# Phasor monitoring of DxPSK signals using software-based synchronization technique

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**Abstract:** We develop a novel phasor monitor to obtain the constellation diagram from asynchronously sampled data measured by using the delay-detection technique. This phasor monitor consists of three parts; a phase-adjustment-free delay-interferometer, an optical front-end made of three photodetectors, and analog-to-digital (A/D) convertors, and a digital signal processor. We operate the A/D convertor at the sampling rate much slower than the symbol rate and acquire the data asynchronously. However, despite the use of such a slow and asynchronous sampling rate, we obtain the clear eye and constellation diagrams by utilizing the software-based synchronization technique based on a novel phased-reference detection algorithm. Thus, the proposed phasor monitor can be implemented without using high-speed A/D convertors and buffer memories, which have been the major obstacles for the cost-effective realization of the phasor monitor. For a demonstration, we realize the proposed phasor monitor by using an A/D converter operating at 9.77 MS/s and used it for the constellation monitoring and bit-error-rate (BER) estimation of 10.7-Gsymbol/s differential quadrature phase-shift keying (DQPSK) and differential 8-ary phase-shift keying (D8PSK) signals.



**OCIS codes:** (060.2330) Fiber optics communications; (060.5060) Phase modulation.

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## 1. Introduction

Due to the recent developments in the advanced modulation formats such as multilevel phase-shift-keying (PSK), it is needed to evaluate the constellation diagram of the phase-modulated signals on the complex plane. Thus, several types of phasor monitors have been proposed by utilizing both coherent and non-coherent detection techniques [1–9]. Among them, the phasor monitor based on the non-coherent detection technique appears to be attractive since it can be implemented by using only the passive optical components (i.e., there is no need to use the local oscillator laser). However, this phasor monitor still requires the use of high-speed analog-to-digital (A/D) convertors and memories operating at the speed faster than the symbol rate [7,8]. As a result, it may be difficult to realize even the non-coherent phasor monitor cost-effectively. To solve this problem, we apply the asynchronous sampling technique to the non-coherent phasor monitor and evaluate its performances. For example, to obtain the constellation diagram from the asynchronously sampled data, we used the software-based synchronization technique based on a novel phase-reference detection algorithm (which can recover the time base synchronized to the signal under test (SUT)) [9]. This synchronization technique enables us to utilize low-speed, free-running A/D converters in the phasor monitor. In addition, unlike other software-based synchronization techniques developed for the optical sampling system, the proposed technique does not require any iteration procedures and the synchronization of the reference clocks between the signal source and sampling system [10,11].

In this paper, we first describe the operating principle of the proposed phasor monitor and the software-based synchronization technique based on the phased-reference detection method. We then implement a phase-adjustment-free phasor monitor by using the proposed technique [8] and evaluate the monitoring errors caused by the use of the asynchronous sampling. The results show that we can obtain clear constellation diagrams of differential quadrature phase-shift-keying (DQPSK) and 8-ary PSK (D8PSK) signals by using the asynchronously sampled data even when we reduce the sampling rate to 9.77 MS/s. We also investigate the effect of the low-speed sampling on the performance of the proposed phasor monitor by measuring the monitoring errors while varying the sampling rate from 156 KS/s to 50 GS/s. No significant difference is observed even when we reduce the sampling rate to be as low as 156 KS/s. Finally, we demonstrate that the proposed phasor monitor can be used for the accurate BER monitoring of DQPSK and D8PSK signals.

## 2. Operating principle of the phasor monitor using the software-based synchronization technique

### *2.1 Demodulation of DxPSK signal by the delay detection*

Figure 1 shows the schematic diagram of the proposed phasor monitor. The optical PSK signal is demodulated by using a delay interferometer (DI) made of a 3x3 coupler (i.e., 120° optical hybrid) [7,8]. The delay time of the DI is adjusted to be the same with the symbol period $T$. The output signals of the DI are sampled by using a sample-and-hold (S/H) amplifier and an A/D converter. Then, we obtain the in-phase and quadrature components of the differential electric field (i.e., differential phasor) of the SUT from the sampled photocurrents $I_j$ ($j$ = 1,2,3) by using the coordinate transformation technique [7].

