



Demultiplexing of nyquist-otdm signal based on temporal magnification aided optical sampling with enhanced performance

Yue, Lei; Kong, Deming; Li, Yan; Wu, Jian

Published in:
IEEE Photonics Journal

Link to article, DOI:
[10.1109/JPHOT.2019.2929213](https://doi.org/10.1109/JPHOT.2019.2929213)

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Yue, L., Kong, D., Li, Y., & Wu, J. (2019). Demultiplexing of nyquist-otdm signal based on temporal magnification aided optical sampling with enhanced performance. *IEEE Photonics Journal*, 11(4), Article 8765390. <https://doi.org/10.1109/JPHOT.2019.2929213>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

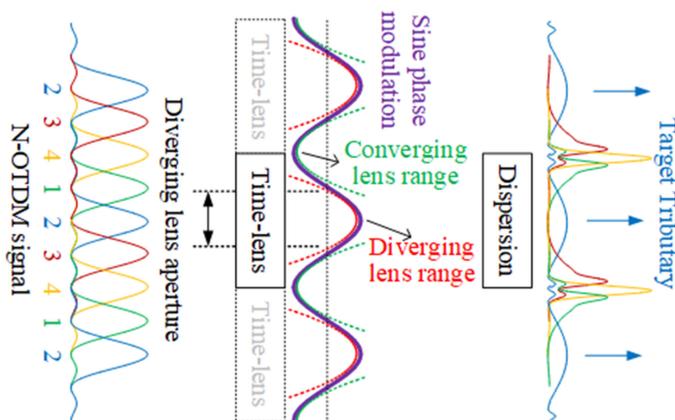
- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Demultiplexing of Nyquist-OTDM Signal Based on Temporal Magnification Aided Optical Sampling With Enhanced Performance

Volume 11, Number 4, August 2019

Lei Yue
Deming Kong
Yan Li
Jian Wu, *Member, IEEE*



DOI: 10.1109/JPHOT.2019.2929213

Demultiplexing of Nyquist-OTDM Signal Based on Temporal Magnification Aided Optical Sampling With Enhanced Performance

Lei Yue ¹, Deming Kong,^{1,2} Yan Li ¹,
and Jian Wu ¹ *Member, IEEE*

¹State Key Laboratory of Information Photonics and Optical Communications, Beijing
University of Posts and Telecommunications, Beijing, 100876, China

²DTU Fotonik, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark

DOI:10.1109/JPHOT.2019.2929213

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see <https://creativecommons.org/licenses/by/4.0/>

Manuscript received June 27, 2019; revised July 10, 2019; accepted July 13, 2019. Date of publication July 17, 2019; date of current version July 30, 2019. This work was supported in part by the 863 Program under Grant 2015AA015503, in part by the National Science Foundation of China (NSFC) under Grant 61505011, Grant 61475022, Grant 61331008, and Grant 61307055, in part by the 973 program under Grant 2014CB340100, in part by the Fund of state key laboratory of IPOC (BUPT), in part by the Fundamental Research Funds for the Central Universities, and in part by the China Postdoctoral Science Foundation. Corresponding author: Yan Li (e-mail: liyan1980@bupt.edu.cn.)

Abstract: Demultiplexing of high-speed Nyquist optical time-division multiplexed (N-OTDM) signal requires ultra-narrow local sampling pulse to avoid the severe inter-symbol-interference (ISI) between each tributary. Unfortunately, generation of such narrow sampling pulse is difficult or usually need complex setup configure at the receiver side, which would cause ineffective cost in application scenarios such as short-reach optical communication or PON applications. In this paper, we propose and demonstrate demultiplexing of N-OTDM signal based on temporal magnification followed by coherent optical sampling to enable broader sampling pulsewidths while reducing the ISI. The target tributary of the N-OTDM signal is temporally magnified and further demultiplexed through coherent optical sampling using Gaussian-shaped or Nyquist-shaped pulses. With the aid of temporal magnification based on a time-lens, the sampling window can be extended during the coherent detection progress at the receiver side. Gaussian sampling pulses with a pulsewidth up to 10.4 ps are enabled for the demultiplexing of a 160 Gbaud N-OTDM signal. Compared with demultiplexing based on Nyquist pulses (i.e., coherent matched sampling) without temporal magnification, the proposed scheme features a better performance with pulsewidths greater than 6 ps. If temporal magnification is combined with coherent matched sampling, Nyquist sampling pulses with a pulsewidth up to 12.4 ps are made possible for the demultiplexing. Therefore, the proposed scheme based on temporal magnification could significantly release the pulsewidth requirement for N-OTDM demultiplexing while mitigating the ISI.

