Analytical BER performance in differential n-PSK coherent transmission system influenced by equalization enhanced phase noise

Tianhua Xu [a,b,c*], Gunnar Jacobsen[c,d], Sergei Popov[c], Jie Li[d], Sergey Sergeyev[e],

Ari T. Friberg[c], Yimo Zhang[a]

[a]Tianjin University, Tianjin, 300072, China

[b]University College London, London, WC1E7JE, United Kingdom

[c]Royal Institute of Technology, Stockholm, SE-16440, Sweden

[d]Acreo Swedish ICT AB, Electrum 236, Kista, SE-16440, Sweden

[e]Aston University, Birmingham, B47ET, United Kingdom

* Corresponding author: Tianhua Xu

Post address: Department of Electronic and Electrical Engineering, Faculty of

Engineering, University College London, London, United Kingdom, WC1E 7JE

Tel: +44-7709662611

Fax: +44-2076793843

E-mail address: xutianhua@tju.edu.cn, tianhua.xu@ucl.ac.uk

ABSTRACT

Long-haul high speed optical transmission systems are significantly distorted by the interplay between the electronic chromatic dispersion (CD) equalization and the local oscillator (LO) laser phase noise, which leads to an effect of equalization enhanced phase noise (EEPN). The EEPN degrades the performance of optical communication systems severely with the increment of fiber dispersion, LO laser linewidth, symbol rate, and modulation format. In this paper, we present an analytical model for evaluating the performance of bit-error-rate (BER) versus signal-to-noise ratio (SNR) in the n-level phase shift keying (n-PSK) coherent transmission system employing differential carrier phase estimation (CPE), where the influence of EEPN is considered. Theoretical results based on this model have been investigated for the differential quadrature phase shift keying (DQPSK), the differential 8-PSK (D8PSK), and the differential 16-PSK (D16PSK) coherent transmission systems. The influence of EEPN on the BER performance in term of the fiber dispersion, the LO phase noise, the symbol rate, and the modulation format are analyzed in detail. The BER behaviors based on this analytical model achieve a good agreement with previously reported BER floors influenced by EEPN. Further simulations have also been carried out in the differential CPE considering EEPN. The results indicate that this analytical model can give an accurate prediction for the DQPSK system, and a leading-order approximation for the D8PSK and the D16PSK systems.

Key words: coherent optical communication, phase shift keying, differential carrier phase estimation, equalization enhanced phase noise, bit-error-rate, signal-to-noise ratio

PACS: 42.25.Kb, 42.79.Sz

1. Introduction

Coherent optical detection allows the significant equalization of transmission system impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), phase noise (PN), and fiber nonlinearities (FNLs) in the electrical domain by using the powerful digital signal processing (DSP) [1-7]. The carrier phase estimation (CPE) can be effectively implemented by employing the feedforward and the feedback algorithms [7-11]. As a conventional feedforward algorithm, the differential phase estimation has been validated as a simple and effective method for the phase noise compensation (PNC) in the coherent transmission system, which is also regarded as a benchmark for evaluating the CPE approaches [12-17]. However, the analysis of the phase noise in the transmitter (Tx) and the local oscillator (LO) lasers is often lumped together, and the interplay between the CD and the PN is not considered in the traditional evaluation of carrier phase estimation (including differential phase estimation). W. Shieh et al. have provided the theoretical assessment to evaluate the equalization enhanced phase noise (EEPN) from the interaction between the LO phase fluctuation and the fiber dispersion [18-21]. C. Xie has investigated the impacts of CD on both the LO phase noise to amplitude noise conversion and the fiber nonlinear effects [22,23]. I. Fatadin et al. have also studied the influence of the EEPN in quadrature phase shift keying (QPSK), 16-level quadrature amplitude modulation (16-QAM) and 64-QAM coherent transmission systems [24]. Meanwhile, the influence of EEPN on different CPE algorithms has also been investigated in detail by using numerical simulations [25-29]. Due to the EEPN, the requirement of laser

linewidth can not be generally relaxed for the transmission system with a higher symbol rate. It would be of importance to investigate the analytical estimation for the performance of bit-error-rate (BER) versus signal-to-noise ratio (SNR) in the carrier phase estimation in coherent optical transmission system considering the influence of EEPN.

In this paper, we present an analytical model for assessing the behavior of BER versus SNR in the differential phase estimation in the long-haul high speed n-level phase shift keying (n-PSK) coherent optical transmission system, where the impact of EEPN is considered. The additional noise variance induced by EEPN has been taken into account in the analytical estimation. Based on this model, we have investigated the performance of BER versus SNR in the differential QPSK (DQPSK), the differential 8-PSK (D8PSK), and the differential 16-PSK (D16PSK) coherent optical transmission systems in detail involving the influence of EEPN. Theoretical results demonstrate that the behaviors of BER versus SNR in the differential phase estimation are significantly distorted by EEPN, with the increment of the LO phase noise, the accumulated fiber dispersion, the symbol rate, and the modulation format. Meanwhile, the results from this model make a good agreement with our previously reported BER floors. Moreover, to investigate the accuracy of this analytical model, numerical simulations have also been implemented for the DQPSK, the D8PSK, and the D16PSK coherent transmission systems with differential carrier phase estimation, considering EEPN. The results indicate that this analytical model can give an accurate

prediction for the DQPSK system, and a leading-order approximation for the D8PSK and the D16PSK systems, when EEPN is considered.

2. Differential carrier phase estimation in coherent transmission system

The setup of *n*-PSK coherent optical transmission system is illustrated in Fig. 1, where the differential carrier phase estimation is employed. The pseudo random bit sequence (PRBS) data are differentially encoded and modulated into the *n*-PSK optical signals, and then fed into the transmission fiber channel. In the receiver end, the received optical signals are mixed with the LO laser and converted into the electrical signals by the photodiodes (PDs). Then the electrical signals are sampled by the analog-to-digital convertors (ADCs) at twice the symbol rate. The digitalized signals are processed by the DSP algorithms, including CD compensation, signal equalization, and differential carrier phase estimation, to mitigate the system impairments.

The differential carrier phase estimation is applied for the carrier phase recovery in the coherent optical detection, where the information is encoded in and extracted from the phase difference between two consecutive symbols [12-17]. In the differential CPE, the k-th symbol information is recovered from the phase difference between the current k-th symbol and the (k+1)-th symbol. Hence, the phase ambiguity $\Delta\varphi$ in the recovered data comes from the carrier phase fluctuation between the two adjacent symbols $\Delta\varphi=\varphi_k-\varphi_{(k+1)}$, during a symbol period [12-17]. Compared to other CPE algorithms such as the block-average (BA) and the Viterbi-Viterbi (VV) methods [7,9,14], differential phase estimation does not require any computational operations

of *n*-power, averaging, and phase unwrapping, and can thus be efficiently implemented in the field-programmable gate array (FPGA) hardware [17]. In the following sections, we will investigate the BER performance in the differential carrier phase estimation considering the impact of EEPN, and our study can be employed as the benchmark and reference for evaluating the effects of EEPN in other CPE methods.

Fig. 1. Schematic of coherent optical transmission system with differential carrier phase estimation. N(t): additive white Gaussian noise (AWGN).

3. Principle of equalization enhanced phase noise

The schematic of EEPN in the coherent optical communication system employing electronic CD post-equalization and carrier phase estimation is depicted in Fig. 2. The Tx laser phase noise passes through both the transmission fiber and the digital CD equalization module, and therefore the net dispersion experienced by the transmitter PN is close to zero. However, the LO phase noise only goes through the digital CD equalization module, of which the transfer function is heavily dispersed in the transmission system without using any optical dispersion compensation (ODC). Consequently, the LO phase noise will interact with the CD equalization module, and will significantly influence the performance of the long-haul high speed coherent system.

Fig. 2. Schematic of EEPN in coherent transmission system. N(t): additive white Gaussian noise (AWGN), ADC: analog-to-digital convertor.

It has been demonstrated that the EEPN scales linearly with the accumulated CD, the

linewidth of LO laser, and the symbol rate [18-20], and the variance of the additional

noise due to the EEPN can be expressed as

$$\sigma_{EEPN}^2 = \frac{\pi\lambda^2}{2c} \cdot \frac{D \cdot L \cdot \Delta f_{LO}}{T_S} \qquad (1)$$

where λ is the central wavelength of the optical wave, c is the light speed in vacuum,

D is the CD coefficient of fiber, L is the fiber length, Δf_{LO} is the 3-dB linewidth of the

LO laser, and T_S is the symbol period of the coherent transmission system.

