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Authors
Tarighat, A
Hsu, R CJ
Sayed, A H
et al.

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Digital Adaptive Phase Noise Reduction in Coherent Optical Links

Alireza Tarighat, *Member, IEEE*, Rick C. J. Hsu, *Student Member, IEEE*, Ali H. Sayed, *Fellow, IEEE*, and Bahram Jalali, *Fellow, IEEE*

***Abstract*—Coherent optical links enable high-density constellations and, consequently, a higher throughput. However, the phase noise associated with the transmitter and the receiver lasers is a challenging issue in coherent lightwave systems. The authors present an approach that relies on using digital signal processing techniques to compensate for the laser phase-noise effects. The proposed approach exploits the digital processing power to address the problems arising from optical imperfections. The authors present an adaptive filtering scheme that reduces the effect of the laser phase noise and, consequently, relaxes the laser linewidth requirement. The proposed approach shows how the signal processing techniques can be exploited to compensate for the optical impairments by utilizing the continuing scale down in size and power in very large scale integration (VLSI) technology.**

***Index Terms*—Adaptive filtering, coherent optical links, laser linewidth, laser phase noise.**

I. Introduction

COHERENT optical links enable high density constellations [such as 64 quadrature amplitude modulation (QAM)] and, consequently, a higher throughput. However, the phase noise associated with the transmitter and receiver lasers is a challenging issue in coherent lightwave systems [1], [2]. In a coherent receiver, a local oscillator (LO) is required to down convert the received signal. In general, the LO will have random phase fluctuations relative to the transmitter oscillator. The distortion due to the transmitter laser and receiver LO phase noise will then appear as a random rotation of points in the received constellation, as shown in Fig. 1. An optical coherent detection requires the coherent combination of the optical signal with a continuous optical field provided by an LO before it falls on the photodetector.

For the coherent receiver in Fig. 2, either homodyne or heterodyne synchronous demodulation schemes can be used, both requiring certain kind of phase locking loop. In the heterodyne case, the phase-locked loop (PLL) is used to recover the intermediate frequency (IF) carrier. PLLs reduce the final phase-noise variance through the loop filter [3]–[6]. However, there are limits on the PLL loop bandwidth, delay and, consequently, the achievable phase-noise variance due to other system tradeoffs such as the loop locking range. In this paper, we show how digital signal processing techniques can be used to relax such tradeoffs and reduce the final phase-noise variance in the system.

In this paper, we present a compensation scheme that is implemented in the digital domain (after the analog to digital converters) in order to reduce the effect of phase noise on the bit error rate (BER) performance. An adaptive tracking scheme is implemented to track and compensate for the phase variations. The training is performed in a decision-directed fashion to avoid the need for a training sequence and a transmission overhead. In this paper, we focus on a receiver that uses the LO in an optical PLL. It is shown that a standard adaptive filter (such as least mean squares (LMS) algorithm) cannot function properly in the decision-directed mode; so instead, a constrained adaptive filter is proposed. The simulation results show a significant improvement in the BER results when the proposed scheme is applied. Such an improvement in the BER curves can significantly relax the requirements on the laser linewidth specifications used in the coherent links.

The paper is organized as follows. The next section describes the phase-noise models and its effect on the recovered data. The adaptive-compensation scheme is presented in Section III. The simulation results are shown in Section IV, and conclusions are given in Section VI.

II. System Formulation

In this section, we formulate a coherent optical link in the presence of a transmitter and a receiver phase noise. We present the equivalent baseband model, assuming that the received signal has been down converted from the optical carrier to the baseband before being digitally processed. Let s_i denote the transmitted signal at time instant i, generally from a QAM constellation. The received baseband complex signal y_i can be written as follows:

$$y_i = he^{j\phi_{\mathrm{ni}}} s_i + n_i \qquad (1)$$

where h is the channel gain (in general a complex number), n_i is the additive complex Gaussian noise at the receiver with variance σ_n^2, and the link signal-to-noise ratio (SNR) is calculated as $\mathrm{SNR} = |h|^2/\sigma_n^2 = R^2 P_{\mathrm{LO}} \bar{P}_s/\sigma_n^2$. The effects of the additive noise sources are lumped into σ_n^2, including the receiver noise, the relative intensity noise, the quantization noise, etc. Furthermore, ϕ_{ni} is a random variable that represents the effect of laser phase noise. It is known that ϕ_{ni} can be modeled as a

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The authors are with the Electrical Engineering Department, University of California, Los Angeles, CA 90095 USA (e-mail: tarighat@ee.ucla.edu; cjhsu@ee.ucla.edu; sayed@ee.ucla.edu; jalali@ee.ucla.edu).

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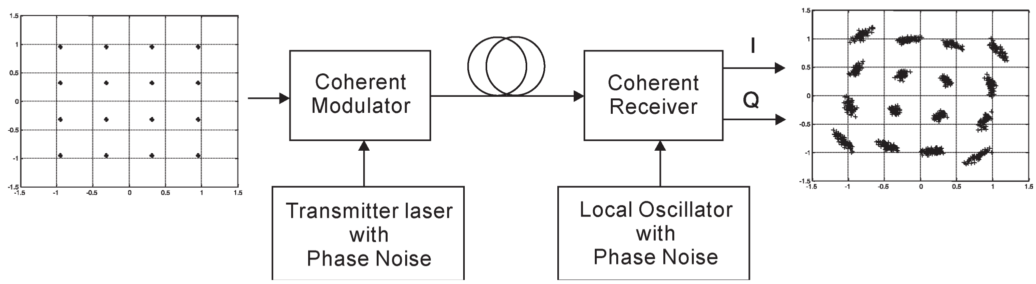

Fig. 1. Coherent transmission over an optical link showing the effects of the phase noise on the recovered constellation at the receiver.