In this phasor monitor, we sample the output signals of the DI asynchronously at the sampling rate $f_s$, which is much slower than the signal's symbol rate $B$. As a result, the phasor monitor acquires all the states of the signal including the transitions between the symbols. For example, Figs. 2(a) and 2(b) show the phase and phasor diagrams of the SUT measured by using the proposed phasor monitor, respectively. The SUT was a 21.4-Gb/s DQPSK signal. We sampled this signal asynchronously at the rate of 9.77 MS/s. Since the sampled signal

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contained the transitions between symbols, the measured phasor diagram (Fig. 2(b)) included all the trajectories of the symbol transitions. In addition, when we simply arranged the phases of the sampled signal as a function of the measured time as shown in Fig. 2(a), we could not differentiate the phase noise and the transitions between symbols. As a result, it was not possible to evaluate the quality of the phase-modulated signal directly from these diagrams.

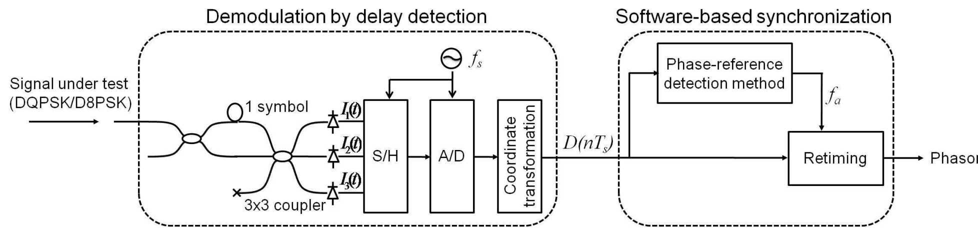


Fig. 1. Schematic diagram of the phasor monitor implemented by using the proposed software-based synchronization technique. $D(nT_s)$: differential electric field, $f_s$: sampling rate, $f_a$: aliased clock frequency.

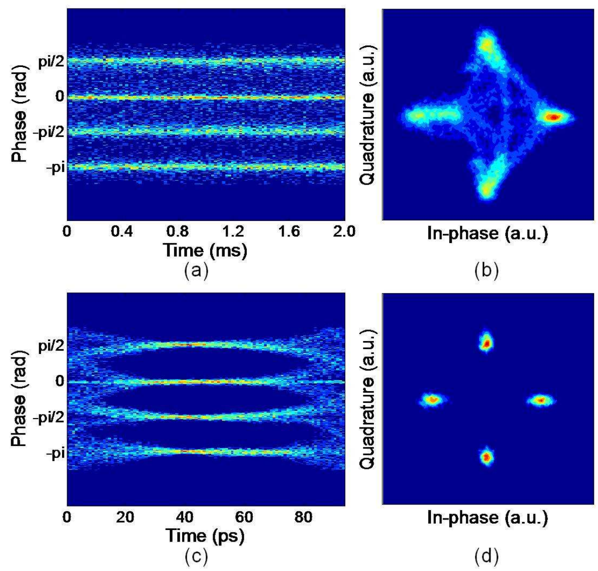


Fig. 2. Phase and differential phasor of DQPSK signal. (a) and (b) are phase and differential phasor measured by using asynchronously sampled data before software synchronization, respectively. (c) and (d) are phase eye diagram and constellation diagram after software synchronization, respectively.

### *2.2 Software-based synchronization using the phase-reference detection method*

To obtain clear phase eye diagram and constellation map from the asynchronously sampled signal, we utilize a novel software-based synchronization technique. Figure 3 illustrates its operating principle. The basic idea is similar to the software-based sampling technique except that this technique does not require the synchronization between the signal source and sampling system [10,11]. In the top trace of Fig. 3, each filled shape represents one symbol of the SUT. The middle trace is the sampling timing of the S/H amplifier. Thus, the signal shown in the first row is sampled at the timing of the sampling clock shown in the second row, and then the sampled data is acquired by the A/D converter at the timing shown in the bottom row. The purpose of the software synchronization is identifying the relative time position of the

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sampled data in the time frame of $T$ (which is designated as "symbol frame" hereafter) and rearranging them.