4. BER performance in differential CPE considering EEPN

The theoretical performance of BER versus SNR in the n-PSK coherent optical

transmission system employing differential carrier phase estimation can be calculated

according to the following expression [12-15],

$$BER \approx \frac{4}{\sqrt{2\pi}n\sigma \log_2 n} \int_{-\infty}^{+\infty} \exp\left(\frac{-8\varepsilon^2}{n^2\sigma^2}\right) \cdot erfc\left[\Gamma \cdot \sqrt{SNR}\right] d\varepsilon \qquad (2)$$

$$\Gamma = \sqrt{1 + \sin\frac{\pi}{n}} - \sqrt{1 - \sin\frac{\pi}{n}} \qquad (3)$$

where σ^2 is the variance of the total phase noise in the coherent transmission system, n

is the level of the modulation format, and SNR represents the signal-to-noise of the

transmission system.

Considering the impact of equalization enhanced phase noise, the variance of the total

noise in the n-PSK coherent transmission system can be expressed as [25,29],

$$\sigma^2 = \sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2 + 2\rho \cdot \sigma_{LO}\sigma_{EEPN} \qquad (4)$$

$$\sigma_{Tx}^2 = 2\pi\Delta f_{Tx} \cdot T_S \tag{5}$$

$$\sigma_{LO}^2 = 2\pi\Delta f_{LO} \cdot T_S \tag{6}$$

where σ_{Tx}^2 and σ_{LO}^2 are the intrinsic phase noise variance of the Tx and the LO lasers respectively, and Δf_{Tx} is the 3-dB linewidth of the Tx laser, and ρ is the correlation coefficient between the LO phase noise and the EEPN. It has been demonstrated that we have $\rho \approx 0$ when the transmission fiber length is larger than 80 km [25].

Therefore, in the long-haul high speed n-PSK coherent optical transmission systems, the total noise variance in the differential carrier phase estimation can be described approximately as follows,

$$\sigma^2 \approx \sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2 \tag{7}$$

By combining Eq. (2) and Eq. (7), we can obtain the analytical model for evaluating the performance of BER versus SNR in the differential n-PSK coherent optical transmission systems.

5. Theoretical results and analysis

In this section, we investigate the performance of BER versus SNR in the optical transmission system considering the influence of EEPN using the proposed theoretical model. The DQPSK, the D8PSK, and the D16PSK optical communication systems are applied as the examples for the analysis. Several transmission scenarios are considered for evaluating the BER performance: 1) different combination of the Tx laser and the LO laser linewidths, while the summation of linewidths are kept constant; 2) different LO laser linewidth; 3) different transmission distance (different fiber dispersion); 4) different symbol rate; 5) different modulation formats (DQPSK,

D8PSK, and D16PSK). The CD coefficient of 16 ps/nm/km is applied in all the evaluations.

Figure 3 shows the BER performance in the 2000 km 28-Gbaud DQPSK coherent transmission system with different combination of the Tx and the LO lasers linewidths while keeping the summation of linewidths constant. It can be seen that the BER behaviors degrade obviously with the increment of the LO laser linewidth. This demonstrates that the EEPN arises from the LO laser phase noise rather than the Tx phase noise, which is consistent with the reported analysis [18-22]. We can also find that the limits of the BER achieve a very good agreement with the BER floors (the dash curve) presented in our previous work [25,29]. Figure 4 shows the BER performance in the 1000 km 28-Gbaud D8PSK transmission system with different distribution of the Tx and the LO lasers linewidths. According to Eq. (1), the EEPN noise variance in the D8PSK transmission system in Fig. 4 is around 1/20 of the EEPN in the DQPSK system in Fig. 3. But the limits of BER behave moderately different in Fig. 3 and in Fig. 4. This indicates that the D8PSK system is more sensitive to the EEPN than the DQPSK system.

Fig. 3. BER performance in 2000 km 28-Gbaud DQPSK system with different distribution of Tx and LO lasers linewidths.

Fig. 4. BER performance in 1000 km 28-Gbaud D8PSK system with different distribution of Tx and LO lasers linewidths.

The performance of BER versus SNR in the 2000 km 28-Gbaud DQPSK coherent transmission system with different laser linewidth is shown in Fig. 5, where the Tx

laser linewidth is equal to the LO laser linewidth. We can see that the performance of the BER in the transmission system degrades obviously with the increment of the LO laser linewidth. It is also found that the performance of BER versus SNR in this model deviates significantly from the traditional analysis of the differential phase estimation [13,14], where the effect of EEPN was not considered. Figure 6 shows the BER performance in the 1000 km 28-Gbaud D8PSK coherent transmission system with different laser linewidth, where the Tx laser linewidth is also equal to the LO laser linewidth.

Fig. 5. BER performance in 2000 km 28-Gbaud DQPSK system with different LO laser linewidth.

Fig. 6. BER performance in 1000 km 28-Gbaud D8PSK system with different LO laser linewidth.

The performance of BER versus SNR in the 28-Gbaud DQPSK coherent transmission system with different fiber length is shown in Fig. 7, where both the Tx and the LO lasers linewidths are 5 MHz. We can find that the behaviors of the BER degrade obviously with the increment of the fiber length, which shows that the EEPN also depends on the accumulated fiber chromatic dispersion. It is also found that the BER floor for 2000 km fiber transmission is around 10^{-3}, which corresponds to the BER threshold for the traditional 7% overhead hard-decision forward error correction (FEC). This means that the maximum reachable transmission distance is around 2000 km for the 28-Gbaud DQPSK coherent transmission system considering the EEPN, when both the Tx and the LO are using the distributed feedback (DFB) lasers with a linewidth of 5 MHz. As a comparison, the performance of BER

versus SNR in the 28-Gbaud D8PSK coherent transmission system with different fiber length is illustrated in Fig. 8, where both the Tx and the LO lasers linewidths are 0.5 MHz.

Fig. 7. BER performance in 28-Gbaud DQPSK system with different fiber length.

Fig. 8. BER performance in 28-Gbaud D8PSK system with different fiber length.

In Fig. 9, the behaviors of BER versus SNR in the 2000 km DQPSK coherent transmission system with different symbol rate are illustrated, where both the Tx and the LO lasers linewidths are also 5 MHz. Three symbol rates are considered for the evaluation: 14-Gbaud, 28-Gbaud, and 56-Gbaud. It is found that, with the increment of the transmission symbol rate, the BER behavior degrades significantly due to the severer EEPN. Therefore, the requirement of laser linewidth will not be relaxed in the long-haul transmission system with a higher symbol rate, due to the influence of EEPN.

Fig. 9. BER performance in DQPSK system with different symbol rate.

The performance of BER versus SNR in the coherent optical transmission system using different modulation formats is shown in Fig. 10, where the DQPSK, the D8PSK, and the D16PSK transmission systems are evaluated at 28-Gbaud. The linewidths of the Tx and the LO lasers are both 100 kHz. In order to study the impact

of the EEPN (rather than the intrinsic laser phase noise) in different modulation formats, we consider two cases of transmission distance (1000 km and 2000 km) to investigate the dispersion dependence of the EEPN. We find that the BER performance is distorted by EEPN more severely with the increment of the modulation formats, and the D16PSK system is the most sensitive to the EEPN.

Fig. 10. BER performance in 28-Gbaud transmission system with different modulation formats.

6. Numerical simulations and analysis

To investigate the accuracy of the proposed analytical model, numerical simulations have been carried out for the DQPSK, the D8PSK and the D16PSK coherent systems by using VPI and Matlab platforms [30,31]. The simulation setup of the 28-Gbaud n-PSK coherent transmission system employing differential CPE is illustrated in Fig.1. The central wavelength of the Tx and the LO lasers are both set as 1553.6 nm. The standard single mode fiber (SSMF) with a CD coefficient of 16 ps/nm/km is employed in all the simulation work. Fiber attenuation, polarization mode dispersion and nonlinear effects are neglected. The CD compensation is implemented by using a frequency domain equalizer (FDE) with appropriate parameters [4,5], and the signal equalization is carried out based on the constant modulus algorithm (CMA) [2]. The BER is estimated from a data sequence of 2^{17} bits. Several scenarios are considered in the simulation work: 1) DQPSK system with both Tx and LO laser linewidths of 5 MHz; 2) D8PSK system with both Tx and LO laser linewidths of 0.5 MHz; 3)

D16PSK system with both Tx and LO laser linewidths of 0.1 MHz. In the all the three systems, the transmission fiber lengths of 0 km and 1000 km are applied respectively, which corresponds to the cases of no EEPN and considerable EEPN.