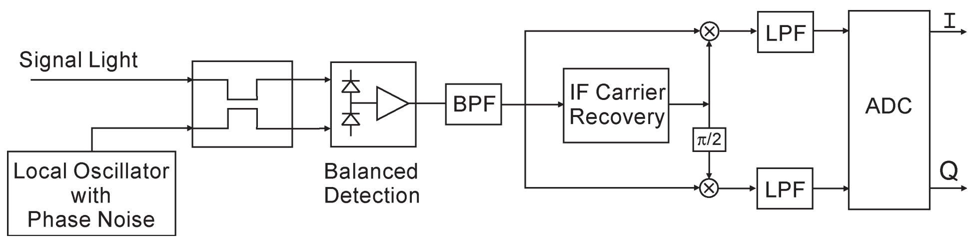

Fig. 2. Coherent optical receiver incorporating a phase-locked loop.

Gaussian random process; its power spectral density (PSD) and variance will strongly depend on the laser linewidth. Assuming that the laser-frequency fluctuations exhibit a white Gaussian distribution with a single-sided PSD [7], [8]

$$S_f(f) = \frac{\Delta\nu}{\pi} \tag{2}$$

where $\Delta\nu$ is the laser linewidth. The PSD of the phase noise is then

$$S_\phi(f) = \frac{\Delta\nu}{\pi f^2}. \tag{3}$$

This results in a Lorentzian laser-field spectrum centered at an optical carrier frequency f_c

$$S_F(f) = \frac{\Delta\nu}{2\pi\left[(f-f_c)^2 + \left(\frac{\Delta\nu}{2}\right)^2\right]}. \tag{4}$$

Assuming that a laser with the above characteristics is used for optical transmission and down conversion, the equivalent baseband phase-noise characteristics can be derived. Let us consider the case where the LO laser is used in the PLLs. The simplest form of PLL is shown in Fig. 3. The closed-loop transfer function can be written as follows:

$$H(s) = \frac{KF(s)}{s + KF(s)} \tag{5}$$

where $K = K_0 K_d$ is the open-loop gain, and $F(s)$ is the transfer function of the loop filter.

A. First-Order Loop

A first-order loop has $F(s) = 1$. We have the closed-loop transfer function from (5)

$$H(s) = \frac{\omega_L}{s + \omega_L} \tag{6}$$

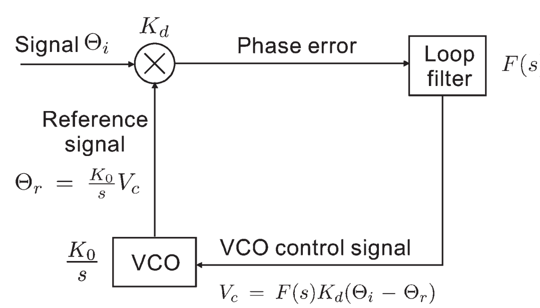

Fig. 3. Block diagram of a PLL system.

where the open-loop gain K is equal to the angular frequency of zero decibel loop gain denoted by ω_L. After corrected by PLL, the phase noise PSD can be expressed as follows:

$$S_\phi^{\mathrm{PLL}}(f) = \frac{\Delta\nu}{\pi f^2}\left|1 - H(j2\pi f)\right|^2 = \frac{\Delta\nu}{\pi}\frac{1}{f^2 + f_L^2} \tag{7}$$

where $f_L = \omega_L/2\pi$ is a measure of loop bandwidth, and the phase-noise variance can be consequently calculated as follows:

$$\sigma_{\phi_n}^2 = \int_0^\infty S_\phi^{\mathrm{PLL}}(f)\,df = \frac{\Delta\nu}{2f_L}. \tag{8}$$

B. Second-Order Loop

For a second-order PLL, the closed-loop transfer function becomes [9]

$$H(s) = \frac{2\eta s\omega_n + \omega_n^2}{s^2 + 2\eta s\omega_n + \omega_n^2} \tag{9}$$

where ω_n is the loop natural frequency, and η is the damping factor. The residual phase noise PSD (when $\eta = 0.707$) can be calculated as follows:

$$S_\phi^{\mathrm{PLL}}(f) = \frac{\Delta\nu}{\pi f^2}\left|1 - H(j2\pi f)\right|^2 = \frac{\Delta\nu}{\pi}\frac{f^2}{f^4 + f_L^4} \tag{10}$$

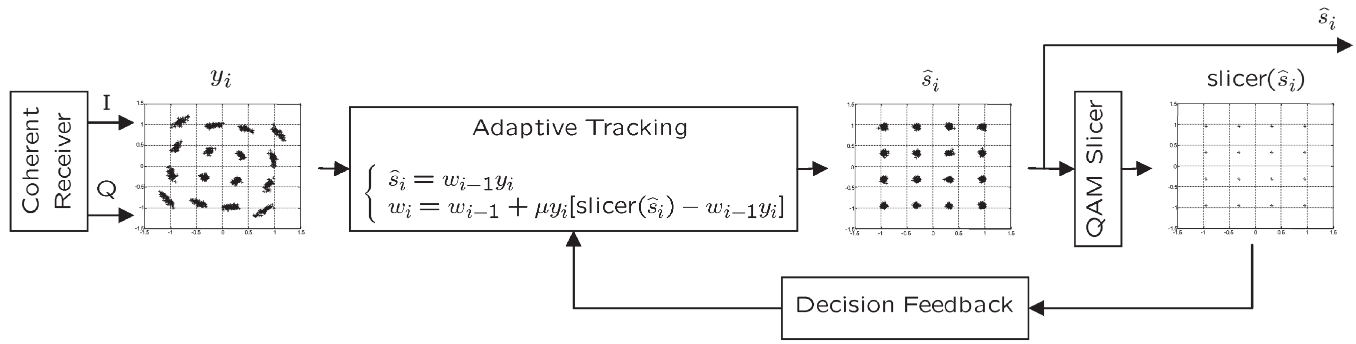

Fig. 4. Proposed adaptive scheme for the phase-noise compensation.

where $f_L = \omega_n/2\pi$ is a measure of the loop bandwidth, and the phase-noise variance can be consequently calculated as follows:

$$\sigma^2_{\phi_n} = \int_0^\infty S_\phi^{\text{PLL}}(f)df = \frac{\Delta\nu}{4\sqrt{2}f_L}. \tag{11}$$

We will provide simulation results for both the above scenarios.