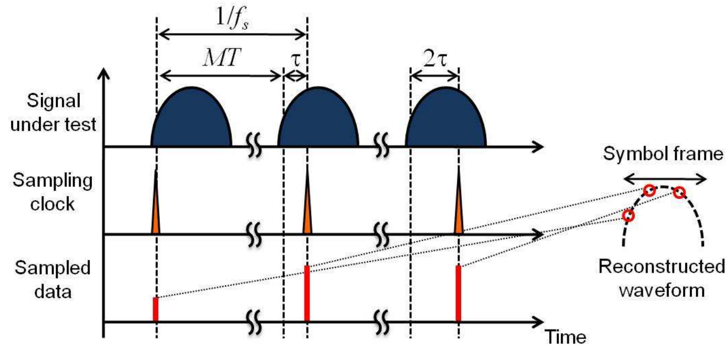


Fig. 3. Timing chart of signal, sampling clock, and sampled data.

Since we use an independent sampling clock source, the symbol rate, $B$ (= $1/T$), is assumed to be not an integer multiple of the sampling rate, $f_s$. Thus, the sampling time with respect to the symbol frame is changed by $\tau$ at every sampling moment, which is described as

$$\tau = \frac{1}{f_s} - MT \tag{1}$$

where the integer $M$ represents the number of the skipped symbols between sampling clocks. Thus, if $\tau/T$ is known, we can identify the position of the sampled data within the symbol frame. We can then rearrange the sampled data into one symbol frame and obtain the eye and constellation diagrams as depicted in the right side of Fig. 3. In the proposed method, $\tau/T$ can be obtained by estimating the symbol rate (i.e., the clock frequency of the SUT) from the asynchronously sampled data. Since the sampling rate $f_s$ is much slower than the symbol rate $B$, the clock component of the original SUT is aliased within $\pm f_s/2$ after sampling at $f_s$. If we denote this aliased clock component as $f_a$, it has the following relation,

$$B = Mf_s + f_a . \tag{2}$$

From (1) and (2), we find,

$$\frac{\tau}{T} = \frac{f_a}{f_s} . \tag{3}$$

Thus, we can obtain $\tau/T$ by measuring the aliased clock frequency $f_a$, and then rearrange the sampled data synchronously into a symbol frame.

For the accurate estimation of the aliased clock frequency, we propose a new algorithm designated as the "phase-reference detection method." Figure 4 shows the block diagram of the proposed algorithm. We first transform the sampled data by using fast Fourier transformation (FFT) and identify the peak frequency, $f_p$, in the range from 0 to $f_s/2$. We note that one may consider $f_p$ as a good approximation of $|f_a|$. However, if we simply use $f_p$, the measured eye and constellation diagrams suffer from severe clock drift. For example, let's consider the case when the difference between $f_p$ and $|f_a|$ is not zero (i.e., the estimation error, $\varepsilon$, is not zero). In this case, the estimated $\tau$ in (3) has an error of $\varepsilon T/f_s$. As a result, the estimated position in time is shifted from the correct position by $\varepsilon T/f_s$ per sample. Thus, if we use $N$-samples, the timing drift is accumulated to be $N\varepsilon T/f_s$. Since $\varepsilon$ is one half of the FFT's resolution $|f_s/(2N)|$ at the maximum, the timing drift can be as large as $|T/2|$. Thus, we have to reduce the estimation error $\varepsilon$ to be much smaller than the FFT's resolution. For this purpose, we extract the aliased clock component, and then detect the phase of the aliased clock by

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using the sinusoidal wave of $f_p$ as a phase reference. For example, we first apply a band-pass filter which has the center frequency at $f_p$, and then convert the filtered spectrum into time domain by using inverse FFT. (It should be noted that, since $|f_a|$ is not always identical to the integer multiple of the FFT's resolution, the aliased clock component is dispersed into several discrete spectral components in the FFT spectrum.) We then generate the sine and cosine waves at the frequency of $f_p$ and detect the phases of the aliased clock components as a function of time. Since the slope of the detected phase (i.e., the phase difference between the aliased clock component and internally generated sinusoidal wave) gradually changes at a rate of $2\pi (|f_a|-f_p)t$, we can obtain $|f_a|-f_p$ from the slope of the detected phases. As a result, we can accurately estimate $|f_a|$ with a resolution much better than $f_s/N$.

