Digital post-processing against inline spectrum narrowing caused by optical node traversals

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Abstract: This paper evaluates performance of digital coherent receivers that execute partial-response spectrum shaping and MLSE to mitigate the inline-spectrum-narrowing impairment caused by traversing multiple optical nodes in photonic networks. Extensive computer simulations confirm that the maximum transmission distances and hop counts of DP 4-QAM and 16-QAM signals in highly dense WDM networks are substantially extended.

Keywords: digital coherent receiver, partial-response coding, spectrum narrowing

Classification: Fiber-Optic Transmission for Communications

References

[1] Y. Mori, H. Hasegawa, and K. Sato, “Joint pre-, inline-, and post-compensation of spectrum narrowing caused by traversing multiple optical nodes,” Proc. ECOC 2017, Gothenburg, Sweden, P1.SC3.45, Sep. 2017. DOI:10.1109/ECOC.2017.8345928
[2] K. Kikuchi, “Fundamentals of coherent optical fiber communications,” J. Lightwave Technol., vol. 34, pp. 157–179, 2016. DOI:10.1109/JLT.2015.2463719
[3] J. G. Proakis and M. Salehi, Digital Communications Fifth Edition, McGraw-Hill, New York, 2008.
[4] J. Li, Z. Tao, H. Zhang, W. Yan, T. Hoshida, and J. C. Rasmussen, “Spectrally efficient quadrature duobinary coherent systems with symbol-rate digital signal processing,” J. Lightwave Technol., vol. 29, pp. 1098–1104, 2011. DOI:10.1109/JLT.2011.2105461
[5] K. Igarashi, T. Tsuritani, I. Morita, and M. Suzuki, “Ultra-long-haul high-capacity super-Nyquist-WDM transmission experiment using multi-core fibers,” J. Lightwave Technol., vol. 33, pp. 1027–1036, 2015. DOI:10.1109/JLT.2015.2396902
[6] S. Yamaoka, Y. Mori, H. Hasegawa, and K. Sato, “Novel demodulation algorithm based on duo-binary spectrum shaping and MLSE for mitigating spectrum narrowing caused by multiple node traversals,” Proc. Advanced Photonics Congress 2018, Zurich, Switzerland, SpW1G.5, July 2018. DOI:10.1364/SPPCOM.2018.SpW1G.5
[7] S. Yamaoka, Y. Mori, H. Hasegawa, and K. Sato, “Novel demodulation
framework based on quadrature duo-binary/quaternary/octernary spectrum shaping and MLSE for mitigating spectrum narrowing caused by node traversals,” Proc. ECOC 2018, Rome, Italy, Mo4F.5, Sept. 2018. DOI:10.1109/ECOC.2018.8535336

[8] N. Stojanovic, Z. Qiang, C. Prodaniuc, and F. Karinou, “Performance and DSP complexity evaluation of a 112-Gbit/s PAM-4 transceiver employing a 25-GHz TOSA and ROSA,” Proc. ECOC, Tu. 3. 4. 5, 2015. DOI:10.1109/ECOC.2015.7341947

[9] A. Masuda, H. Taniguchi, S. Yamamoto, Y. Ogiso, and M. Fukutoku, “96-Gbaud PAM-4 transmission with 1 sample/symbol under 2-GHz bandwidth limitation using NL-MLSE based on third-order Volterra filter,” Proc. ECOC, We4G. 5, 2018. DOI:10.1109/ECOC.2018.8535509

[10] S. L. Woodward, M. D. Feuer, and P. Palacharla, “ROADM-node architectures for reconfigurable photonic networks,” in Optical Fiber Telecommunications Sixth Edition, ed. I. P. Kaminow, Academic Press, 2013.