III. Adaptive Compensation

We use an adaptive filter [10] to compensate for phase-noise effects. The adaptive filter is intended to track the phase variations and compensate them. Although we will only discuss an LMS filter in this paper, other filters, such as recursive least squares (RLS), can be used as well. Due to the fast rate of the variation in the phase noise, a training-based compensation is not feasible since it would require a constant stream of training. Instead, we train the adaptive filter in a decision-directed fashion, where the estimated data is passed through a slicer[1] and directed back to the filter for adaptation—see Fig. 4. With a relatively low BER, these estimates are sufficient for training purposes. The adaptive tracking is implemented as follows. Denoting the estimate for the transmitted sample s_i by $\hat{s}_i$, then [10]

$$\begin{cases} \hat{s}_i = w_{i-1}y_i \\ w_i = w_{i-1} + \mu y_i\left[\text{slicer}(\hat{s}_i) - w_{i-1}y_i\right] \end{cases} \tag{12}$$

where w_i is the filter coefficient to be estimated recursively, and slicer$(\hat{s}_i)$ is the closest point in the constellation to the estimated sample $\hat{s}_i$, as shown in Fig. 4.

A problem with the decision-directed approach is the ambiguity in the phase at the receiver. If the coefficient w_i is phase rotated by a multiple of $\pi/2$, then the receiver has no means of correcting for it. This is due to the fact that a rotated (by a multiple of $\pi/2$) QAM constellation would still be observed and processed as if there was no rotation from the receiver point of view. Note that such undesired rotations are likely to occur since we need to use relatively large step sizes in order to track the rapid phase variations closely. Therefore, if during an update iteration the phase of w_i is mistakenly rotated by more than $\pi/2$ due to a large error signal or a large step size, the filter no longer will be able to correct for it, and all information bits received afterward will be lost. One solution would be to use known pilot bits in order to adjust (calibrate) the phase of the recovered constellation. However, this would result in a transmission overhead and would require changes in transmitted packets.

To address this issue, we suggest a constrained-adaptive scheme, which prevents large incidental changes in the phase without any degradation in performance, i.e., still using a relatively large step size. The constraint would block an update to w_i that could potentially change the slicer's output and could consequently lead to the ambiguity issue. Different conditions and schemes can be used to constrain the update equations. A simple yet effective scheme is as follows:

$$\begin{cases} \text{calculate} \\ \quad \hat{s}_i = w_{i-1}y_i \\ \quad w_{i,\text{LMS}} = w_{i-1} + \mu y_i\left[\text{slicer}(\hat{s}_i) - w_{i-1}y_i\right] \\ \text{if slicer}(w_{i-1}y_i) = \text{slicer}(w_{i,\text{LMS}}y_i) \text{ then} \\ \quad w_i = w_{i,\text{LMS}} \\ \text{otherwise} \\ \quad w_i = w_{i-1} + \alpha\mu y_i\left[\text{slicer}(\hat{s}_i) - w_{i-1}y_i\right] \end{cases} \tag{13}$$

for some positive relatively small α, e.g., 0.1. In other words, any update suggested by the standard LMS algorithm is performed only if the update does not cause a dramatic change in the slicer's output. The programmable parameter α used in the algorithm is basically a design parameter and should be chosen based on the system parameters. The only limitation with the constrained-adaptive algorithm is the possibility that the convergence of the tracking scheme might be degraded, since some updates are discarded. This is not a limiting factor, since this constraining condition is exercised very infrequently while it prevents the undesired rotations in the phase very effectively.

IV. Simulations

A coherent single mode fiber (SMF) link is simulated to evaluate the performance of the proposed phase noise compensation scheme. A 10-Gsps coherent optical link is simulated with different transmission constellation densities (quadrature phase shift keying (QPSK) to 64 QAM). The simulations are performed for both the PSD functions (7) and (10),

[1]A slicer basically finds the closest point in the transmission constellation to an estimated point.

