

Phase Noise Measurement in Single Carrier Digital Modulations

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Abstract. The paper shows a new algorithm for the phase noise measurement. The algorithm is based on the constellation examination of the IQ plane of the single carried digital modulated signal. It can be used to measure the phase noise both on the carrier signal and on the demodulated signal. Advantages of the proposed algorithm are: (i) the number of samples in practice does not affects the error, (ii) the percentage error is reduced if compared with other methods, and (iii) the phase noise shape weakly affects the error. The paper provides the theoretical background and reports the results of numerical experiments that validate the proposed algorithm.

Keywords: Phase noise, Digital modulations, Constellation.

I. Introduction

The measurement of the phase noise of the single carrier digital modulated signal is a phenomenon of actual interest in the communication networks because (i) in the receiver's station it limits immunity against nearby interference signals, and (ii) in the transmitter station it can swamp out nearby channels [1].

The phase noise may be measured by examining the carrier signal in the time-domain [2] or in the frequency domain [3]-[6], depending on the application.

The most common method followed in the digital communication systems is based on the direct spectrum analysis [7]. Three main approaches are used. The first involves measuring phase noise directly by means of a spectrum analyser. This measurement can be carried out as long as the analyser has negligible phase noise than the measured source. In [4] the investigation of the phase noise spectral contents of sinusoidal carrier in a wide range of frequencies offset with variable frequency resolution is given. The multi-resolution analysis permits to grant the finer the frequency resolution closer the analysis to the carrier frequency. In the second approach [5], a source is phase locked to the same frequency with 90° offset. The mixed product of the signal under test and the reference signal is measured using the FFT analyser. The third approach [6] uses a discriminator and compares the signal to itself delayed in time. The great advantage is that it does not require an excellent reference.

The basic disadvantage of all these approaches are the fact that the spectral analysis is greatly influenced by (i) the number of the processed samples, and (ii) the shape of the noise taken into account. In order to overcome these disadvantages, in the paper a new algorithm is proposed. It is designed (i) to be used for the single carrier digital modulations that can be shown in the IQ plane, and (ii) to be integrated in the intelligent measurement instrument able to characterize the signaling quality whichever digital modulation is used [8]. Such measurement instrument is designed by scaled block structure each one performing the specific measurement task [9], [10]. The input block furnishes the fundamental information concerning the identification and classification of the modulation type. The proposed algorithm performs the phase noise measurement by using only the information coming out from the modulation classifier. These information concern both the modulation scheme and the level number among (i) the amplitude modulated signals, M-ary Quadrature Amplitude Modulation (M-QAM) and M-ary Amplitude Shift Keying (M-ASK), and (ii) the angle modulated signals, M-PSK.

The proposed algorithm is based on the constellation examination of the IQ plane of the signal. Therefore, it can be used to measure the phase noise (i) on the carrier signal, and (ii) on the single carried digital modulated signal. This approach is particular convenient and permits to realise a very fast and reliable algorithm. For the practical estimation of the phase noise the algorithm requires the knowledge of both the carrier frequency and the phase offset. These two parameters are previously evaluated on the base of the approach shown in [9].

In the following (i) the theoretical background of the algorithm, and (ii) the description of the algorithm steps, are given. Successively, the basic properties of the algorithm are shown by comparing with that one based on the FFT computation. The results of several numerical experiments showing the performance of the algorithm are finally described.

II. Phase noise measurement algorithm

Table 1 Expression of the carried information A_k .

Digital modulation	Carried information A_k
M-ASK	$A_k = 2i - M - 1, i = 0, 1, \dots, M - 1$
M-PSK	$A_k = e^{j\frac{2\pi i}{M}}, i = 0, 1, \dots, M - 1$
M-QAM	$A_k = a_k + jb_k, a_k, b_k = 2i - M - 1, i = 0, 1, \dots, M - 1$

modulation parameters, and (iii) to down convert the signal. The modulation classification is the first step to be executed because the proposed algorithm can be used only for M-ASK, M-PSK and M-QAM modulations, as shown later. The second step consists of measuring the carrier frequency and the carrier offset to permit both the correct down conversion and synchronisation of the received signal. These two steps can be executed on the basis of the procedure given in [8] and [9].