The simulation results of the DQPSK, the D8PSK, and the D16PSK coherent transmission systems with and without EEPN (0 km and 1000 km fibers) are shown in Fig. 11, where the results are compared to their corresponding theoretical results (dashed lines for 0 km fiber, solid lines for 1000 km fiber) based on the analytical model. Here a BER range of 10^{-4} to 0.5 is considered, where we can ensure an accurate BER estimation in the simulations. It can be seen that, when no EEPN exists in the systems (0 km fiber case), the analytical evaluations are identical to the simulation results. When EEPN exists in the systems (1000 km fiber case), the analytical prediction is accurate for the DQPSK system, while some deviations can be found in the high SNR region for the D8PSK and the D16PSK systems. This is because that the influence of EEPN is actually a complicated combination of enhanced phase noise, enhanced amplitude noise and time jitter, etc. [18-20,24,28,29], and the leading order Taylor expansion ($e^x \approx 1+x$), which ensures a conversion between the phase noise impact and the amplitude noise impact in n-PSK systems, is not accurate for a large EEPN and higher modulation formats. A higher order Taylor expansion in Eq. (2), Eq. (4) and Eq. (7) is required for further refinement, to give a more accurate prediction for the D8PSK, the D16PSK, and even the D64PSK coherent transmission systems.

Moreover, to be focused on the influence of EEPN in differential CPE, the impacts of fiber nonlinearities are neglected in both theoretical analysis and numerical simulations for evaluating the BER performance. Based on this analytical model, further analysis considering both the EEPN and the fiber nonlinear effects can also be investigated by involving the interference of fiber nonlinearities as an additional additive noise according to the Gaussian noise (GN) model [32].

Fig. 11. BER performance based on the analytical model (lines) and the numerical simulations (markers).

7. Discussions

It has been verified that the behavior of the feedback carrier phase estimation using the one-tap normalized least-mean-square (NLMS) algorithm resembles the differential phase estimation [5,10,25]. Therefore, the theoretical BER evaluation based on this model is also suitable for the one-tap NLMS carrier phase estimation. Besides, it is noted that this analytical model is applicable and available for both the single-polarization and the dual-polarization coherent optical transmission systems.

Several approaches have been investigated to mitigate the impact of EEPN in the long-haul coherent optical communication systems with electronic dispersion equalization, including dispersion pre-compensation, receiver extracted pilot tone,

partially modulated pilot carrier, and digital coherence enhancement, etc. [26-28,33-36]. Among these methods, the digital coherence enhancement shows the best performance [26,36], while it requires a complicated hardware implementation to measure the LO laser phase fluctuation. By contrast, EEPN does not exist in the coherent transmission systems using optical dispersion compensation, such as dispersion compensating fibers (DCFs) and dispersion compensating modules (DCMs) [18,19,22,25,37,38]. However, the management and the compensation of the fiber nonlinearities in such systems should be seriously considered. One promising method can be the optical back-propagation (OBP) which can compensate the fiber dispersion and the nonlinear interference simultaneously [39,40]. Both EEPN and fiber nonlinearities can be mitigated with a low complexity in the coherent transmission systems using OBP, which is a very promising approach for the real-time implementation of the high speed transmission system. Relevant research will be carried out in our future work.

8. Conclusion

In this paper, we present an analytical model for evaluating the BER performance in the differential *n*-PSK coherent transmission system considering the influence of equalization enhanced phase noise. Compared to the traditional analysis of differential phase estimation, this model has involved the additional noise variance induced by EEPN, which should be considered in the long-haul high speed transmission system. Theoretical results demonstrate that the BER performance degrades significantly with

the increment of LO laser linewidth, fiber dispersion, symbol rate, and modulation format, due to the influence of EEPN. The results from this theoretical model achieve a good agreement with the previously reported BER floors. Further simulations have also been carried out in the DQPSK, the D8PSK, and the D16PSK systems using differential CPE. The results indicate that this analytical model can give an accurate prediction for the DQPSK system, and a leading-order approximation for the D8PSK and the D16PSK systems. This model can be applied for predicting the BER behaviors in both the differential phase estimation and the one-tap NLMS feedback carrier phase estimation, and can also be employed as a reference for the evaluation of other CPE methods in the long-haul high speed coherent optical transmission systems, where the equalization enhanced phase noise can not be neglected.

Future work will incorporate improving the accuracy of this model using higher-order Taylor expansion and developing the analytical models for the BER evaluation in other carrier phase estimation approaches, such as the block average and the Viterbi-Viterbi algorithms [7,9,14], considering the impacts of EEPN. In addition, optical back-propagation will also be investigated for mitigating the EEPN and compensating the fiber nonlinearities in the long-haul transmission systems.

Acknowledgements

References

[1] P. S. Henry, Lightwave primer, IEEE J. Quantum Electron. 21 (1985) 1862-1879.

[2] E. Ip, A. P. T. Lau, D. J. F. Barros, J. M. Kahn, Coherent detection in optical fiber systems, Opt. Express 16 (2008) 753-791.

[3] S. J. Savory, Digital filters for coherent optical receivers, Opt. Express 16 (2008) 804-817.

[4] T. Xu, G. Jacobsen, S. Popov, J. Li, E. Vanin, K. Wang, A. T. Friberg, Y. Zhang, Chromatic dispersion compensation in coherent transmission system using digital filters, Opt. Express 18 (2010) 16243-16257.

[5] T. Xu, G. Jacobsen, S. Popov, J. Li, K. Wang, A. T. Friberg, Normalized LMS digital filter for chromatic dispersion equalization in 112-Gbit/s PDM-QPSK coherent optical transmission system, Opt. Commun. 283 (2010) 963-967.

[6] Y. Gao, F. Zhang, L. Dou, Z. Chen, A. Xu, Intra-channel nonlinearities mitigation in pseudo-linear coherent QPSK transmission systems via nonlinear electrical equalizer, Opt. Commun. 282 (2009) 2421-2425.

[7] S. Tsukamoto, K. Katoh, K. Kikuchi, Coherent demodulation of optical multilevel phase-shift-keying signals using homodyne detection and digital signal processing, IEEE Photon. Technol. Lett. 18 (2006)1131-1133.

[8] E. Ip, J. M. Kahn, Feedforward carrier recovery for coherent optical communications, J. Lightwave Technol. 25 (2007) 2675- 2692.

[9] A. J. Viterbi, A. M. Viterbi, Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission, IEEE Trans. Inf. Theory 29 (1983) 543-551.

[10] Y. Mori, C. Zhang, K. Igarashi, K. Katoh, K. Kikuchi, Unrepeated 200-km transmission of 40-Gbit/s 16-QAM signals using digital coherent receiver, Opt. Express 17 (2009) 1435-1441.

[11] M. G. Taylor, Phase estimation methods for optical coherent detection using digital signal processing, J. Lightwave Technol. 27 (2009) 901-914.

[12] S. Benedetto, E. Biglieri, V. Castellani, Digital transmission theory, Prentice-Hall Inc., New Jersey, 1987.

[13] G. Jacobsen, Laser phase noise induced error rate floors in differential n-level phase-shift-keying coherent receivers, Electron. Lett. 46 (2010) 698-700.

[14] E. Vanin, G. Jacobsen, Analytical estimation of laser phase noise induced BER floor in coherent receiver with digital signal processing, Opt. Express 18 (2010) 4246-4259.

[15] T. Broderick, Estimation of bit error rate for pseudo-linear differential phase shift keyed transmission links, Opt. Commun. 282 (2009) 1455-1462.

[16] J. G. Proakis, M. Salehi, Digital communications, 5th ed., McGraw-Hill, New York, 2007.

[17] I. Fatadin, D. Ives, S. J. Savory, Differential carrier phase recovery for QPSK optical coherent systems with integrated tunable lasers, Opt. Express 21 (2013) 10166-10171.

[18] W. Shieh, K. P. Ho, Equalization-enhanced phase noise for coherent detection systems using electronic digital signal processing, Opt. Express 16 (2008) 15718-15727.

[19] A. P. T. Lau, T. S. R. Shen, W. Shieh, K. P. Ho, Equalization-enhanced phase noise for 100Gb/s transmission and beyond with coherent detection, Opt. Express 18 (2010) 17239-17251.

[20] K. P. Ho, A. P. T. Lau, W. Shieh, Equalization-enhanced phase noise induced time jitter, Opt. Lett. 36 (2011) 585-587.

[21] K. P Ho, W. Shieh, Equalization-enhanced phase noise in mode-division multiplexed systems, J. Lightwave Technol. 31 (2013) 2237-2243.

[22] C. Xie, Local oscillator phase noise induced penalties in optical coherent detection systems using electronic chromatic dispersion compensation, Tech. Dig. Conf. Opt. Fiber Commun. (2009) OMT4.