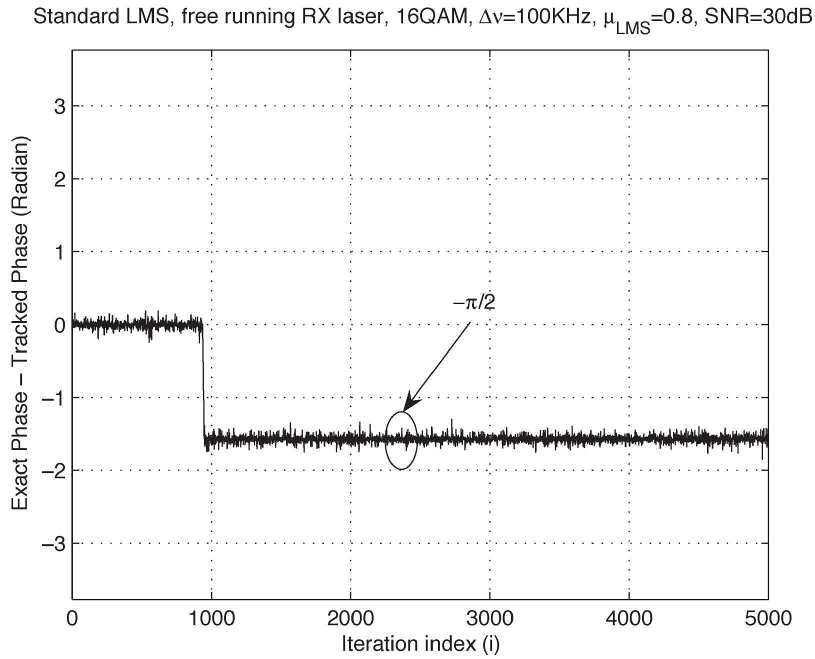

Fig. 5. Standard LMS: The difference between the real phase noise and the tracked phase in a system with the following parameters: 16-QAM constellation, $\Delta\nu = 100$ KHz, $\mu_{\mathrm{LMS}} = 0.8$, SNR $= 30$ dB. It can be seen that a standard LMS can lead to an undesired phase rotation of multiple of $\pi/2$.

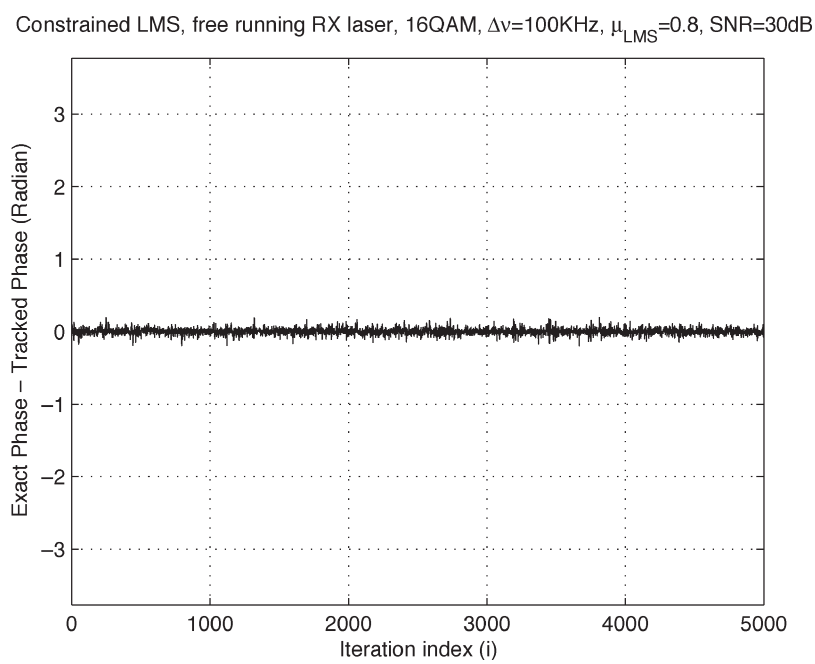

Fig. 6. Proposed constrained LMS: The difference between the real phase noise and the tracked phase in a system with the following parameters: 16-QAM constellation, $\Delta\nu = 100$ KHz, $\mu_{\mathrm{LMS}} = 0.8$, SNR $= 30$ dB. It can be seen that the proposed constrained LMS can prevent the undesired phase rotation seen in Fig. 5.

corresponding to the first and second order transfer functions. Packets of data are transmitted through the fiber, where different received SNR values are modeled through different fiber loss values. To better illustrate the performance of the proposed algorithm, other nonideal effects such as nonlinearity and dispersion are not included in the simulations. The phase noise ϕ_i is generated to have a Gaussian distribution with a power spectrum density defined by (7) or (10). This is done by generating a white Gaussian random process and passing it through a filter that has a frequency response equal to the square root of the desired phase noise PSD model. The packet at the transmitter is then modulated over a QAM constellation, up converted, and transmitted through the fiber. At the receiver, an additive white Gaussian noise is added to the received signal to model the effects of thermal noise, relative intensity noise, and quantization noise. The effect of phase noise at the LO is added to the received signal. The received signal is then processed by the proposed structure shown in Fig. 4.

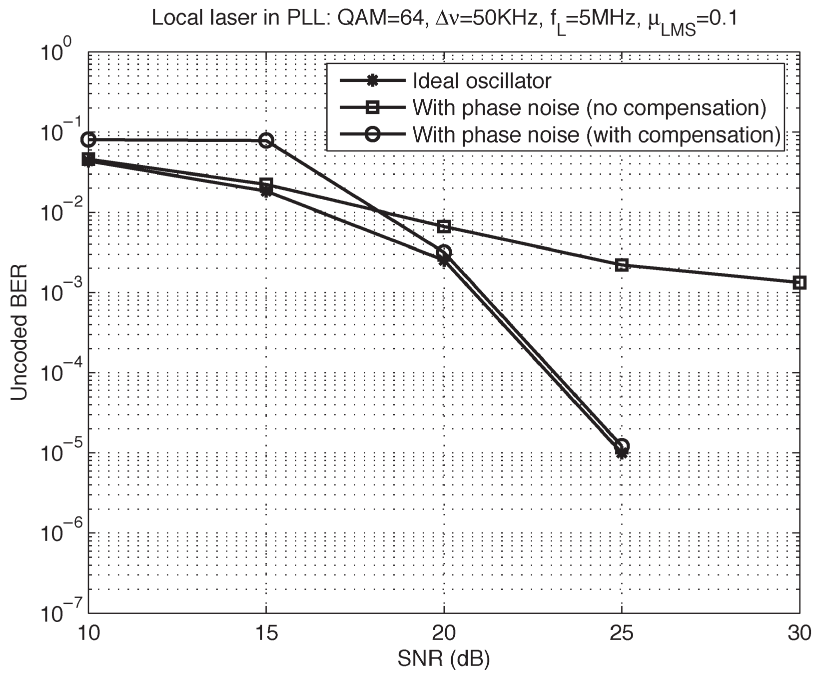

Fig. 7. Uncoded BER versus SNR for a coherent link with an LO in the PLL mode. The PSD corresponding to a first-order transfer function given by (7) is used in the simulation. The system parameters are: transmit constellation of 64 QAM, an LMS step size of $\mu_{\mathrm{LMS}} = 0.1$, laser linewidth of $\Delta\nu = 50$ KHz, and a PLL bandwidth of $f_L = 5$ MHz.