By denoting with $\phi_c(t)$ the instantaneous phase noise fluctuation of the transmitted carrier signal and $\phi_{dw}(t)$ the instantaneous phase noise fluctuation of the sinusoidal reference signal used in the down conversion systems, the signal $s_d(t)$ is:

$$s_d(t) = \sum_k A_k e^{j(\phi_c(t) - \phi_{dw}(t) + \varphi_i)} g(t - kT_s) \quad (1)$$

where: φ_i is the phase angle characterizing the modulation scheme and it is well known, A_k maps the transmitted symbols, T_s is the symbol time, and $g(t)$ is the finite energy signal with the T_s duration. The expressions of A_k for M-ASK, M-PSK and M-QAM modulations are given in Table 1. The argument of $s_d(t)$ is:

$$\arg(s_d(t)) = \phi_c(t) - \phi_{dw}(t) + \varphi_i \quad (2)$$

In particular, it is $\varphi_i = \text{cost}$ for M-ASK, $\varphi_i = 2\pi i/M$ for M-PSK, $\varphi_i = \text{atan}(b_k/a_k)$ for M-QAM. The argument of $s_d(t)$ is influenced by the noise phase and, if $\phi_{dw}(t)$ is negligible respect to $\phi_c(t)$, the phase noise fluctuation of the transmitted sinusoidal carrier signal can

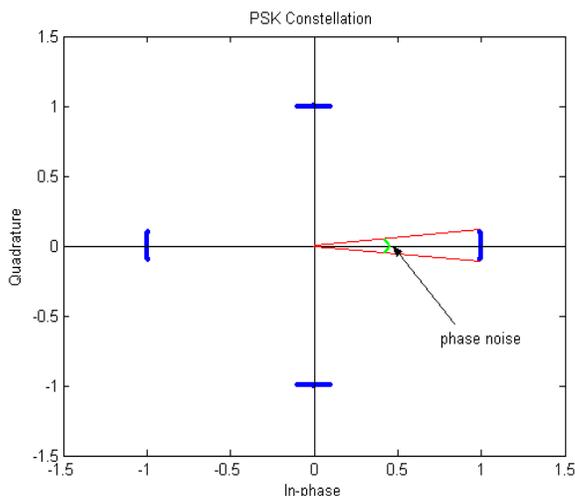


Figure 1 Constellation of the 4-PSK modulation and phase noise influencing the ideal symbols.

be evaluated from (2), otherwise the phase noise depending on both $\phi_c(t)$ and $\phi_{dw}(t)$ can be evaluated. In order to examine the argument of $s_d(t)$ the constellation of the IQ plane is taken into account. As it is shown in (1) and (2), each symbol is influenced by the phase noise fluctuation in the same manner, and, as a consequence, only one symbol in the constellation can be examined. The phase noise is measured by evaluating the peaks of the fluctuations around the ideal symbol of the constellation in the IQ plane, as shown in Figure 1.

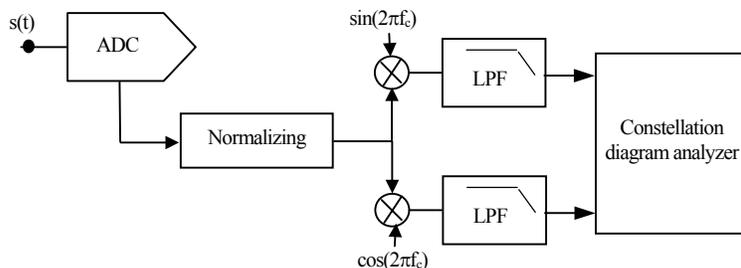


Figure 2 Block diagram of the IQ based algorithm.

The block diagram of the IQ based algorithm is shown in Figure 2. The input signal is digitised by the Analogue to digital Converter (ADC), successively it is normalised and, at the end, the I and Q components are obtained. In the case the carrier phase offset ψ occurs in the signal demodulation,

each symbol in the constellation is rotated of the angle ψ from the ideal symbol [9]. The algorithm can be always used, but it need (i) to detect the phase offset ψ according to the method shown in [9], and (ii) to taken into account that the real symbol is rotated.

