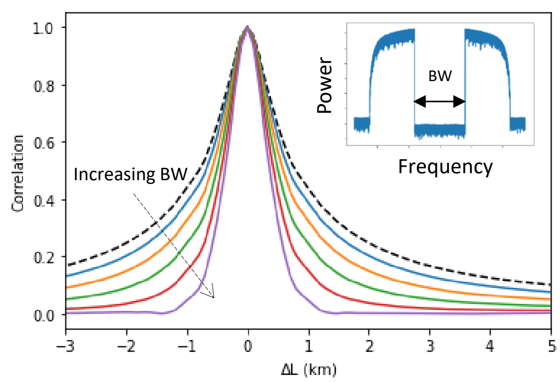


Fig. 2: Dispersion correlation curves under different DBF condition. Black dashed curve: no DBF, colored curves: under brick wall shaped DBF with different filtering BW. The dashed arrow indicates the direction of BW increase. Inset shows a signal spectrum under DBF.

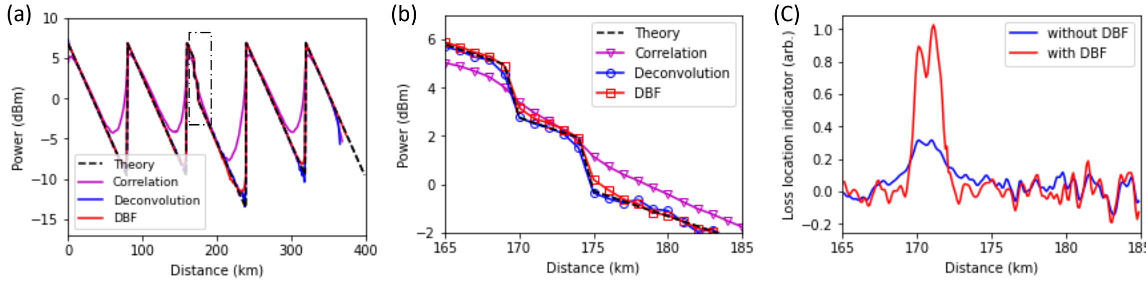


Fig. 3: (a) Longitudinal power profile estimation. (b) Magnified power profile estimation near artificial losses (c) Location-resolved loss location indicator

## 4. Results and Discussion

Proposed DBF is confirmed by performing a longitudinal power profile estimation. The propagation of a signal was simulated by solving nonlinear Schrödinger equation with split step method with 0.1 km steps. Simulated link is a dispersion uncompensated link consists with 5×80 km SSMF spans. The signal under test is 68 GBaud DP-QPSK. Two artificial losses (2 dB each) are applied in the middle of the link to test the spatial resolution.

Longitudinal power profile estimated with CM [1-3] is shown in Fig. 3(a). The enlarged plot of the dash-dot rectangle is in Fig. 3(b). The black dashed line is real power profile and magenta curve is estimated power profile. As it is predicted in Fig. 1(b), the power profile estimated by CM is convoluted, thus it has low spatial resolution and inaccurate estimation at the span input/output. However, the estimation can be improved by applying deconvolution as shown in Fig. 3(a) (blue curve). The deconvoluted power profile is almost identical with the real power profile, which shows the same quality as the MMSE method in [6] under noise-less, distortion-less condition. Instead of deconvolution, we can also apply DBF to the power profile estimated by CM. In Fig. 3(a), the power profile with DBF is shown as red curve. Deconvolution shows better spatial resolution and accuracy than DBF, however the deconvolution is not trivial in practical application because it is noise sensitive and instable process. In practical application, we can use DBF first to decrease the correlation width which makes deconvolution easier, and then apply deconvolution to achieve best resolution and accuracy.

The loss location indicators are shown in Fig. 3(c) for 1 km spaced artificial losses. It shows that the two loss locations are detectable with using DBF while it is not recognizable without DBF. In addition, the indicator is stronger with DBF because it is following the abrupt power changes much better than the case without DBF as shown in Fig. 3(b). Therefore, DBF can provide significant improvement on both spatial resolution and consequent detection accuracy.

In this paper, we only considered brick wall shaped filter, but it is one specific example of the DBFs. Depending on link condition and signal parameters, there can exist better digital filter to use. Therefore, it is worth to investigate various filter types and their optimum filter parameters for other scenarios. In addition, cascaded DBFs can be another option to further improve the spatial resolution.

## 5. Conclusion

We proposed digital block filtering method to improve the spatial resolution and accuracy of the location-resolved performance monitoring. Also, we showed that the deconvolution and/or DBF can improve the spatial resolution as same as MMSE method under noise-less, distortion-less condition. This method can be applied to other monitoring methods which is utilizing nonlinear distortions.

## 6. References

[1] T. Tanimura, K. Tajima, S. Yoshida, S. Oda, and T. Hoshida, "Experimental demonstration of a coherent receiver that visualizes longitudinal signal power profile over multiple spans out of its incoming signal", European Conference on Optical Communication (ECOC 2019) (2019).

[2] A. May, F. Boitier, A. Courilleau, B. A. Ayoubi and P. Layec, "Demonstration of Enhanced Power Losses Characterization in Optical Networks", *2022 Optical Fiber Communications Conference and Exhibition (OFC)* (2022).

[3] C. Hahn, J. Chang and Z. Jiang, "Localization of Reflection Induced Multi-Path-Interference Over Multi-Span Transmission Link by Receiver-side Digital Signal Processing," *2022 Optical Fiber Communications Conference and Exhibition (OFC)* (2022).

[4] T. Sasai, M. Nakamura, E. Yamazaki, S. Yamamoto, H. Nishizawa, and Y. Kisaka, "Digital longitudinal monitoring of optical fiber communication link," J. Light. Technol. **40**, 2390–2408 (2022).

[5] S. Gleb, P. Konstantin, J. Luo, and B. Zheng, "Fiber link anomaly detection and estimation based on signal nonlinearity," European Conference on Optical Communication (ECOC) (2021).

[6] T. Sasai, E. Yamazaki, M. Nakamura, and Y. Kisaka, "Closed-form Expressions for Fiber-Nonlinearity-Based Longitudinal Power Profile Estimation Methods," European Conference on Optical Communication (ECOC 2022) (2022).