The recovered data is then compared to the original transmitted data for BER calculation. The above process is repeated over many packet realization and for different received SNR values. Information bits are grouped into packets: enough to form 8000 64-QAM symbols per packet transmission (equivalent to a total of $8000 \times 6 = 48\,000$ randomly generated information bits). Each BER point in the plots is the average result of 100 packet transmissions.

A. Standard Versus Constrained LMS

We simulated the performance of the modified LMS algorithm versus the standard LMS in avoiding the undesired phase rotations that are multiples of $\pi/2$. As seen in Figs. 5 and 6, a standard LMS in a decision-directed mode has resulted in a phase rotation of $-\pi/2$ due to lack of a pilot sequence, while the constrained scheme helped avoiding it. The simulation parameters are 16-QAM constellation, $\Delta\nu = 100$ KHz, $\mu_{\mathrm{LMS}} = 0.8$, and SNR $= 30$ dB.

B. BER Versus SNR

We simulate the performance of the compensation scheme compared to an ideal system, as well as a system with no compensation scheme. The BER versus SNR links are plotted for different system parameters as follows. We simulated two scenarios: one assuming the phase-noise PSD given by (7) corresponding to a first-order transfer function and the other assuming the phase-noise PSD given by (10) corresponding to a second-order transfer function. The results in Figs. 7–9 are conducted using the phase-noise PSD given by (7), while the results in Fig. 10 are conducted using the phase-noise PSD given by (10). In Fig. 7, the laser linewidth is $\Delta\nu = 50$ KHz, the loop bandwidth is $f_L = 5$ MHz, the transmit constellation is 64 QAM, and the LMS step size is $\mu_{\mathrm{LMS}} = 0.1$. In Fig. 8, the laser linewidth is $\Delta\nu = 500$ KHz, the loop bandwidth is $f_L = 50$ MHz, the transmit constellation is 64 QAM, and the LMS step size is $\mu_{\mathrm{LMS}} = 0.1$. In both cases, the ratio between $\Delta\nu$ and f_L is the same (equal to 0.01), and consequently, the phase-noise variance given by $(\Delta\nu/2f_L)$ is the same. This explains why the BER curves for a system with no compensation is the same in both plots, for two different values of laser linewidth. In order to illustrate the relative improvement in BER floor, a simulation was conducted for a system with a relatively large laser linewidth, such that the BER floor is observable at around 10^{-6}. In Fig. 9, the laser linewidth is $\Delta\nu = 300$ KHz, the loop bandwidth is $f_L = 5$ MHz, the transmit constellation is 64 QAM, and the LMS step size is $\mu_{\mathrm{LMS}} = 0.1$. These parameters result in a very poor BER floor of 10^{-2} if no compensation is performed. Using the proposed compensation scheme, the BER floor is reduced to less than 10^{-6}—see Fig. 9.

As seen in the plots, the proposed scheme achieves an acceptable performance for both values of the laser linewidth. The reason for the poor performance of the proposed scheme at relatively low SNR values (15 dB) is the degradation in the decision-directed loop, since more estimation errors are likely to happen. However, this is not a limiting factor, since the practical optical links operate at high SNR values (25 dB and above for 64-QAM constellation), where the proposed scheme is performing well. Furthermore, it can be seen that the adaptive tracking scheme is able to compensate for the phase noise in both cases (first- and second-order transfer functions) to an acceptable degree.

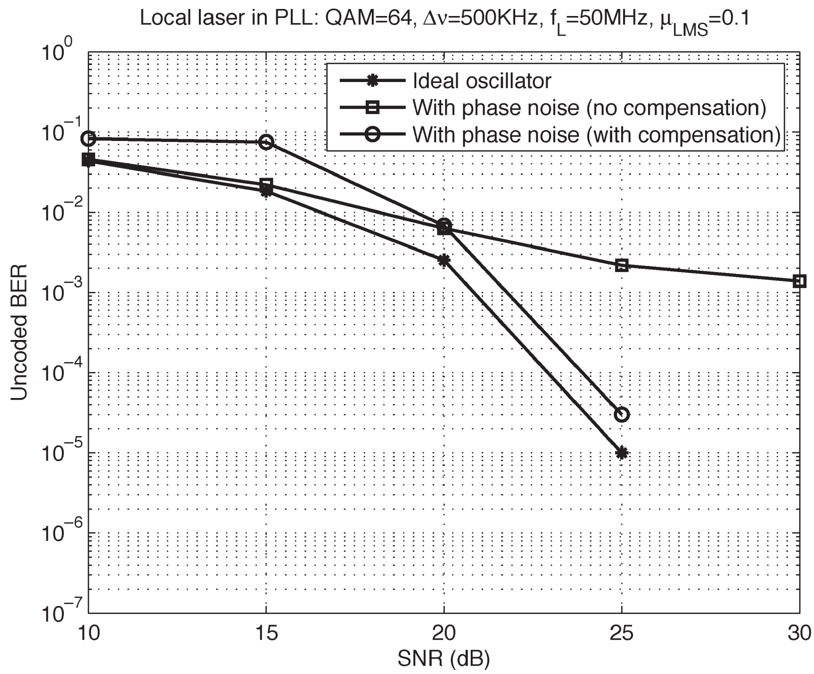

Fig. 8. Uncoded BER versus the SNR for a coherent link with an LO in the PLL mode. The PSD corresponding to a first-order transfer function given by (7) is used in the simulation. The system parameters are the transmit constellation of 64 QAM, an LMS step size of $\mu_{\mathrm{LMS}} = 0.1$, a laser linewidth of $\Delta\nu = 500$ KHz, and a PLL bandwidth of $f_L = 50$ MHz.