As it can be deduced from (1), the proposed algorithm is not limited to the modulated signals. It is usable in the case of sinusoidal shape signals, also. In particular, the phase noise of the transmitted sinusoidal carrier signal can be directly evaluated. It is worth highlighting that the band limiting filter used in the real communication standard influences both the peaks and the frequency of the noise. Consequently, the phase noise detected on the carrier and on the demodulated signal can differ. Then, applied to the demodulated signal, the algorithm furnishes the peak of the phase noise propagated from the carrier to the demodulated signal.

The feature making general valid the algorithm is the IQ plane examination. As a consequence, the IQ based algorithm permits to evaluate the phase relation avoiding heavy numerical processing and it shows important properties.

In order to highlight all the properties, the algorithm was tested by means of numerical procedures. The numerical tests was organised so as to compare the performance with that of the algorithm based on the FFT computation.

A. Properties of the IQ algorithm

Four are the fundamental properties arising from the IQ based algorithm:

1. *The number of samples in practice doe not affects the error.* Figure 3 shows the percentage error trend in the case of the IQ based algorithm and the FFT based. In this last algorithm the number of samples heavily influences the error because the accuracy of the FFT depends on the number of samples. Therefore, if the number of samples is multiple of 512 the error is minimum, but always greater than the error in the case of the IQ based algorithm. The main advantage of this property consists of the possibility of capturing a longer time interval by means of the availability memory and, as a consequence, of reducing the sampling frequency.
2. *The percentage error is reduced.* In Figure 4 the percentage error trend is compared in the case of the IQ based algorithm and the FFT based for different value of the phase noise, by using 1024 samples. The IQ based algorithm is characterised by constant and very small error values. In the case of the FFT based algorithm the error increases as the phase noise increases.

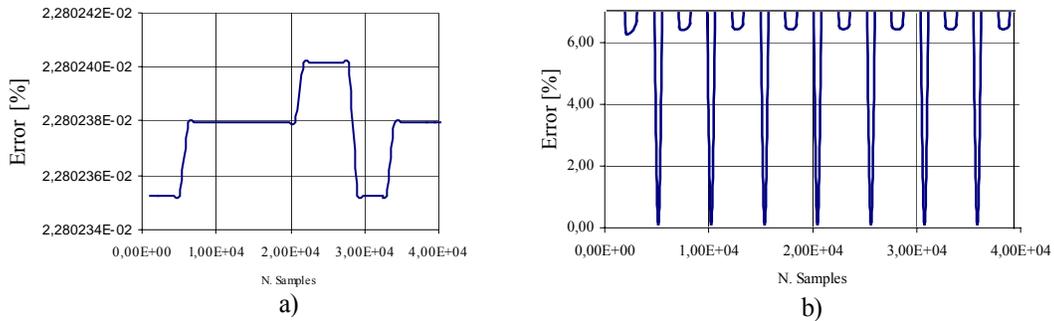


Figure 3 Percentage error versus the sample number for a) IQ based algorithm and (b) FFT based algorithm.

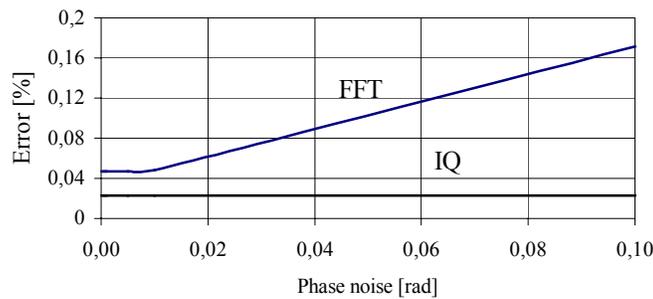


Figure 4 Comparison between the percentage error trend in the case of the IQ based algorithm and the FFT based algorithm for different values of the phase noise and 1024 samples.