[23] C. Xie, WDM coherent PDM-QPSK systems with and without inline optical dispersion compensation, Opt. Express 17 (2009) 4815-4823.

[24] I. Fatadin, S. J. Savory, Impact of phase to amplitude noise conversion in coherent optical systems with digital dispersion compensation, Opt. Express 18 (2010) 16273-16278.

[25] T. Xu, G. Jacobsen, S. Popov, J. Li, A. T. Friberg, Y. Zhang, Analytical estimation of phase noise influence in coherent transmission system with digital dispersion equalization, Opt. Express 19 (2011) 7756-7768.

[26] G. Colavolpe, T. Foggi, E. Forestieri, M. Secondini, Impact of phase noise and

compensation techniques in coherent optical systems, J. Lightwave Technol. 29 (2011) 2790-2800.

[27] G. Jacobsen, T. Xu, S. Popov, J. Li, A. T. Friberg, Y. Zhang, EEPN and CD study for coherent optical nPSK and nQAM systems with RF pilot based phase noise compensation, Opt. Express 20 (2012) 8862-8870.

[28] G. Jacobsen, T. Xu, S. Popov, S. Sergeyev, Study of EEPN mitigation using modified RF pilot and Viterbi-Viterbi based phase noise compensation, Opt. Express 21 (2013) 12351- 12362.

[29] T. Xu, G. Jacobsen, S. Popov, J. Li, A.T. Friberg, Y. Zhang, Carrier phase estimation methods in coherent optical transmission systems influenced by equalization enhanced phase noise, Opt. Commun. 293 (2013) 54-60.

[30] www.vpiphotonics.com

[31] www.mathworks.com

[32] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, F. Forghieri, The GN-model of fiber non-linear propagation and its applications, J. Lightwave Technol. 32 (2014) 694-721.

[33] G. Jacobsen, M. Lidón, T. Xu, S. Popov, A. T. Friberg, Y. Zhang, Influence of pre- and post-compensation of chromatic dispersion on equalization enhanced phase noise in coherent multilevel systems, J. Opt. Commun. 32 (2011) 257-261.

[34] G. Jacobsen, T. Xu, S. Popov, J. Li, A. T. Friberg, Y. Zhang, Receiver implemented RF pilot tone phase noise mitigation in coherent optical nPSK and nQAM systems, Opt. Express 19 (2011) 14487- 14494.

[35] T. Xu, G. Jacobsen, S. Popov, J. Li, S. Sergeyev, Mitigation of EEPN in long-haul n-PSK coherent transmission system using modified optical pilot carrier, Tech. Dig. Conf. Asia Commun. Photon. (2013) AF3E.1.

[36] D. Lavery, R. Maher, M. Paskov, B. C. Thomsen, P. Bayvel, S. J. Savory, Digital coherence enhancement enabling 6-GBd DP-64QAM using a 1.4-MHz linewidth laser, IEEE Photon. Technol. Lett. 25 (2013) 2213-2216.

[37] I. Kaminow, T. Li, A. E. Willner, Optical fiber telecommunications VIA: components and subsystems, 6th ed., Academic Press, Oxford, 2013.

[38] G. P. Agrawal, Fiber-optic communication systems, 4th ed., John Wiley & Sons, Inc., New York, 2010.

[39] S. Kumar, D. Yang, Optical backpropagation for fiber-optic communications using highly nonlinear fibers, Opt. Lett. 36 (2011) 1038-1040.

[40] X. Liang, S. Kumar, J. Shao, Ideal optical backpropagation of scalar NLSE using dispersion-decreasing fibers for WDM transmission, Opt. Express 21 (2013) 28668-28675.

Figure Captions

Fig. 1. Schematic of coherent optical transmission system with differential carrier phase estimation. N(t): additive white Gaussian noise (AWGN).

Fig. 2. Schematic of EEPN in coherent transmission system. N(t): additive white Gaussian noise (AWGN), ADC: analog-to-digital convertor.

Fig. 3. BER performance in 2000 km 28-Gbaud DQPSK system with different distribution of Tx and LO lasers linewidths.

Fig. 4. BER performance in 1000 km 28-Gbaud D8PSK system with different distribution of Tx and LO lasers linewidths.

Fig. 5. BER performance in 2000 km 28-Gbaud DQPSK system with different LO laser linewidth.

Fig. 6. BER performance in 1000 km 28-Gbaud D8PSK system with different LO laser linewidth.

Fig. 7. BER performance in 28-Gbaud DQPSK system with different fiber length.

Fig. 8. BER performance in 28-Gbaud D8PSK system with different fiber length.

Fig. 9. BER performance in DQPSK system with different symbol rate.

Fig. 10. BER performance in 28-Gbaud transmission system with different modulation formats.