1 Introduction

To accommodate the growing network traffic, spectral efficiency of photonic networks must be improved. The spectral efficiency can be improved by the use of highly dense wavelength-division multiplexing (WDM) and the higher-order modulation formats with coherent detection. In such spectrally efficient systems, the signal suffers from severe signal-spectrum narrowing caused by traversing the wavelength-selective switches (WSSs) within optical nodes [1]. The inline spectrum narrowing might occur at every optical-node traversal. The spectrum narrowing results in intersymbol interference (ISI) as the global transfer function of concatenated WSSs does not satisfy the Nyquist ISI criterion. Furthermore, the narrowed signal spectrum is contaminated by amplified-spontaneous-emission (ASE) noise generated from the optical amplifiers. As the signal repeatedly undergoes such filtering-and-amplification processes, the ISI and ASE noise impair the signal in an interactive manner. The ISI itself can completely be equalized by digital filters in digital coherent receivers [2]. However, such linear equalizers enhance the intra-band noise power because the low-power frequency components of the filtered signal are emphasized for ISI compensation [1]. Maximum likelihood sequence estimation (MLSE) can perform symbol decision under the influence of ISI without the noise enhancement [3]. However, the computational complexity of MLSE is high owing to the uncertain impulse response of the channel. Another candidate is partial-response coding, e.g. duo-binary, in conjunction with MLSE [4, 5]; it realizes a narrow signal bandwidth by deliberately imposing deterministic ISI at the transmitter side. The partial-response-coded signal possesses high spectrum-narrowing tolerance; however, its short intersymbol distances on the constellation map result in low ASE-noise tolerance. In addition, the noise enhancement accompanying ISI compensation is inevitable [6, 7].

Given this background, we showed effectiveness of receiver-side partial-response filters in conjunction with MLSE decoding in highly dense WDM networks using wavelength routing [6, 7]. The 4/16/64-QAM (M-QAM) signal spectrum narrowed by traversing optical nodes is shaped with a digital filter in the digital
coherent receiver as if the signal is coded by a two-tap partial-response filter; in other words, the $M$-QAM signal is converted into the two-tap partial-response-filtered (PRF) $M$-QAM signal at the receiver side. By allowing the deterministic two-symbol-length ISI, the noise enhancement inherent in the conventional systems can be suppressed. The symbols are then decoded by the simple two-symbol MLSE. Although this scheme can extend the maximum transmission distances and hop counts, the noise enhancement still occurs if the received signal spectrum is extremely narrow due to a large number of node hops.

This paper extended the allowable ISI length to 3 and 4, where spectrum shaping is performed as if the received signals are coded by the $n$-tap ($n = 2$, 3, or 4) partial-response filter best suited to the received signals. As a result, the impact of noise is reduced. Then, simple $n$-symbol MLSE conducts symbol decision under the residual deterministic $n$-symbol-length ISI. The maximum transmission distances and hop counts of dual-polarization (DP) $M$-QAM signals in highly dense WDM networks are more extended when the impacts of spectrum narrowing is severe.

2 Digital signal processing for inline spectrum narrowing

Fig. 1 shows the post-processing scheme in the digital coherent receiver; the conventional scheme is also illustrated. The $M$-QAM signal carried by the network experiences multiple filtering-and-amplification processes along the channel. In the conventional scheme, the received signal is then equalized by a digital filter in the digital coherent receiver. In the equalization process, noise enhancement is unavoidable and the signal-to-noise ratio (SNR) is degraded. In contrast, the spectrum of the received $M$-QAM signal is shaped to yield an $n$-tap PRF $M$-QAM signal spectrum using a digital filter in the digital coherent receiver. This filtering process allows deterministic $n$-symbol-length ISI and so can suppress the noise enhancement inevitable in the conventional scheme. Then, the simple $n$-symbol MLSE conducts symbol decision under the residual deterministic $n$-symbol-length ISI. We can thus alleviate the impairment stemming from the spectrum narrowing. Fig. 2 shows the trade-off between spectrum-narrowing tolerance and noise tolerance regarding the number of taps of partial-response filter $n$. The upper row illustrates signal spectra after partial-response filters. As $n$ increases, noise is suppressed more since the filter shape becomes narrower. However, the shorter intersymbol distance due to deterministic ISI results in lower noise tolerance as shown in the lower row. Hence the optimum $n$ should be selected so as to maximize the transmission performance.