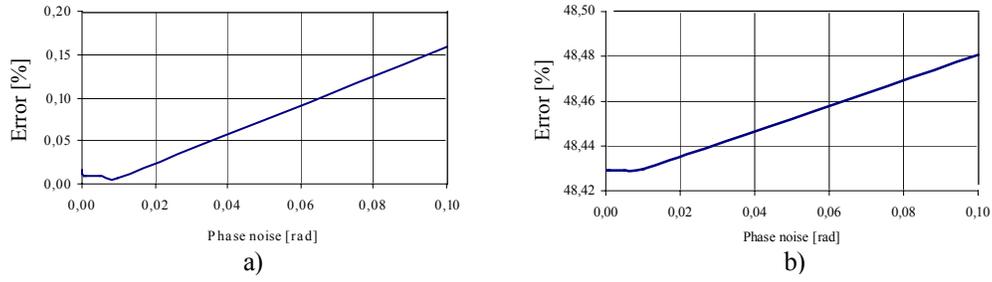


Figure 5 Percentage error versus the phase noise in the case of a) IQ based algorithm and b) FFT based algorithm, by using 1024 samples. The phase noise is constituted by the sum of two sinusoid with equal amplitude and frequency equal to 500Hz and 700Hz, respectively.

3. *The phase noise shape weakly affects the error.* Figure 5 shows the percentage error trend in the case of the IQ based algorithm and the FFT based algorithm, by using 1024 samples and considering the phase noise in the very narrow frequency band. In particular, it is imposed the phase noise constituted by the sum of two sinusoid with equal amplitude and frequency equal to 500Hz and 700Hz, respectively. As shown in the Figure 5, the error is very high in the case of FFT based algorithm. On the contrary, the error sensitivity in the case of the IQ based algorithm is greater than for FFT based algorithm.
4. *The IQ method is usable both for sinusoidal and modulated signals.* According to the theory and shown from (1), the phase error of the sinusoidal carrier signal exactly propagates on the modulated signal. Consequently, the phase error of the carrier signal can be detected by analysing the modulated signal on the IQ constellation plane. Band limiting filters used according to the communication standard can made different the phase noise on the carrier signal and on the demodulated signal.

III. Numerical characterisation

The algorithm was characterized in the Matlab environment. In all the numerical tests it was assumed: (i) the phase noise: characterized by sinusoidal shape, (ii) the peak values of the phase noise variable in the range $[10^{-4}, 10^1]$ rad, (iii) the carrier frequency f_c variable in the range [1.3, 3] kHz, and (iv) the ratio between the sampling frequency f_s and f_c equal to 10^2 . The digital modulated signals taken into account were: 8-ASK, 4-PSK and 256-QAM. In order to evaluate the measurement results, the percentage error from the assigned value was estimated.

Many tests were carried out in order to verify the reliability and effectiveness of the proposed algorithm. In the following, the effects of the bit number of ideal ADC on the phase noise measurement was shown and discussed, only.

As shown in Figure 6, in order to reduce the error without increasing the cost of the hardware, the minimum bit number is 16. Indeed, bit number greater than 16 does not reduce the error, on the contrary, bit number smaller dramatically increases the error, as shown in Figure 6 b) in the case the bit number is equal to 12.

By considering superimposed noise to the signal amplitude, the error increases. The maximum error is lower than

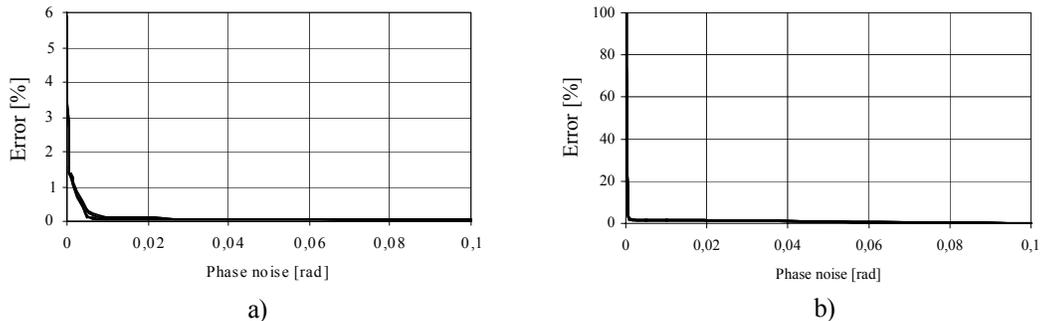


Figure 6 Percentage error trend of the IQ based algorithm versus the phase noise for sinusoidal carrier and demodulated signals in the case a) ideal ADC with 16 bit and b) ideal ADC with 12 bit.