Fig. 11. BER performance based on the analytical model (lines) and the numerical simulations (markers).
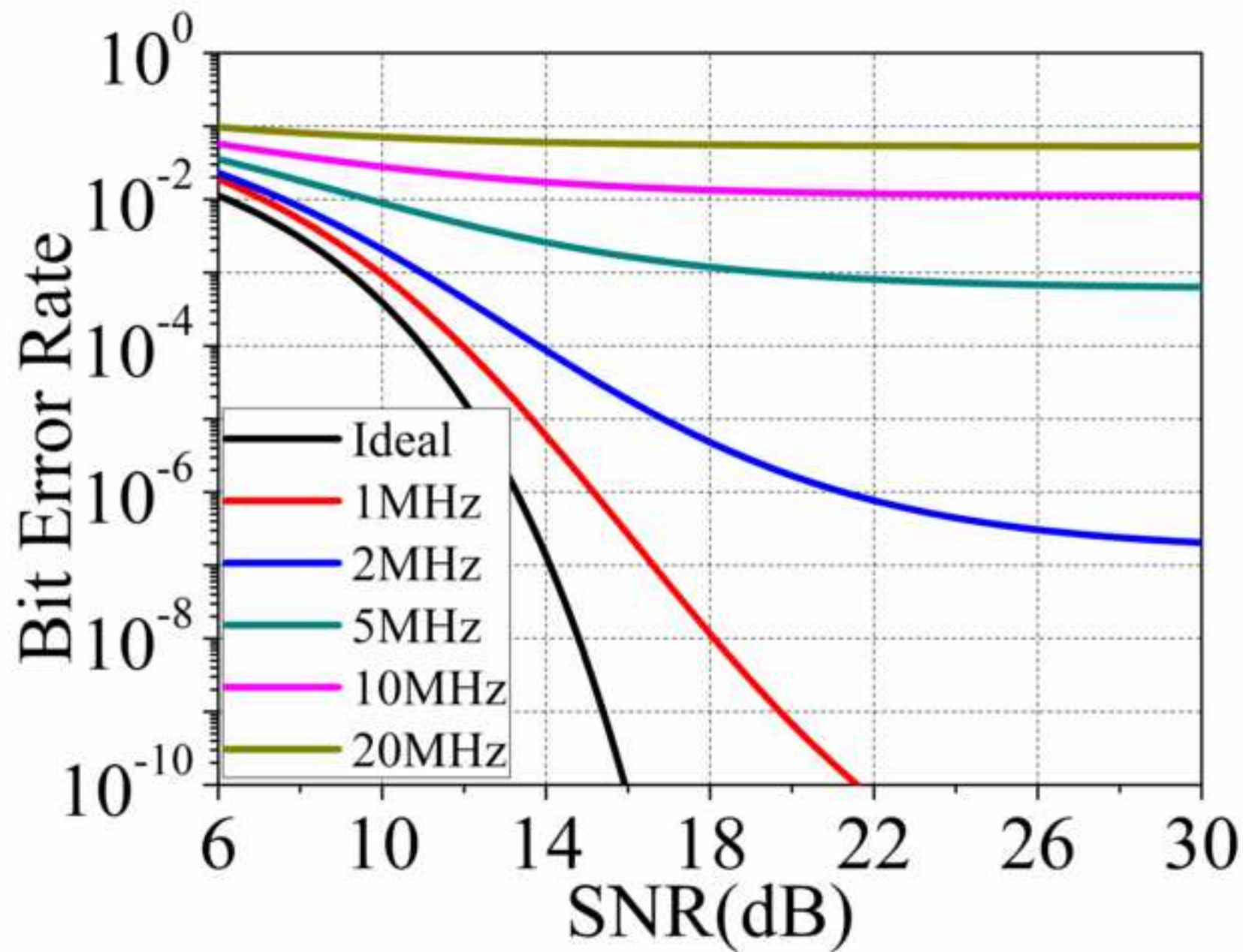
Figure(1)
Click here to download high resolution image