Index Terms: Optical communications, coherent communications.

1. Introduction

High spectral single-channel transmission has become the target of intensive research as required by the growing demand for network resource. Nyquist optical time-division multiplexing (N-OTDM) [1] has been a research interest due to its capability to achieve fundamental minimum bandwidth, as well as its tolerance to transmission impairments such as chromatic dispersion [2], polarization

mode dispersion [3], and self-phase modulation [4]. Combined with other multiplexing techniques, it has been proved to achieve an ultra large transmission capacity of 43 Tbit/s [5]. N-OTDM signal can be generated through spectral engineering of a Gaussian-pulse carried OTDM signal [6] or from a Nyquist pulse train [1]. However, demultiplexing of N-OTDM signal usually requires an ultra-narrow optical gate to sample the inter-symbol-interference (ISI) -free point out of each symbol on a certain tributary [1]. Unfortunately, such narrow optical gate with a high optical signal-to-noise ratio (OSNR) is usually difficult to realize at the receiver side, especially for the demultiplexing of high speed N-OTDM signal [7]. Furthermore, applying a very narrow optical gate to the N-OTDM signal would result in severe power loss and subsequent OSNR degradation. Similar scenario can be expected if the N-OTDM signal is converted to and further demultiplexed in the frequency domain [6], [8] using optical bandpass filters (OBPF). The demultiplexing performance would also be degraded due to inter-carrier-interference (ICI).

Recently, we have proposed coherent matched sampling to enable high performance detection of N-OTDM signal [9]. Compared with optical sampling with Gaussian-shaped pulses, the proposed scheme with Nyquist-shaped pulses could mitigate the ISI with the same pulse width. In this paper, demultiplexing of N-OTDM signal based on temporal magnification followed by coherent optical sampling is investigated and demonstrated in a 160 Gbaud experiment. Aided by temporal magnification based on a time-lens, the sampling window can be significantly extended with a lower OSNR. Gaussian sampling pulses with a pulse width up to 10.4 ps are enabled for the demultiplexing. Compared with coherent matched sampling, the proposed scheme is found to have a better performance with sampling pulse widths greater than 6 ps. In addition, the combination of both temporal magnification and coherent matched sampling is also investigated, featuring relatively the best performance with sampling pulse widths greater than 8 ps. And a pulse width up to 12.4 ps is enabled for the demultiplexing of the N-OTDM signal. Therefore, the proposed scheme based on temporal magnification could significantly release pulse width requirement for N-OTDM demultiplexing while mitigating the ISI.

2. Principle of the Temporal Magnification

Figure 1 depicts the principle of the temporal magnifier. The principle originates from the well-known space-time duality theory [10]. Diffractive propagation of spatial light beams is in closest analogy to the dispersive propagation of temporal optical pulses. An analogy also exists between a spatial light beam passing through a spatial lens and a temporal optical pulse being phase modulated parabolically. The parabolic phase modulation is defined as a time-lens [11], which can be practically achieved by electro-optic phase modulation [12] or nonlinear optical processes [13].

