Phase Noise Effect on the Minimum Shift Keying Modulator

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***Abstract*— It is essential to synchronize the receiver and the transmitter during any transmission. In a given receiver, the sensitivity of the synchronization system is usually higher than the sensitivity of the detection system. The performance of the synchronization system and the detection system in a given receiver depends on the signal to noise ratio at the input of the receiver. Phase noise must be carefully considered when applying any signal processing method, which involves synchronization. The effect of amplitude noise on the sensitivity of the receiver is a well-studied subject. On the other hand, the impact of phase noise on the phase synchronization process is not well-studied in literature. In this paper, the effect of phase noise on the Minimum Shift Keying (MSK) modulator is studied. The Bit Error Rate (BER) is used to demonstrate the impact of the different phase noise levels. Based on the simulation results we can conclude that the effect of phase noise on the synchronization system is negligible.**

Keywords- phase noise; synchronization; sensitivity; signal processing; time synchronous averaging; Internet of Things; Low Power Wide Area Network.

I. Introduction

The communication range and power efficiency are considered among the most critical issues for system design in the domain of Low Power Wide Area Networks (LPWAN) technologies dedicated to the Internet of Things (IoT) communication.

All LPWAN standards and technologies, such as SigFox [1], LoRa [2], Narrowband IoT (NB-IoT) [3], try to increase their efficiency in terms of both power consumption and data range. There are strict limitations by communication regulators like the Federal Communications Commission (FCC) [4] and the European Telecommunications Standards Institute (ETSI) [5]. These factors are related directly to the receiver sensitivity. Increasing the receiver sensitivity improves the link budget, which increases (under certain circumstances) the propagation distance.

A well-known technique to improve the receiver sensitivity is to increase the bandwidth, which can be viewed as a solution in the frequency domain. For example, in the spread spectrum technique, a narrow-band signal spreads over a wider frequency band. The power remains the same, but the power spectral density decreased as the signal spreads over a larger band and the receiver sensitivity improvement is related to the spreading factor.

Another solution to increase the sensitivity of the receiver is to decrease the data rate. Retransmitting the signal and process it later in the receiver is an example of this method. This can be viewed as spreading the signal over the time of the transmission (a time-domain solution).

In [6], the Time Synchronous Averaging (TSA) method is proposed to increase the sensitivity of a digital receiver based on the signal retransmission. It is shown that the synchronization system limits the performance of the TSA method. A new synchronization method was developed later. The performance of the TSA method with this new synchronization method is presented in [7]. Processing the signals and extracting the synchronization information from the transmitted signal with very low Signal to Noise Ratio (SNR) (even signals with SNR smaller than 1) is possible with this new synchronization method. TSA method is widely used in communications [8], medicine [9], mechanics [10], electronics and all scientific fields which treat periodic weak signals corrupted by noise [11].

Generally speaking, in the TSA method, the sampling is initiated by a trigger pulse as an input to the analyzer. These trigger pulses must be synchronized with the periodic signal. Time alignment is an essential parameter to the analysis of the repetitive signals, especially in the TSA method [12].

The efficiency of the TSA method is limited by the synchronization of the received data blocks. Synchronization is divided into synchronization in phase and frequency. Phase noise impacts the synchronization by varying the length of the repetitive data. The oscillator phase noise is presented briefly in Section II. Section III presents the applied method to study and simulate the effect of phase noise. In Section IV, the simulation results for the effect of the phase noise on the MSK modulator are presented. In this section, the phase noise effect is also simulated for a given transceiver, and the results are compared with other RF components. We conclude the work in Section V.

II. Phase noise in local oscillator

While an amplitude noise impacts the signal amplitude, any random fluctuation in the phase of a waveform in the frequency domain is presented by phase noise. Oscillator

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imperfection is one of the primary sources of phase noise. The noise in the local oscillator could be some multiplicative phase distortion during the up/down conversion at the transmitter and the receiver. The intensity of this noise depends on the quality of the RF component used in the transmitter/receiver.