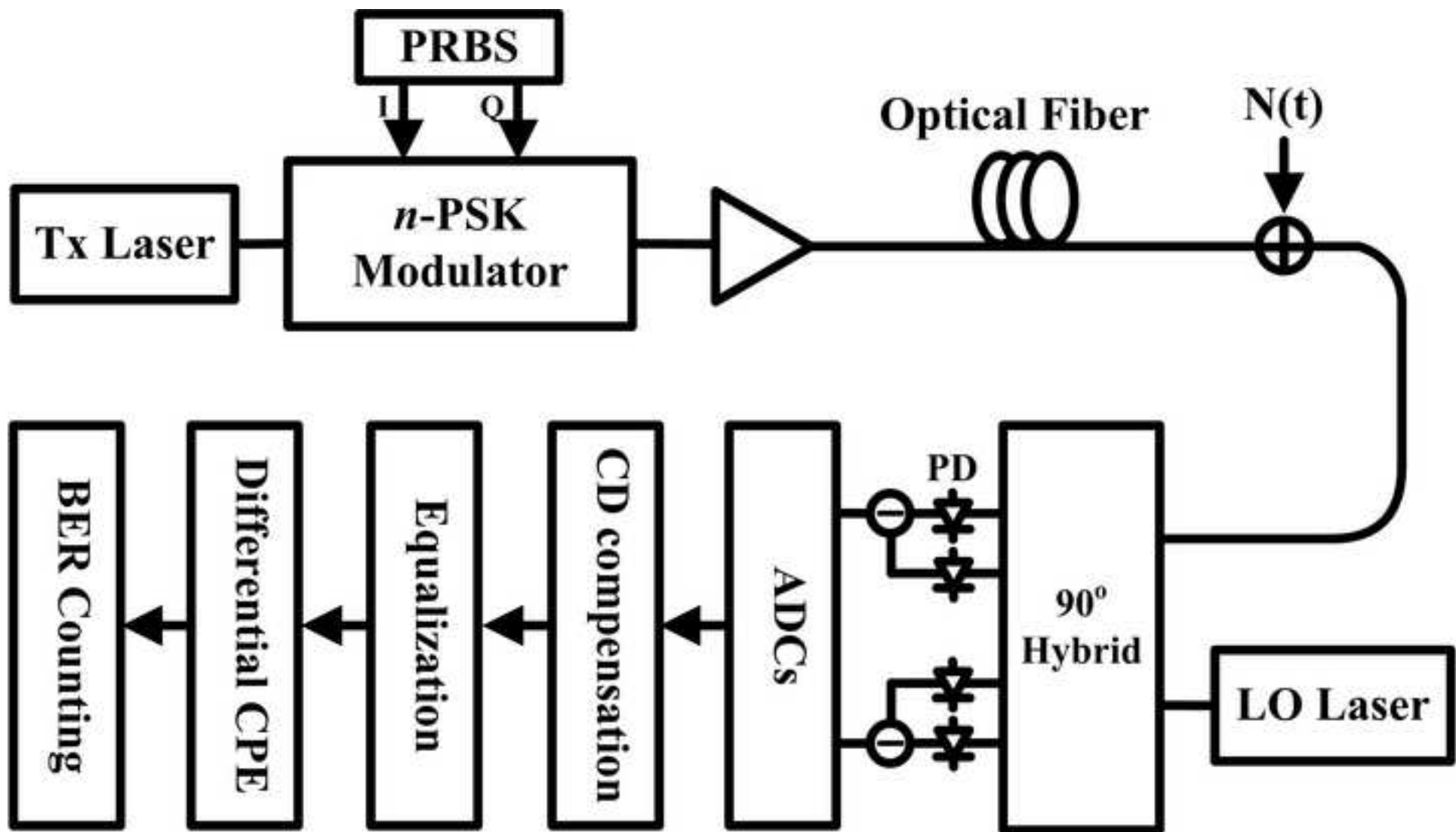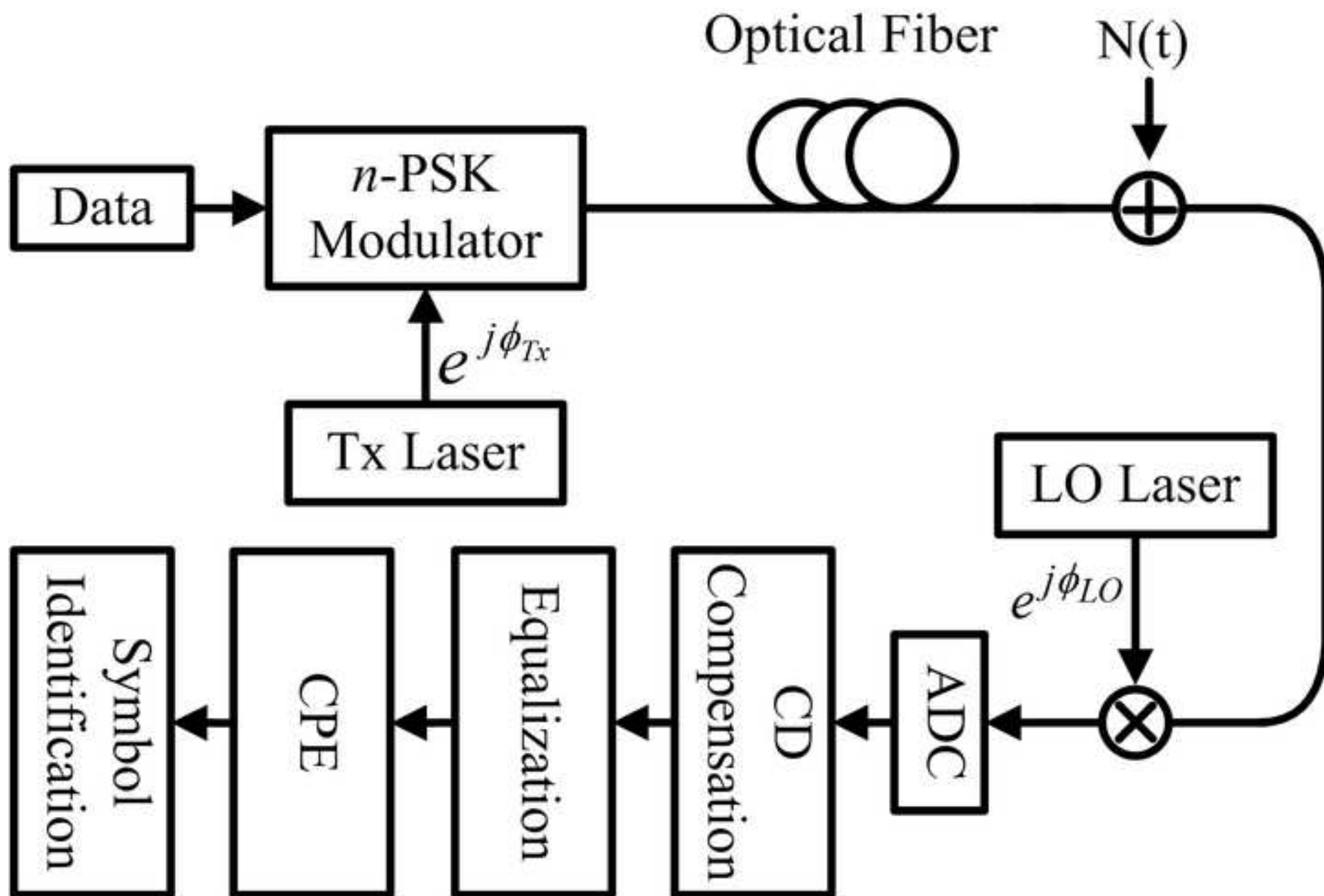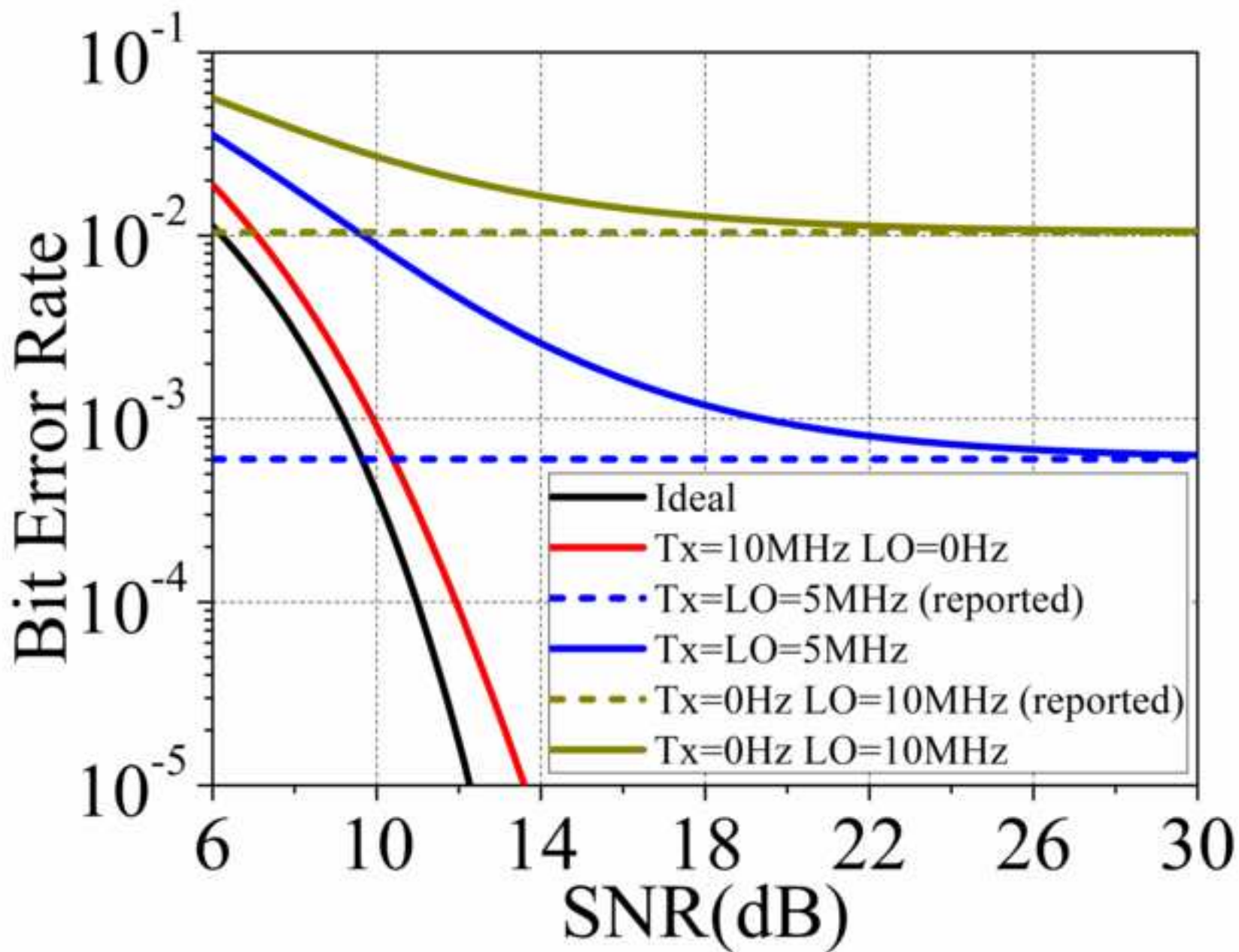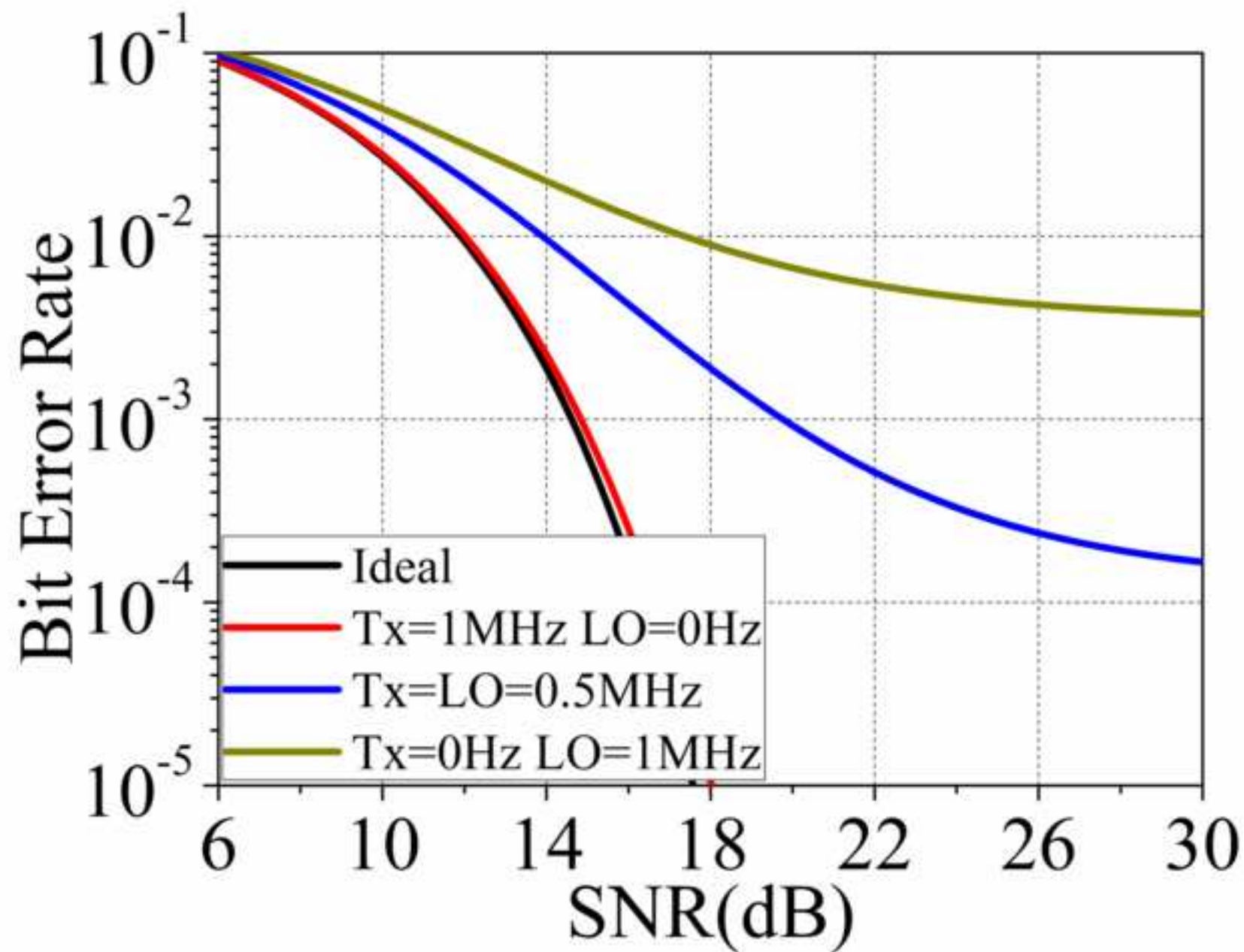
Figure(6)
Click here to download high resolution image