Figure 1(a) shows the magnification scheme for a spatial light beam using free space optics. If a converging lens is applied, the output beam diameter ϕ_o and the input beam diameter ϕ_i has a relationship described as $1/\phi_i + 1/\phi_o = 1/\phi_f$, where ϕ_f is the focal length. The magnification factor is defined as $M = -\phi_o/\phi_i$. According to the space-time duality, a temporal optical pulse can be magnified with two pieces of dispersive elements and a time-lens with parabolic phase modulation. Then the magnification factor for the temporal pulse can be defined as $M = -D_o/D_i$ [13]. The focal dispersion D_f describes the strength of the phase modulation, where the chirp rate $K = 1/D_f$.

Shown in Fig. 1(b), if a certain magnification factor is not desired, the magnification system can be simplified using a diverging lens [14]. Analogously, a temporal magnification scheme with a temporal diverging lens, shown in Fig. 1(c), can be used. For the magnification of an N-OTDM tributary, electro-optic phase modulation is utilized for the implementation of the time lens. The N-OTDM signal is phase modulated by a base rate sine wave such that the target tributary is aligned with the peak of induced phase. Followed by a piece of optical fiber with a dispersion ($D = \beta_2 L$) of the same sign as the chirp rate, the target tributary can then be temporally magnified. As a result, the temporally magnified tributary can then be demultiplexed using optical sampling with a greater sampling pulse width, featuring a reduced ISI. Note that due to the periodic polarity reversal of the sine wave, other tributaries of the N-OTDM signal are squeezed temporally, as the phase

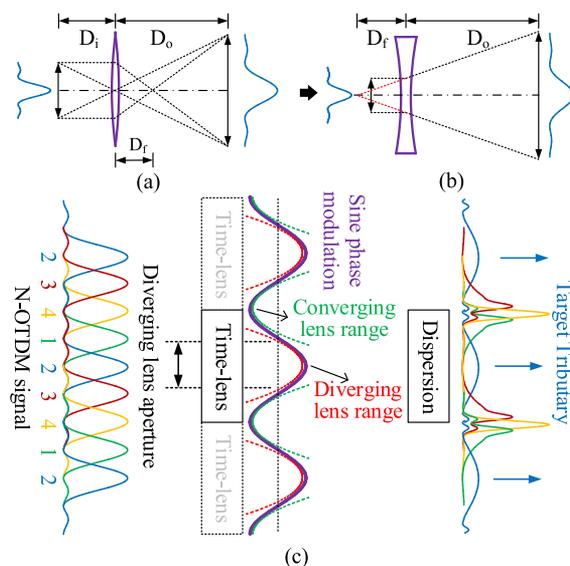


Fig. 1. The principle of temporal magnification on an N-OTDM tributary. (a) spatial magnification using a converging lens with a determined magnification factor; (b) spatial magnification using a diverging lens; (c) temporal magnification using a time-lens for one N-OTDM tributary. (D_i : input distance; D_o : output distance; D_f : focal length.)

modulation there performs as a temporal converging lens. Since sine wave is utilized for the phase modulation instead of a parabolic wave for simplicity, the diverging lens has only around 15% range over a single period (for a covariance <0.01). Such a range can be defined as the diverging lens aperture.

3. Experimental Setup

Figure 2(a) shows the experimental setup. A Gaussian-shaped optical pulse source centered at 1550.116 nm with a repetition rate of 40 GHz and a pulse width of 1.8 ps [9], is applied for the generation of both the 160 Gbaud N-OTDM signal and the sampling pulses. For the generation of the 160 Gbaud N-OTDM signal, the pulse source is firstly QPSK modulated with a 2^7-1 pseudorandom binary sequence (PRBS). Then it is fourfold multiplexed in time domain using a delay line based multiplexer. The generated 160 Gbaud OTDM signal is further spectral engineered by a wavelength selective switch (Finisar Waveshaper 4000 s) into Nyquist shape with a roll-off factor of approximately zero. On the other hand, for the generation of the sampling pulses, the pulse source is directly spectral engineered into Gaussian shapes or Nyquist shapes with various pulse widths.