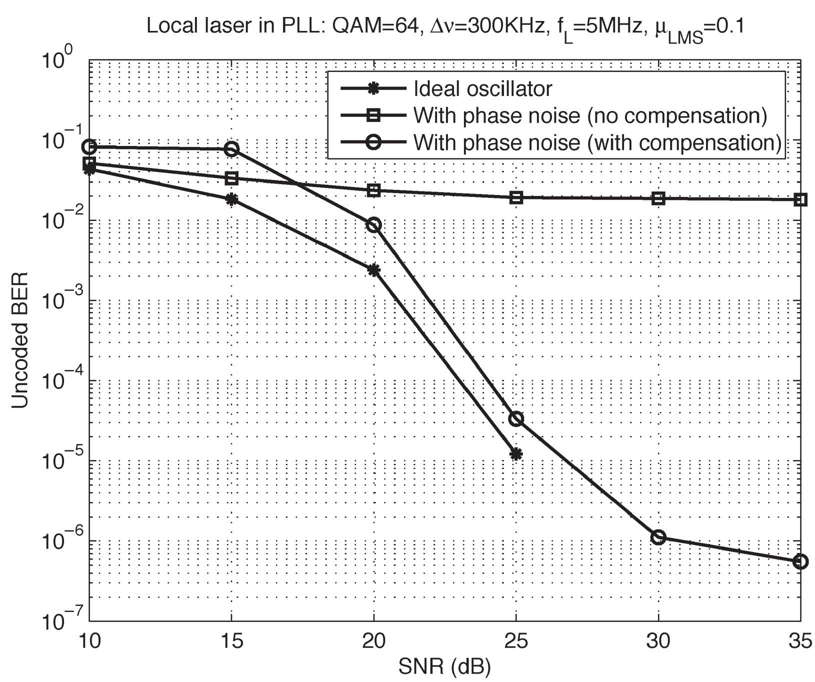

Fig. 9. Uncoded BER versus the SNR for a coherent link with an LO in the PLL mode. The PSD corresponding to a first-order transfer function given by (7) is used in the simulation. The system parameters are: the transmit constellation of 64 QAM, an LMS step size of $\mu_{\mathrm{LMS}} = 0.1$, a laser linewidth of $\Delta\nu = 300$ KHz, and a PLL bandwidth of $f_L = 5$ MHz. Note that due to the relatively large phase-noise variance corresponding to these parameters, the BER floor achieved by the compensation scheme is observed within the simulated BER range.

C. BER Versus Laser Linewidth

To illustrate the gain achieved in terms of laser linewidth requirements, the BER versus laser linewidth $(\Delta\nu)$ at SNR $=$ 25 dB are plotted for a fixed loop bandwidth $(f_L = 5$ MHz$)$ in Fig. 11. A 64-QAM constellation is used with the LMS step size in the range of $\mu_{\mathrm{LMS}} = 0.05{-}0.20$. As can be seen from the plot, the laser linewidth requirement to achieve a target BER is significantly relaxed when the compensation scheme is used.

V. Analog-to-Digital Conversion

High-speed analog-to-digital converters (ADCs) are required in a gigabit-per-second fiber-optic link to convert the continuous-time signal into a discrete-time form. Depending on

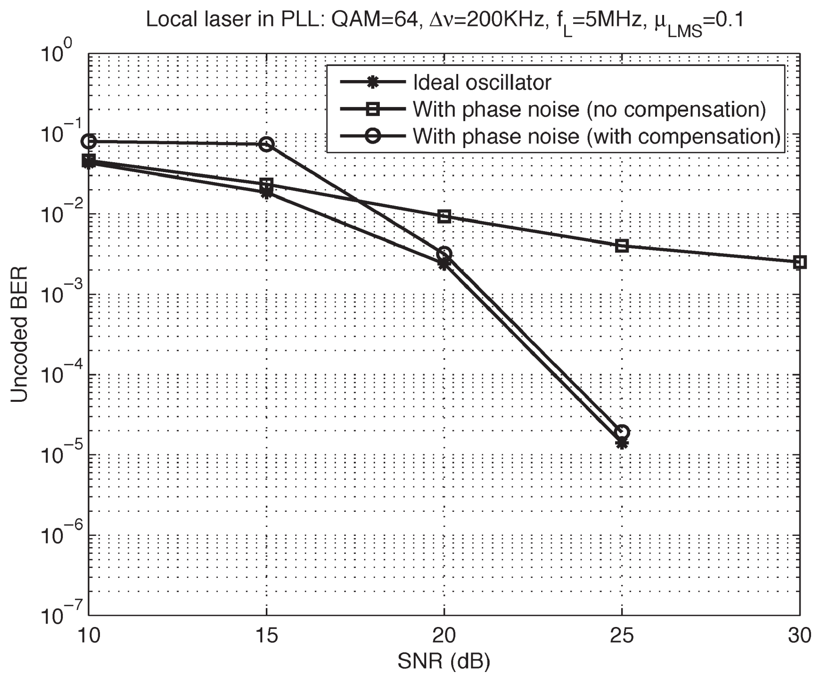

Fig. 10. Uncoded BER versus the SNR for a coherent link with an LO in the PLL mode. The PSD corresponding to a second-order transfer function given by (10) is used in the simulation. The system parameters are the transmit constellation of 64 QAM, an LMS step size of $\mu_{\text{LMS}} = 0.1$, a laser linewidth of $\Delta\nu = 300$ KHz, and a PLL bandwidth of $f_n = 5$ MHz.