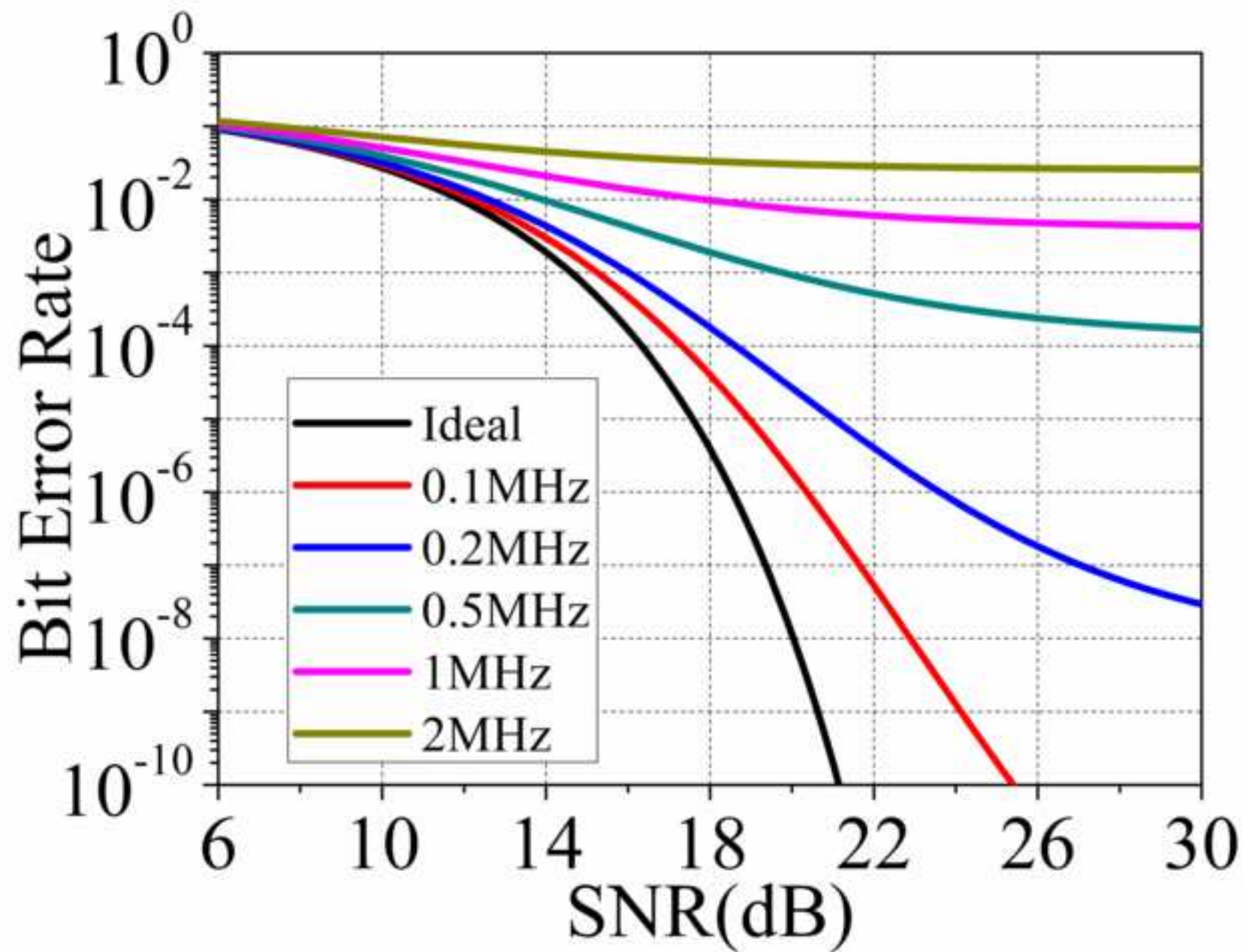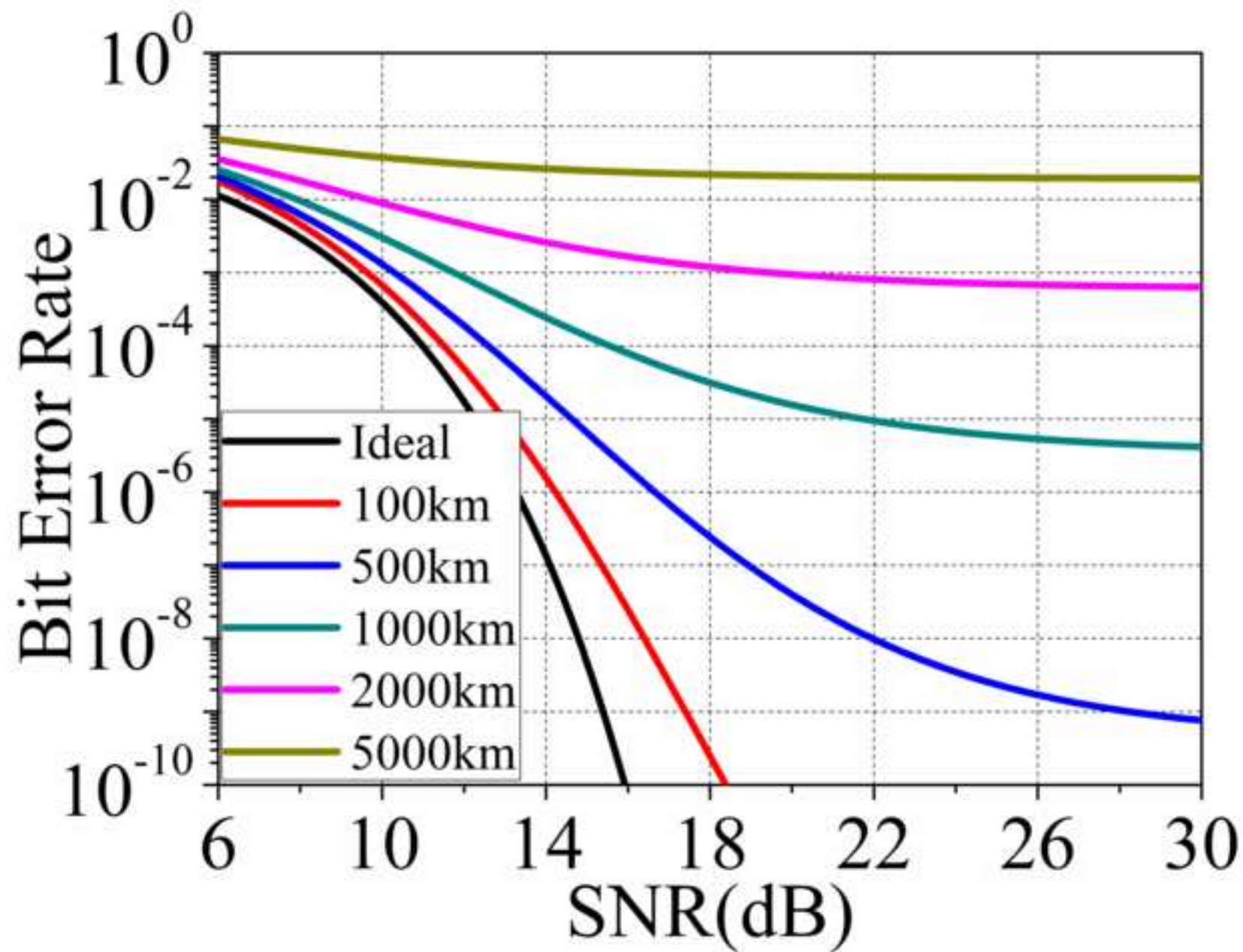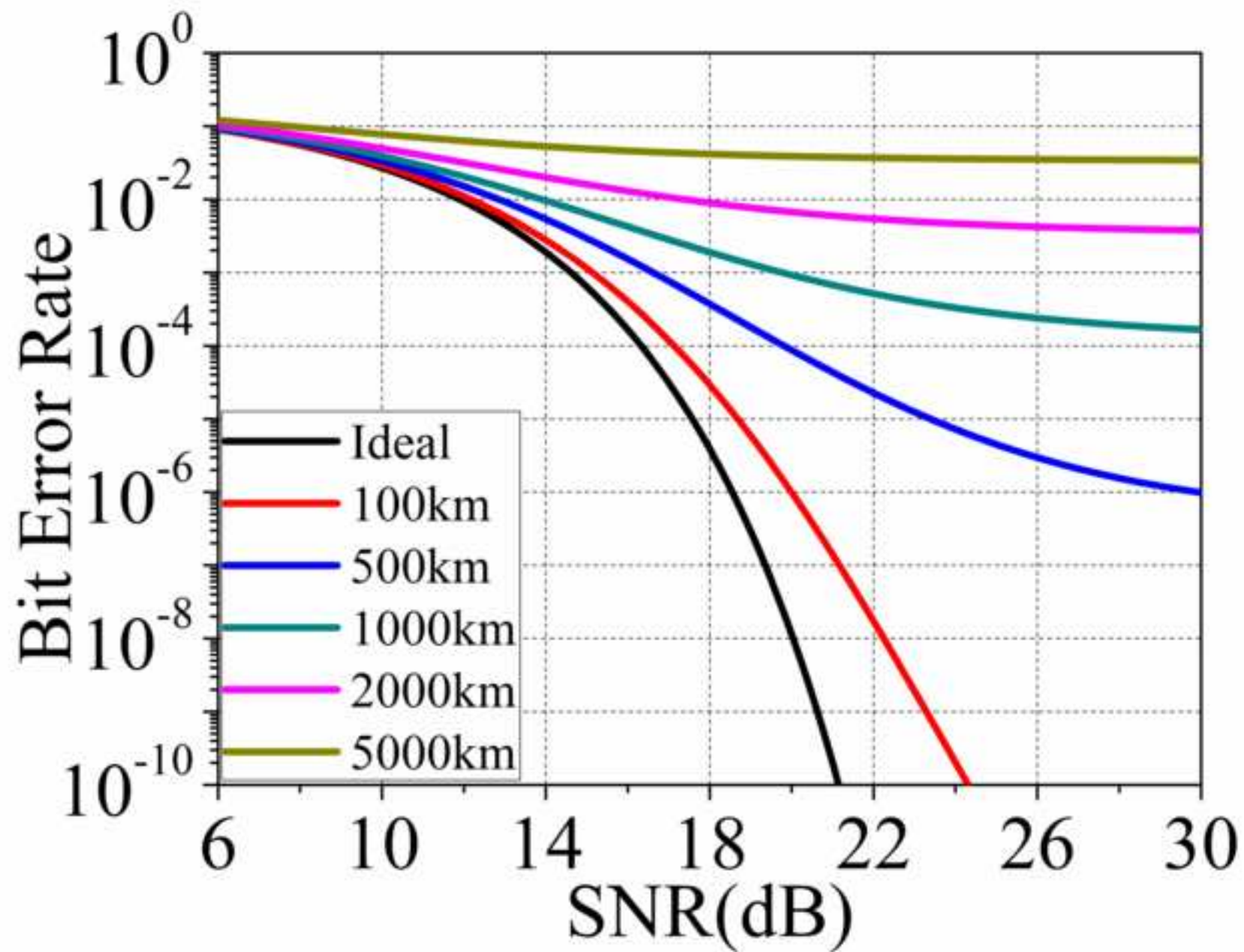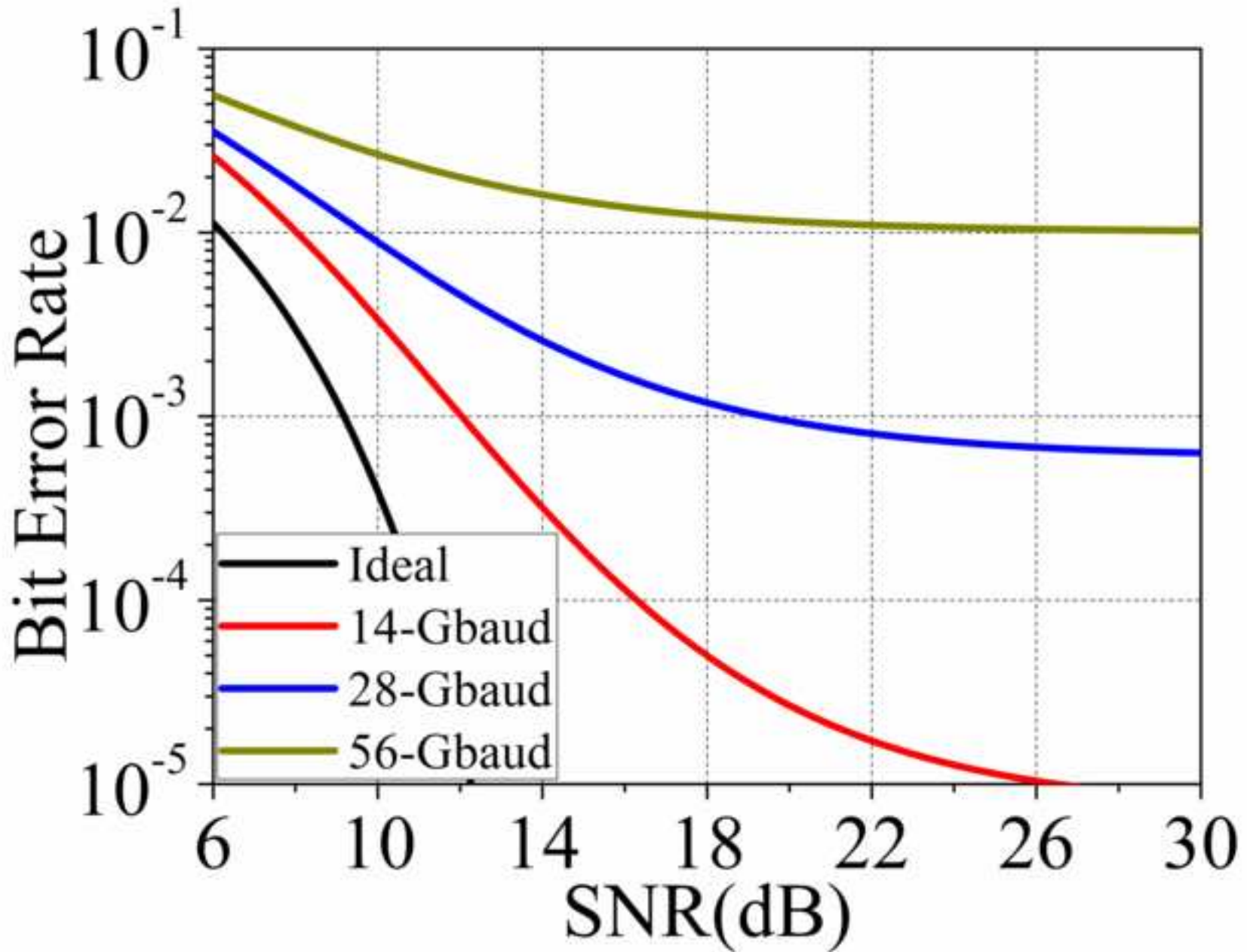**Figure(8)**