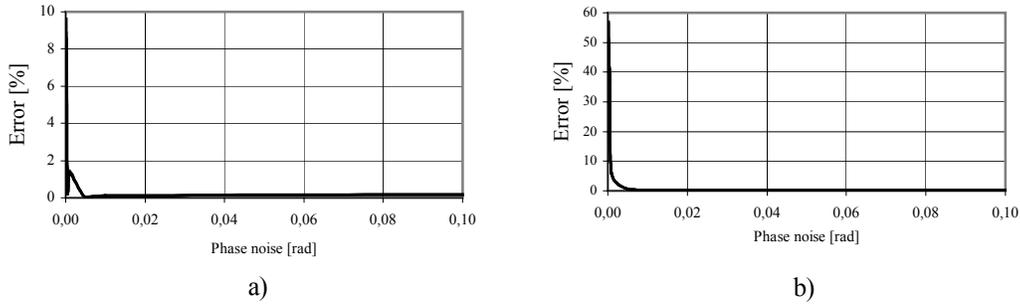


Figure 7 Percentage error trend of the IQ based algorithm versus the phase noise in the case SNR in the range [100, 150] dB, phase noise constituted by two sinusoidal signals at frequency equal to 500Hz and 700 Hz, respectively, and a) ideal ADC with 16 bit and b) ideal ADC with 12 bit.

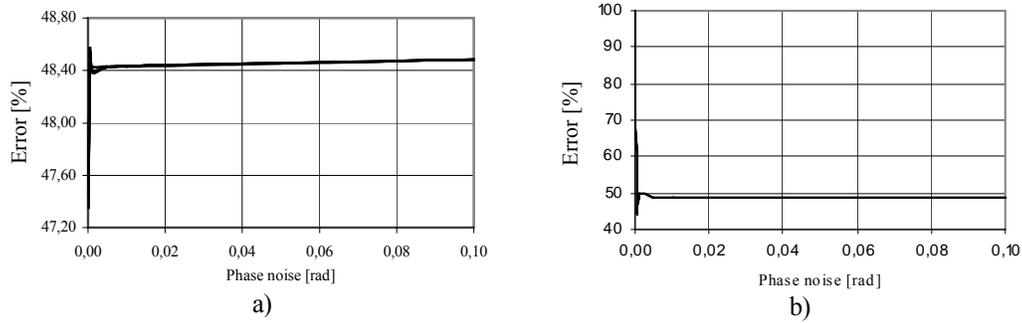


Figure 8 Percentage error trend of the FFT based algorithm versus the phase noise in the case a) ideal ADC with 16 bit and b) ideal ADC with 12 bit and SNR in the range [100, 150] dB.

10%, as shown in Figure 7 a), in the case (i) both the noise is superimposed and the phase noise is constituted by two sinusoidal signals at different frequency, and (ii) the bit number is equal to 16. On the contrary, bit number smaller dramatically increases the error, as shown in Figure 7 b) in the case the bit number is equal to 12. The results shown in Figure 7 a) and b) refers to: (i) the values of the superimposed noise are established so as the SNR was in the range [100, 150] dB, and (ii) the two sinusoidal signals representing the phase noise have frequency equal to 500 Hz and 700Hz, respectively. In this manner the low pass filter used for the signal demodulation does not influence the phase noise characteristics.

In the case the FFT based algorithm is considered, the maximum error is lower than 10%, as shown in Figure 8 a), in the case (i) both the noise is superimposed and the phase noise is constituted by only one sinusoidal signal, and (ii) the bit number is equal to 16. On the contrary, bit number smaller dramatically increases the error, as shown in Figure 8 b) in the case the bit number is equal to 12. The other operating conditions are similar to those of Figure 7.

Other numerical tests are performed on the 4-PSK modulated signals of the UMTS standard [11], [12] in order to verify that the effect of the band limiting of the real filter does not influences the algorithm performance.

IV. Conclusions

An algorithm for the phase noise measurement in the single carrier digital modulated signals has been presented. The algorithm operates in the IQ plane and can be used to measure the phase noise both on the carrier signal and on the demodulated signal.

The theoretical aspects and the properties of the proposed algorithm have been highlighted and discussed in comparison with the FFT based algorithm.

The numerical tests support the theoretical developments and denote that the algorithm is particularly attractive robust and accurate if compared with the frequency domain analysis.

ACKNOWLEDGMENTS

The authors wish to thank Prof. Pasquale Daponte for his helpful suggestions and active interest during all the phases of the research.

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