The temporal magnifier, shown in Fig. 2(b), mainly consists of a phase modulator and a piece of dispersion compensating fiber (DCF). The phase modulator works as the temporal diverging lens. The choice of magnification factor is of great significance since the adjacent two tributaries of the target tributary will also be partly magnified if the magnification factor is too large, and also the power loss after magnification and demultiplexing would be increased, causing performance degradation. On the other hand, if the target tributary is insufficiently magnified, the ISI between adjacent tributaries would not be completely removed, as can be illustrated in Fig. 1(c). We adjusted the magnification factor and found it is desired around a value of 2 in our system under a pulse width around 6 ps through numerical simulation. Hence in the experiment a 40 GHz sine wave is applied with a peak-to-peak voltage of $2.8 V_\pi$ ($K = 0.28 p s^2$). The 25 m DCF has a dispersion $D = \beta_2 L = 3.7 p s^{-2}$. (The calculated magnification factor is 2.08). Insets show the simulated optical eyediagrams and spectra of the N-OTDM before and after magnification. The target tributary of the

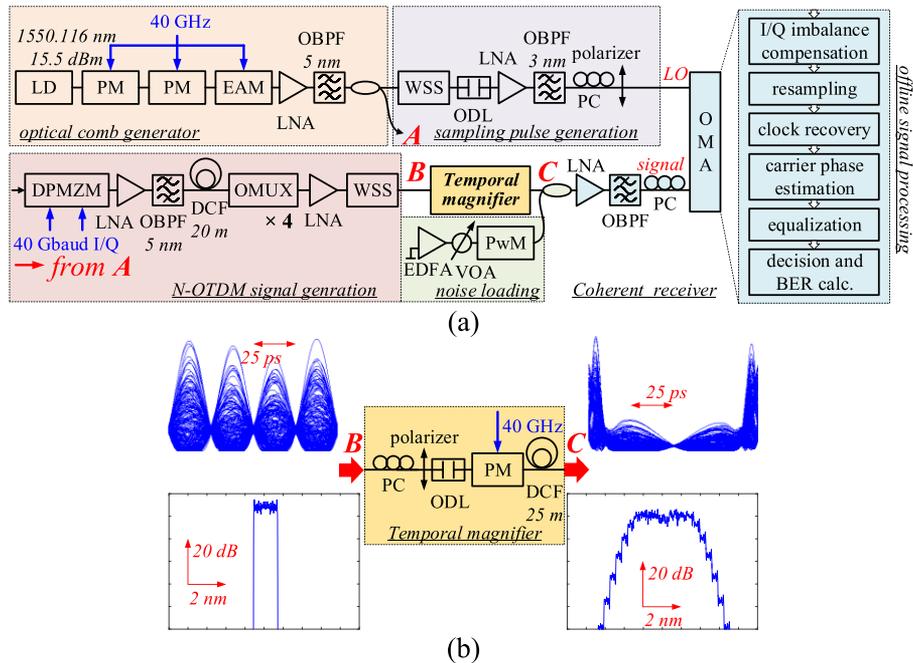


Fig. 2. (a) Experimental setup; (b) detailed setup of the temporal magnifier with simulation results. (LD: laser diode; EAM: electro-absorption modulator; LNA: low noise amplifier; VOA: variable optical attenuator; ODL: optical delay line; PC: polarization controller; OMUX: optical multiplexer; PwM: power meter)

N-OTDM signal is temporally magnified and the other tributaries are temporally squeezed. The magnified tributary can then be sampled out with a greater sampling pulse width.

For performance comparison, demultiplexing of the N-OTDM signal using coherent matched sampling [9] based on optical Nyquist pulses is also investigated with the same setup, where the temporal magnifier is turned off and the dispersion is pre-compensated in the waveshaper. In addition, when investigating the performance combining temporal magnification and coherent matched sampling, the temporal magnifier is turned back on.