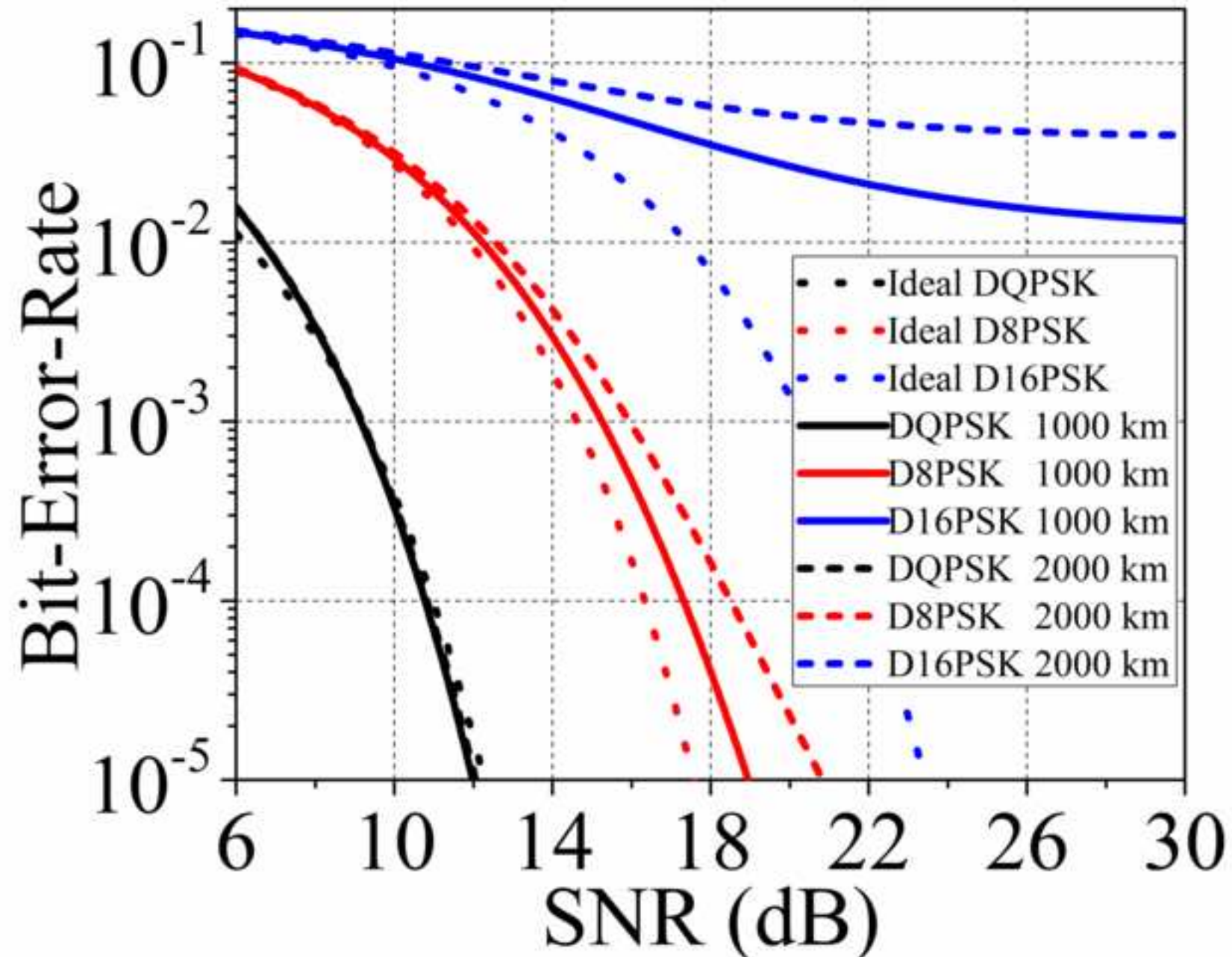**Click here to download high resolution image**

Figure(10)
Click here to download high resolution image

Figure(11)
Click here to download high resolution image