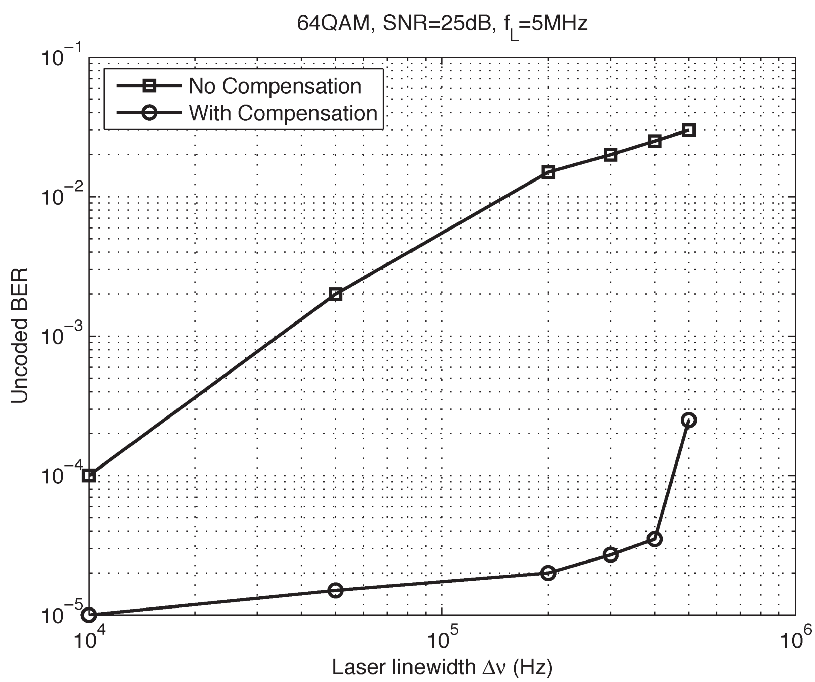

Fig. 11. Uncoded BER versus the laser linewidth $\Delta\nu$ for a fixed loop bandwidth $f_L = 5$ MHz, a 64-QAM constellation, and an SNR of 25 dB.

the required SNR (for a target BER), a certain number of bits are needed for digital conversion. The number of bits in the ADC is chosen such that the quantization noise is below (by some margin) the maximum noise level allowed for the system to operate. The required effective number of bits (ENOB) can be calculated as $\text{ENOB} = (\text{SNR(dB)} - 1.76)/6.02$ [11]. Considering the toughest ADC requirement for the systems simulated in this section (10 Gb/s, 64-QAM link), five ENOB at 1.67-Gsps ADC is required to support 25-dB SNR with about a 6-dB margin. Note that for systems with a lower link throughput or lower-density constellations (e.g., 16 QAM), the ADC requirement is significantly relaxed.

VI. Conclusion

The proposed approach in this paper relies on using signal processing techniques to compensate for the laser phase noise in the digital domain. An adaptive tracking scheme is presented that reduces the effect of the laser phase noise and, consequently, relaxes the laser linewidth requirement. The proposed approach shows how signal processing techniques can be exploited to compensate for the optical impairments by utilization of the continuing scale-down in VLSI technology.

REFERENCES

[1] L. G. Kazovsky, "Impact of laser phase noise on optical heterodyne communication systems," *J. Opt. Commun.*, vol. 7, no. 2, pp. 66–77, 1986.

[2] ——, "Performance analysis and laser linewidth requirements for optical PSK heterodyne communication systems," *J. Lightw. Technol.*, vol. LT-4, no. 4, pp. 415–425, Apr. 1986.

[3] ——, "Decision driven phase-locked-loop for optical homodyne receivers: Performance analysis, design considerations and laser linewidth requirements," *J. Lightw. Technol.*, vol. LT-3, no. 6, pp. 1238–1247, Dec. 1985.

[4] S. Norimatsu and K. Iwashita, "PSK optical homodyne detection using external cavity laser diodes in Costas loop," *IEEE Photon. Technol. Lett.*, vol. 2, no. 5, pp. 374–376, May 1990.

[5] L. G. Kazovsky, "Balanced phase-locked loops for optical homodyne receivers: Performance analysis, design considerations and laser linewidth requirements," *J. Lightw. Technol.*, vol. LT-4, no. 2, pp. 182–195, Feb. 1986.

[6] L. N. Langley, M. D. Elkin, C. Edge, M. J. Wale, U. Gliese, X. Huang, and A. J. Seeds, "Packaged semiconductor laser optical phase-locked loop (OPLL) for photonic generation, processing and transmission of microwave signals," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1257–1264, Jul. 1999.

[7] T. Okoshi and K. Kikuchi, *Coherent Optical Fiber Comminications*. Tokyo, Japan: Kluwer, 1988.

[8] K. Kikuchi, T. Okoshi, M. Nagamatsu, and N. Henmi, "Degradation of bit error rate in coherent optical communications due to spectral spread of the transmitter and the local oscillator," *J. Lightw. Technol.*, vol. LT-2, no. 6, pp. 1024–1033, Dec. 1984.