At the receiver side, the signal is firstly noise loaded for OSNR calculation to evaluate the BER performance. Then it is pre-amplified, filtered, and mixed with the base rate sampling pulses through an optical hybrid in the optical modulation analyzer (32 GHz analog bandwidth with 80 GHz sampling rate) for coherent optical sampling and demultiplexing. Common digital signal processing algorithms are utilized for offline processing, including I/Q imbalance compensation via Gram-Schmidt orthogonalization procedure, Gardner symbol timing recovery, fourth power carrier phase estimation, blind adaptive equalization based on constant modulus algorithm combined with least mean square algorithm, and finally QPSK decision and BER calculation. A total number of 1 million symbols (2 million bits) are evaluated for the calculation of each BER value.

4. Results and Discussions

Figure 3(a) depicts the measured eye diagrams and optical spectra of the N-OTDM signal before and after temporal magnification. It can be seen from the eye diagrams that the target tributary of the signal is effectively magnified in time domain. A broader pulse can then be used to demultiplex the tributary with reduced ISI. Note that the optical spectrum of the N-OTDM signal is broadened due to phase modulation. Figs. 3(b) and (c) show optical spectra of the Gaussian-shaped and Nyquist-shaped sampling pulses with various pulse widths, respectively. Insets give corresponding eye diagrams of these pulses.

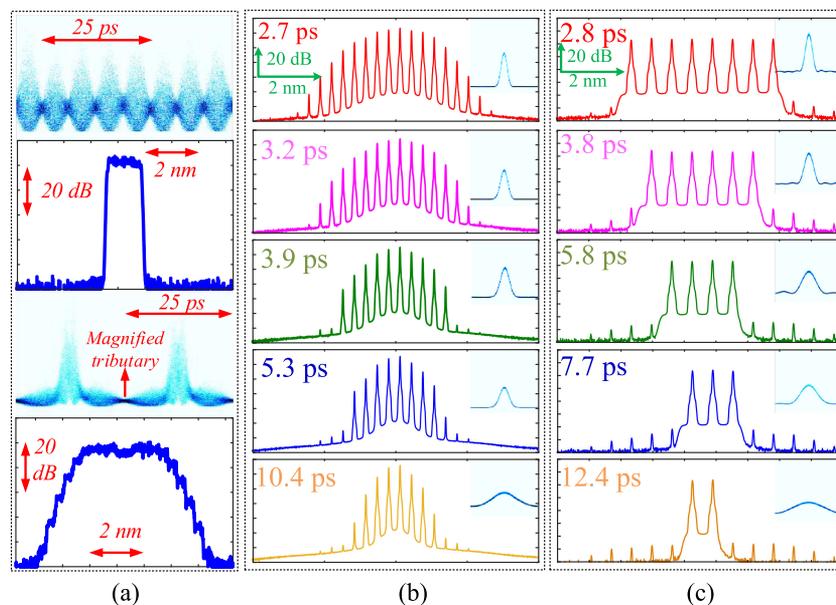


Fig. 3. Eye diagrams and optical spectra of (a) the N-OTDM and the tributary-magnified N-OTDM signal, (b) Gaussian and (c) Nyquist sampling pulses.

BER results of the 160 Gbaud N-OTDM signal using Gaussian-shaped sampling pulses with or without temporal magnification are shown in Fig. 4(a) and (b), respectively. Fig. 4(c) and (d) are the BER results using coherent matched sampling based on Nyquist pulses, with or without temporal magnification, respectively. Insets of these figures are the signal constellation maps at a BER value around 10^{-6} (2×10^{-1} for 5.3 ps Gaussian-shaped pulses in Fig. 3(a), and 7.7 ps Nyquist-shaped pulses in Fig. 3(c)). It can be seen that for Gaussian-shaped sampling, the performance of the unmagnified N-OTDM signal degraded severely along with the increment of the sampling pulse width, due to ISI. However, with the aid of temporal magnification, Gaussian-shaped sampling would also work for a pulse width of 5.3 ps or even 10.4 ps. On the other hand, for coherent matched sampling based on Nyquist pulses, the performance of the unmagnified N-OTDM signal also degrades with the increment of pulse width. But due to the ISI-suppression nature of coherent matched sampling, the demultiplexing could work well for a pulse width of 5.8 ps, outperforming Gaussian-shaped sampling. Furthermore, the combination of temporal magnification and coherent matched sampling is also investigated. The target tributary of the N-OTDM signal is temporally magnified and then demultiplexed using Nyquist-shaped pulses. The results show that a pulse width of 7.7 ps or even 12.4 ps would therefore work for the demultiplexing of the magnified N-OTDM tributary. Compared with temporal magnification followed by Gaussian-shaped sampling, the demultiplexing window has been further extended.