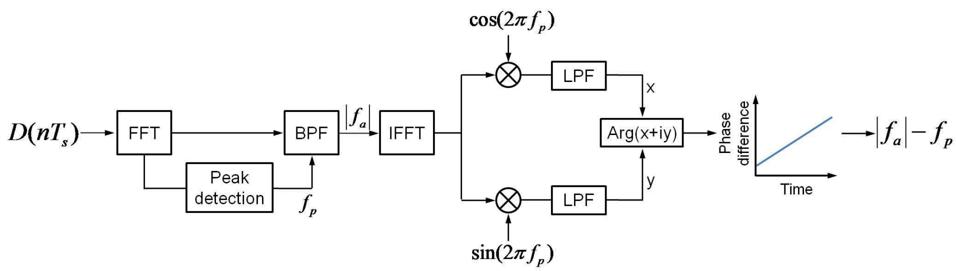


Fig. 4. Block diagram of the proposed software-based synchronization algorithm.

Figure 5(a) shows the power spectrum of the 10.7-Gsymbol/s DQPSK signal (shown in Figs. 2(a) and 2(b)) sampled at 9.77 MS/s. For comparison, we also show the power spectrum of the same signal sampled at 50 GS/s (i.e., faster than Nyquist rate) in Fig. 5(b). Although the sampling rate of our phasor monitor was much slower than the symbol rate, we could clearly distinguish the clock component from the data components. Thus, by applying the proposed phase-reference detection method, we could also estimate the aliased clock frequency with high precision. For example, when the number of samples was 10000, the estimation error of the clock frequency was measured to be merely ± 16 Hz (which was 60 times smaller than the spectral resolution of FFT). Then, by using (3), we could easily rearrange the sampled data to be synchronized to the symbol frame and reconstruct the phase eye diagram as shown in Fig. 2(c). In addition, by selecting the sampled data near the center portion of the symbol frame only, we could also obtain the constellation diagram shown in Fig. 2(d).

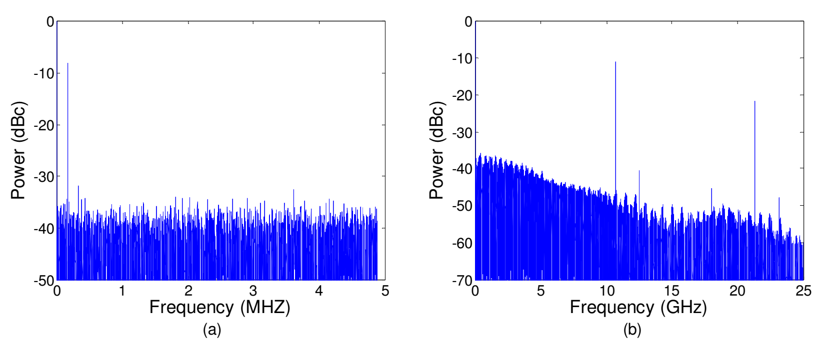


Fig. 5. (a) Power spectrum of the 10.7-Gsymbol/s DQPSK signal obtained by sampling asynchronously at 9.77 MS/s (i.e., the aliased signal). (b) power spectrum of the same DQPSK signal obtained by sampling at 50-GS/s (i.e., the original spectrum).

We note that $f_a$ can be a negative number. In this case, the reconstructed eye diagram becomes a mirror image of the original eye diagram. However, it is not a problem for obtaining the constellation diagram or evaluating the eye opening of the phase eye diagram, since we use only the sampled data in the vicinity of the center of the symbol frame. It should also be noted that our software-based synchronization algorithm is fast and straightforward

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since it does not use any iteration procedures (unlike the algorithms reported in [10]). Also, it does not require any information of the SUT in advance. Thus, the operation of this phasor monitor is easy and adjustment-free. In addition, it can be realized by using low-speed A/D converters, which is a great advantage over the previously proposed phasor monitors [1–8].