[9] R. E. Best, *Phase-Locked Loops*. New York: McGraw-Hill, 2003.

[10] A. H. Sayed, *Fundamentals of Adaptive Filtering.* New York:Wiley, 2003.

[11] Analog Devices Engineering Staff, *Data Conversion Handbook*, 2005, Norwood, MA: Elsevier.

Alireza Tarighat (S'00–M'05) received the B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1998. He received the M.Sc. and Ph.D. degrees, both in electrical engineering from the University of California, Los Angeles (UCLA), in 2001 and 2005, respectively.

During the summer of 2000, he was with Broadcom, El Segundo, CA, where he worked on designing IEEE 802.11a transceivers. From 2001 to 2002, he was with Innovics Wireless, Los Angeles, working on the application specified integrated circuit (ASIC) implementation of advanced antenna diversity and rake processing for third-generation wideband code division multiple access (3G WCDMA) mobile terminals. Since June 2005, he has been with WiLinx, Los Angeles, developing CMOS solutions for ultra wideband (UWB) systems. His research interests include communication systems and signal processing techniques, including multiple input, multiple output optical frequency division multiplexing (MIMO OFDM) systems, multiuser MIMO communications, optical communications, and experimental and practical implementation of communication systems.

Mr. Tarighat was the recipient of the Gold Medal of the National Physics Olympiad, Iran, in 1993, and the Honorable Mention Diploma of the 25th International Physics Olympiad, Beijing, China, in 1994.

Rick C. J. Hsu (S'03) received the B.S. degree in physics and the M.S. degree in electrical engineering from the National Taiwan University, Taipei, Taiwan, R.O.C., in 1999 and 2001, respectively. Since 2003, he has been working toward the Ph.D. degree with the Department of Electrical Engineering at University of California, Los Angeles (UCLA).

His current research interests include fiberoptic communication systems and microwave photonics.

Ali H. Sayed (S'90–M'92–SM'99–F'01) received the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 1992.

He is a Professor and the Chairman of Electrical Engineering Department at University of California, Los Angeles (UCLA). He is also the Principal Investigator of the UCLA Adaptive Systems Laboratory (www.ee.ucla.edu/asl). He is the author or coauthor over 250 journals and conference publications and is the author of the textbook *Fundamentals of Adaptive Filtering* (New York: Wiley, 2003), the coauthor of the research monograph *Indefinite Quadratic Estimation and Control* (Philadelphia, PA: SIAM, 1999), and of the graduate-level textbook *Linear Estimation* (Englewood Cliffs, NJ: Prentice-Hall, 2000). He is also coeditor of *Fast Reliable Algorithms for Matrices with Structure* (Philadelphia, PA: SIAM, 1999). He has contributed several articles to engineering and mathematical encyclopedias and handbooks and has served on the program committees of several international meetings. His research interests include adaptive and statistical signal processing, filtering and estimation theories, signal processing for communications, interplays between signal processing and control methodologies, system theory, and fast algorithms for large-scale problems.

Dr. Sayed is a recipient of the 1996 IEEE Donald G. Fink Award, a 2002 Best Paper Award from the IEEE Signal Processing Society, the 2003 Kuwait Prize in Basic Science, the 2005 Frederick E. Terman Award, the 2005 Young Author Best Paper Award from the IEEE Signal Processing Society, and two Best Student Paper awards at international meetings. He is also a member of the technical committees on Signal Processing Theory and Methods (SPTM) and on Signal Processing for Communications (SPCOM), both of the IEEE Signal Processing Society. He is a member of the editorial board of the IEEE SIGNAL PROCESSING MAGAZINE. He has served as Editor-in-Chief of the IEEE TRANSACTION ON SIGNAL PROCESSING (2003–2005) and is now serving as Editor-in-Chief of the *EURASIP Journal on Applied Signal Processing*. He is the General Chairman of International Conference on Acoustics, Speech, and Signal Processing (ICASSP) 2008.

Bahram Jalali (S'86–M'89–SM'97–F'04) received the B.S. degree in physics from Florida State University, Tallahassee, in 1984 and the M.S. and Ph.D. degrees in applied physics from Columbia University, New York, NY, in 1986 and 1989, respectively. He is a Professor of electrical engineering, the Director of the Defense Advanced Research Projects Agency (DARPA) Center for Optical A/D System Technology (COAST), and the Director of the Optoelectronic Circuits and System Laboratory at the University of California, Los Angeles (UCLA). From 1988 to 1992, he was a Member of Technical Staff at the Physics Research Division of American Telephone & Telegraph (AT&T) Bell Laboratories, Murray Hill, NJ, where he conducted research on ultrafast electronics and optoelectronics. He was responsible for successful development and delivery of 10-Gbps lightwave circuits to the U.S. Air Force in 1992. While on leave from UCLA from 1999 to 2001, he founded Cognet Microsystems, a Los Angeles-based fiber optic component company. He served as Cognet's CEO, President, and Chairman from the company's inception to its acquisition by Intel Corporation in April 2001. From 2001 to 2003, he served as a consultant in the Communication Group of Intel Corporation. He is the author or coauthor of over 200 publications and is the holder of six U.S. patents. His research interests include microwave photonics, integrated optics, and fiber optic ICs.

Dr. Jalali is the Chair of the Los Angeles Chapter of the IEEE Lasers and Electro Optics Society (LEOS). He was the General Chair for the IEEE International Conference on Microwave Photonics (MWP) in 2001 and its Steering Committee chair from 2001 to the present. He is also a member of the California Nano Systems Institute (CNSI). He is a member of the Board of Trustees of the California Science Center. He received the BridgeGate 20 Award in recognition of his contributions to the Southern California economy.