Figure 5 gives the performance comparison with different receiving OSNRs. Firstly, if temporal magnification is off, coherent matched sampling outperforms Gaussian sampling for all measured pulse widths, as can be expected from our previous works [9]. Secondly, for Gaussian sampling, temporal magnification aided demultiplexing would help to achieve a better performance with pulse widths greater than 4 ps, due to the reduction of the ISI. However, for a pulse width less than 4 ps, the performance is slightly degraded. This can be explained that if short optical pulses are applied as a sampling gate, the power loss and further OSNR degradation of the target tributary after demultiplexing and amplification would neutralize the benefits of ISI reduction as a result of temporal magnification. This also explains that an optimum sampling pulse width of 3.9 ps exists for this scheme.

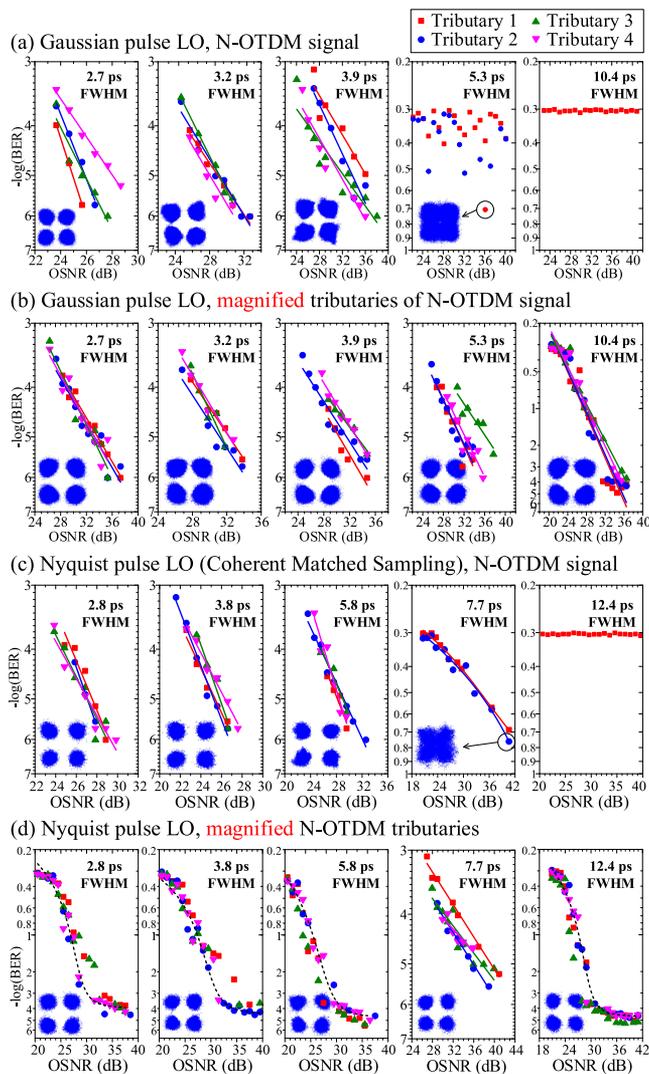


Fig. 4. BER results of the 160 Gbaud N-OTDM signal using Gaussian sampling pulses without (a) and with (b) temporal magnification, and using coherent matched sampling without (c) and with (d) temporal magnification.