## 3. Demonstration of the proposed phasor monitor for DxPSK signals

### *3.1 Experimental setup*

We implemented the proposed phasor monitor based on the software-based synchronization technique and evaluated its performances by using 10.7-Gsymbol/s DQPSK and D8PSK signals. These signals were obtained by modulating the output of a tunable laser with a QPSK modulator (and a phase modulator for D8PSK). The wavelength and the linewidth of the tunable laser were 1548.2 nm and 170 kHz, respectively. The pattern length was $2^{15}-1$. For the demodulation of these signals, we used a fiber Michelson DI made of a 3x3 coupler and Faraday rotator mirrors (FRMs) [7]. Due to the use of the FRMs, this DI was polarization-independent. For the asynchronous sampling, we used a digital storage oscilloscope as a low-speed A/D converter. We operated this storage oscilloscope by using its internal clock source (i.e., free-running clock source) and set the sampling rate to be in the range from 156 KS/s to 50 GS/s. The asynchronously sampled data was processed by using a computer.

### *3.2 Measured constellation diagrams*

Figure 6 shows the constellation diagrams of the DQPSK and D8PSK signals obtained by using the asynchronously sampled signals with various optical signal-to-noise ratios (OSNRs). The sampling rate was set to be 9.77 MS/s. To obtain these constellation diagrams, we first plotted the phase diagram (such as the one in Fig. 2(c)), decided the center position of the symbol, and then selected the data in the vicinity of the center position in the range of 10% of the symbol frame. The number of samples was 10,000. Figures 6(a) and 6(b) show constellation diagrams of DQPSK signals with the OSNR of 20.0 dB and 10.8 dB, respectively. Even for the signal having low OSNR, the proposed method worked correctly and we could obtain the constellation diagram. We also conducted the same experiment for D8PSK signals. Figures 6(c) and 6(d) shows the result of the D8PSK signals with OSNR of 22.6 dB and 12.4 dB, respectively. From these results, we concluded that the proposed method could provide sufficient amplitude and phase resolutions even for the multilevel modulation formats.

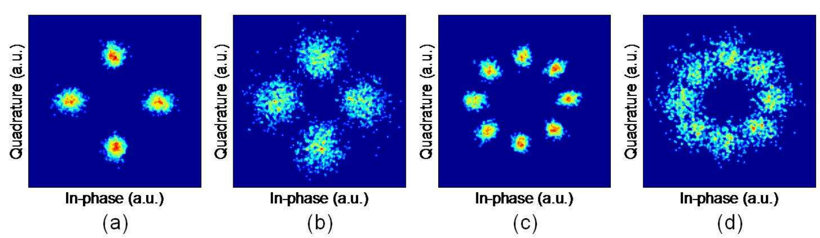


Fig. 6. The measured constellation diagrams of the DQPSK and D8PSK signal for various OSNRs. (a), (b): Phasor diagrams of DQPSK signals at OSNR 20.0 dB and 10.8 dB, respectively. (c), (d): Phasor diagrams of D8PSK signals at OSNR 22.6 dB and 12.4 dB, respectively.

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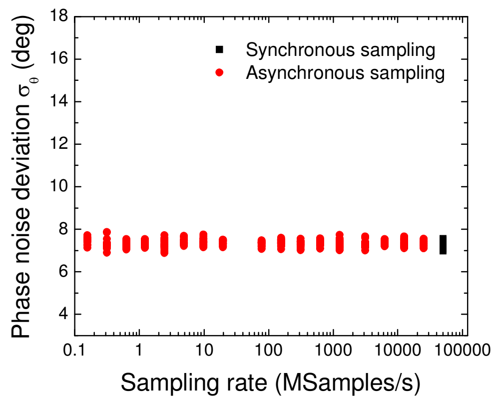


Fig. 7. Standard deviations of the optical phase noises of DQPSK signal as a function of the sampling rate.