It has been proven that the receiver-side spectrum shaping followed by MLSE can improve the transmission performance of point-to-point non-coherent systems in which the signal spectrum is severely narrowed due to the transmitter/receiver electrical band limitation [8, 9]. In contrast, the subjects of this paper are inline spectrum narrowing caused by WSSs and the mitigation scheme executed in the digital coherent receiver. Hence, the filtering source, noise source, and detection scheme differ from those discussed in the literatures [8, 9].
3 Simulations

We executed computer simulations assuming nonlinear transmission systems. A transmitter generates a power-optimized 32-Gbaud DP 4/16/64-QAM (M-QAM) signal. The signal is then combined with closest eight wavelength channels through a WSS. The grid interval is 37.5 GHz considering highly dense WDM networks. The signals are then launched into a fiber link. Each link consists of a 50-km or 100-km single-mode fiber (SMF) and an erbium-doped fiber amplifier (EDFA). The loss coefficient, dispersion parameter, and nonlinear coefficient of the SMF are 0.2 dB/km, 17 ps/nm/km, and 1.5/ W/km, respectively. The noise figure of the EDFA is 5 dB. The power of each channel is then amplified to −1 dBm and the signal enters the next node. The route-and-select (R&S) node architecture (WSS-WSS) is assumed [10]; the node loss is 15 dB. The passband of each WSS is calculated by convoluting a rectangular function with 37.5-GHz bandwidth and a Gaussian function with 10-GHz 3-dB bandwidth; here, the 3-dB bandwidth of the

![Fig. 1. Concept of digital signal processing for inline spectrum narrowing.](image)

| The number of taps $n$ | Conv. | $n=2$, $h=[1 \ 1]$ | $n=3$, $h=[1 \ 2 \ 1]$ | $n=4$, $h=[1 \ 3 \ 3 \ 1]$ |
|------------------------|-------|---------------------|------------------------|------------------------|
| Ideal signal spectrum  | ![Diagram](image) | ![Diagram](image) | ![Diagram](image) | ![Diagram](image) |
| Spectrum-narrowing tolerance | Low | High |
| Ideal constellation map of a 4-QAM signal | ![Diagram](image) | ![Diagram](image) | ![Diagram](image) | ![Diagram](image) |
| Noise tolerance | High | Low |

![Fig. 2. Trade-off between spectrum-narrowing tolerance and noise tolerance regarding the number of filter taps $n$, where $h$ denotes the impulse response of the partial-response filter.](image)

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Gaussian function determines the cut-off characteristics. After multiple node hops, the target signal is dropped and detected by a digital coherent receiver. After compensation for chromatic dispersion, the DP M-QAM signal is polarization-demultiplexed by a two-by-two butterfly-structured finite-impulse-response (FIR) filter with 16 tap coefficients adapted by the least-mean-square algorithm [2]; at the same time, the signal spectrum is converted into a proper $n$-tap PRF M-QAM signal spectrum. After that, the $n$-tap PRF M-QAM signal is decoded by the simple $n$-symbol MLSE [3]. Finally, the bit-error ratio (BER) is calculated. The target BER is $10^{-2}$ considering the use of forward error correction (FEC). For reference, conventional demodulation schemes were also evaluated.

Fig. 3 depicts BER versus transmission distance and hop count, where the modulation order $M$ and inter-node distance are changed. We find that improvement in the 50-km-span systems is more prominent than that in the 100-km-span systems. This is because the signal spectrum is more narrowed in the 50-km-span systems with the given transmission length. Compared to the conventional scheme, the proposed scheme can attain much longer transmission distance and larger hop count when $M = 4$ and $M = 16$. As for the cases where $M = 64$, less improvement is observed because such systems are more susceptible to ASE noise and fiber nonlinearity rather than to spectrum narrowing. Such features are in good agreement with the qualitative prediction shown in Fig. 2. When the spectrum narrowing is the dominant cause of performance degradation, the BER is substantially improved; for example, the maximum hop count of the 4-QAM signal can be extended by 16 for the 50-km-span system and by 8 for the 100-km-span system; the corresponding distance increases are 800 km and 800 km. Thus, the use of appropriate partial-response filter can substantially extend the transmission distances and hop counts.
4 Conclusions

We confirmed the effectiveness of a combination of partial-response spectrum shaping and MLSE to alleviate the impact of the spectrum narrowing caused by traversing multiple optical nodes. Extensive computer simulations confirmed the effectiveness in highly spectrally efficient WDM networks based on wavelength routing. For example, we can extend the maximum hop count of a 32-Gbaud DP-QPSK signal by 8, when the inter-node distance is 100 km; the distance increase is 800 km. The scheme can utilize conventional coherent transmitters; only the receiver’s digital signal processing needs to be modified.

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