Since coherent matched sampling can also significantly reduce the ISI using Nyquist pulses [9], it is desired to compare the performance of both coherent matched sampling and temporal magnification based schemes. It is observed that with a pulse width less than 6 ps, coherent matched sampling has a performance advantage over temporal magnification followed by Gaussian sampling. The reason can be explained that after temporal magnification, the power of the target tributary is distributed more widely. When short optical pulses are applied as a sampling gate, the demultiplexed tributary would suffer from more power loss and subsequent OSNR degradation. Note that along with the increment of OSNR, the performance difference between these two schemes does get smaller. On the other hand, for a sampling pulse width greater than 6 ps, temporal magnification followed by Gaussian sampling has a better performance than coherent matched sampling. The target tributary cannot be accurately detected (with BER value about 0.5) with coherent matched sampling, while the average BER value of 10^{-3} in different OSNR conditions can be found using temporal magnification followed Gaussian sampling. It is because the condition of coherent matched sampling can no longer be preserved for such broader Nyquist sampling

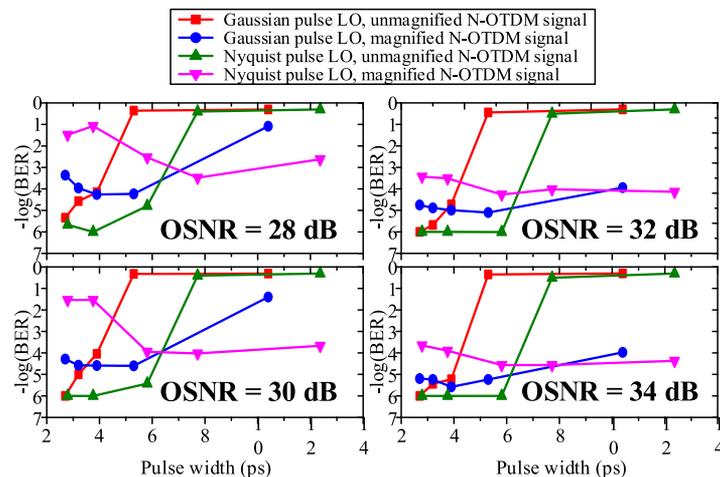


Fig. 5. Performance comparison of Gaussian sampling with or without temporal magnification and coherent matched sampling.

pulses [9]. In short, temporal magnification would allow N-OTDM signal to be demultiplexed by even broader pulses while mitigating the ISI.

As temporal magnification and coherent matched sampling are both proposed for the mitigation of ISI, it makes sense to investigate the performance by combining both techniques. Compared with coherent matched sampling for unmagnified N-OTDM signal, the orthogonality condition of coherent matched sampling can still be partly preserved using broader Nyquist pulses after temporal magnification. As a result, a relatively best performance can be observed with pulse width greater than 8 ps. And a pulse width up to 12.4 ps can be used to enable the demultiplexing of the 160 Gbaud N-OTDM signal. This means that the requirement on the sampling pulse width could be released by half. Note that the OSNR degradation is still responsible for the worse performance with a pulse width less than 6 ps. Nevertheless, the combination of temporal magnification and coherent matched sampling would further extend the demultiplexing window, greatly reducing the complexity to generate the local sampling pulses.

5. Conclusion

Demultiplexing of N-OTDM signal based on temporal magnification and coherent optical sampling is proposed and demonstrated in a 160 Gbaud experiment. With temporal magnification, Gaussian sampling pulses with a pulse width up to 10.4 ps are enabled for the demultiplexing of the N-OTDM signal. Compared with coherent matched sampling, temporal magnification followed by Gaussian-shaped sampling with pulse widths greater than 6 ps can enable the demultiplexing operation while the transmission outage would be happened with coherent matched sampling. If combined with coherent matched sampling with Nyquist pulses, the requirement on the sampling pulse width could be further released by half, demultiplexing the N-OTDM signal with 12.4 ps pulse width can achieve similar performance with 6 ps Gaussian-shaped sampling. Overall, the proposed scheme could significantly release the pulse width requirement for N-OTDM demultiplexing.