*3.3 Effect of sampling rate*

To evaluate the effect of the sampling rate on the performance of the proposed phasor monitor, we measured the constellation diagram while varying the sampling rate. In this experiment, we used the standard deviation of the optical phase noise $\sigma_\theta$ as a measure of the quality of the software synchronization [8]. As described above, an inaccurate estimation of the aliased clock component can result in the timing jitter. As a result, the constellations become excessively blurred (since the constellation diagram contains the transitions between symbols). Thus, by evaluating $\sigma_\theta$, we can confirm if the software-based synchronization method properly works. Figure 7 shows the standard deviation of the measured optical phase noise of the DQPSK signal having OSNR of 18.1 dB. The sampling rate was varied in the range of 156 KS/s to 50 GS/s. For the statistical purpose, we carried out the same measurement 20 times for each sampling rate. The results show that $\sigma_\theta$ and their standard error were measured to be 7.4 degree and 0.15 degree, respectively. This small standard error was attributed to the finite number of samples rather than the inaccurate clock estimation. The theoretically estimated value of this error (by using 10000 samples) was 0.164 degree, which was in good agreement with the measured value. It should be noted that there was no significant difference in the measured phase deviations by using the asynchronous and synchronous (i.e., using the transmitter's clock) sampling techniques. Thus, we concluded that the proposed software-based synchronization technique could be used to reduce the required sampling frequency drastically.

*3.4 BER estimation using the measured constellation diagram*

We examine the possibility of estimating the BER of DxPSK signals by using the measured constellation diagrams (obtained by using the proposed phasor monitor). It has been recently reported that the BER of DxPSK signal can be expressed as a function of the optical phase noise of the symbols [8,13]. In this work, as described in [8], we estimated $\sigma_\theta$ by using the asynchronously sampled data, and investigated its correlation with BERs. The sampling rate was 9.77 MS/s and the number of samples was 19532. The total sampling time was 2 ms. The reference BER was obtained by measuring the actual BER using a DxPSK receiver (in which the bit errors of all tributaries were counted by assuming Gray coding) [8]. Figure 8(a) shows the measured results for DQPSK and D8PSK signals in comparison with the theoretically calculated curves [14]. The measured data agreed well with the theoretically calculated curves. Thus, we could estimate the BER from Fig. 8(a) by using the measured value of $\sigma_\theta$. The results in Fig. 8(b) confirmed that the proposed phasor monitor could estimate the BER

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accurately. Thus, the proposed software-based synchronization technique could be used for the BER estimation as well as the phasor monitoring.

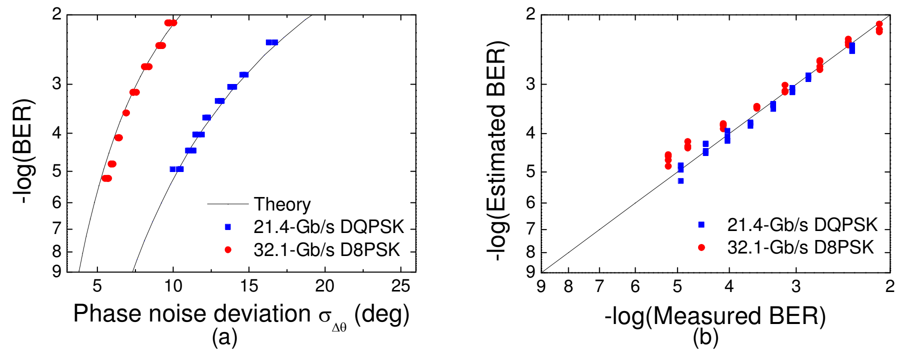


Fig. 8. Estimated BERs for 10.7-GSymbol/s DQPSK and D8PSK signals. (a) Measured BER vs. phase noise deviation of the symbols obtained from the constellation diagram. The solid curves represent the theoretically calculated values. (b) Measured BER vs. estimated BER by using the proposed phasor monitor.

## 4. Conclusion

A potentially inexpensive phasor monitor for DxPSK signals was developed by utilizing the non-coherent detection technique with low-speed, free-running A/D converters and the software-based synchronization technique based on the novel phase-reference detection algorithm. This algorithm enabled us to properly rearrange the asynchronously sampled data into one symbol frame by using the relation between the symbol rate and the sampling rate. Thus, by using the proposed phasor monitor, we could obtain the constellation diagrams of the 10.7-Gsymbol/s DQPSK and D8PSK signals (and estimate their BERs as well) from the asynchronously sampled data. The accuracy of this phasor monitor was not deteriorated even when the sampling rate was reduced to be as low as 156 KS/s. Thus, we concluded that the effect of the sampling rate on the performance of the proposed phasor monitor was negligible, which, in turn, facilitated the use of inexpensive low-speed A/D converters.


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