References

- [1] M. Nakazawa, T. Hirooka, P. Ruan, and P. Guan, "Ultrahigh-speed 'orthogonal' TDM transmission with an optical Nyquist pulse train," *Opt. Express*, vol. 20, no. 2, pp. 1129–1140, 2012.
- [2] T. Hirooka, P. Ruan, P. Y. Guan, and M. Nakazawa, "Highly dispersion tolerant 160 Gbaud optical Nyquist pulse TDM transmission over 525 km," *Opt. Express*, vol. 20, no. 14, pp. 15001–15007, 2012.

- [3] K. Harako, D. Seya, T. Hirooka, and M. Nakazawa, "640 Gbaud (1.28 Tbit/s/ch) optical Nyquist pulse transmission over 525 km with substantial PMD tolerance," *Opt. Express*, vol. 21, no. 18, pp. 21062–21075, 2013.
- [4] T. Hirooka and M. Nakazawa, "Linear and nonlinear propagation of optical Nyquist pulses in fibers," *Opt. Express*, vol. 20, no. 18, pp. 19836–19849, 2012.
- [5] H. Hu *et al.*, "Single source 5-dimensional (space-, wavelength-, time-, polarization-, quadrature-) 43 Tbit/s data transmission of 6 SDM \times 6 WDM \times 1.2 Tbit/s Nyquist-OTDM-PDM-QPSK," in *Proc. Conf. Lasers Electro Opt.*, 2014, Paper. JTh5B.10.
- [6] H. Hu *et al.*, "1.28 Tbaud Nyquist signal transmission using time-domain optical fourier transformation based receiver," in *Proc. Conf. Lasers Electro Opt.*, 2013, Paper. CTh5D.5.
- [7] K. Kimura, J. Nitta, M. Yoshida, K. Kasai, T. Hirooka, and M. Nakazawa, "A new optical phase-locked system between ultrashort pulses for 640 gbaud nyquist OTDM coherent QAM transmission," in *Proc. Eur. Conf. Opt. Commun.*, 2017, Paper. M1F.2.
- [8] H. Hu, D. Kong, E. Palushani, M. Galili, H. C. H. Mulvad, and L. K. Oxenløwe, "320 Gb/s nyquist OTDM received by polarization-insensitive time-domain OFT," *Opt. Express*, vol. 22, no. 1, pp. 110–118, 2014.
- [9] D. Kong *et al.*, "A novel detection scheme for Nyquist optical time-division multiplexed signal with coherent matched sampling," in *Proc. Opt. Fiber Commun. Conf.*, 2015, Paper. W3C.4.
- [10] B. H. Kolner, "Space-time duality and the theory of temporal imaging," *IEEE J. Quantum Electron.*, vol. 30, no. 8, pp. 1951–1963, Aug. 1994.
- [11] B. H. Kolner and M. Nazarathy, "Temporal imaging with a time lens," *Opt. Lett.*, vol. 14, no. 12, pp. 630–632, 1989.
- [12] M. Nakazawa, T. Hirooka, F. Futami, and S. Watanabe, "Ideal distortionfree transmission using optical Fourier transformation and Fourier transform-limited optical pulses," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1059–1061, Apr. 2004.
- [13] R. Salem, M. A. Foster, A. C. Turner, D. F. Geraghty, M. Lipson, and A. L. Gaeta, "Optical time lens based on four-wave mixing on a silicon chip," *Opt. Lett.*, vol. 33, no. 10, pp. 1047–1049, 2008.
- [14] Y. Xing, L. Huo, Q. Wang, D. Wang, and C. Lou, "Enhanced all-LiNbO₃ OTDM demultiplexing using a diverging time lens," in *Proc. Conf. Lasers Electro Opt.*, 2013, Paper. CM4G.5.