Phase noise could be regarded as either natural phase noise caused by the local oscillator itself or "external" phase noise caused by vibration. In both cases, it is an essential problem for dynamic applications. The natural phase noise is mostly because of the oscillator's frequency instabilities. It is relevant for both static and dynamic applications. Any net changes in phase angle will result in an inaccuracy in the output frequency. The stability of the output frequency of the local oscillator is essential for any synchronization method. The output signal of a typical oscillator in the presence of the amplitude and phase noise is:

$$V(t) = A_0 \sin(2\pi f_0 \, t + \Delta\emptyset(t)) \quad (1)$$

A_0 is the nominal peak voltage and will establish the SNR and $\Delta\emptyset(t)$ represents the phase noise. Fig. 1 [13] presents the effect of phase noise on the oscillator output signal.

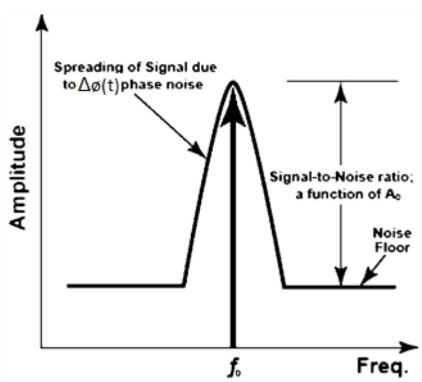

Figure 1. Oscillator output signal in the presence of phase noise

All oscillators have an amplitude limiting mechanism. The amplitude fluctuations are usually significantly attenuated and could be almost completely removed from the carrier at some frequencies [14]. Despite amplitude noise, the phase noise could not be reduced or filtered as it is very close to the carrier. However, phase noise in an oscillator can be reduced by various architecture choices and manufacturing technologies. The bipolar transistor and the Heterojunction Bipolar Transistor (HBT) are more efficient compared to the Field-Effect Transistors (FET), for example.

The Leeson model is essential to illustrate the phase noise spectrum concerning the carrier. The model is simple and effective and forms the theoretical basis of an oscillator phase noise. It is expressed as the following formula [15] and [16]:

$$S_{\Delta\emptyset}(f_m) = \frac{FkT}{2P_{si}}\left(1 + \frac{f_c}{f_m}\right)\left[1 + \frac{1}{f_m^2}\left(\frac{f_0}{2Q_L}\right)^2\right] \quad (2)$$

$S_{\Delta\emptyset}(f_m)$ is the single-sideband output phase noise power spectral density, F is the noise figure, k is the Boltzmann constant and equals to 1.38×10^{-23} (J/K), T is the absolute temperature, P_{si} is the input signal power, f_m is the offset frequency, f_c is the corner frequency, f_0 is the carrier frequency, and Q_L is the loaded quality facture. The phase noise curve based on (2) is illustrated in Fig. 2 [16].

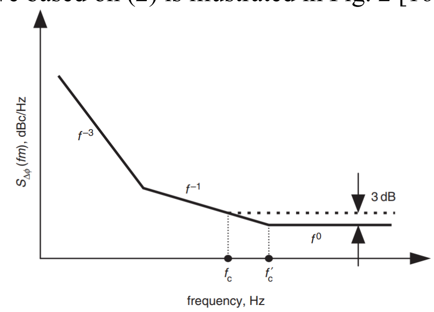

Figure 2. Phase noise curve of a high Q oscillator

The phase noise shows various behaviours depending on the frequency region and the distance from the carrier frequency. For example, a $1/f^3$ noise (30 dB per octave) is respected for the frequencies which are very close to the offset frequency. The Leeson model suggests increasing the resonator Q and signal amplitudes as a solution to reduce the phase noise. In this research, we are mostly focused on this region.

III. Methodology

Regarding the application goal (synchronization for the TSA method), the communication range, the receiver complexity as well as the energy efficiency, the MSK modulation technique was used in these simulations. The simulations were done in Matlab by generating the transmission data with time series. Amplitude noise and phase noise were added to the transmitted signal via Additive White Gaussian Noise (AWGN) channel and the phase noise block, respectively. The schematic of the simulation model is presented in Fig. 3. The simulation results are compared with theoretical BER for the MSK modulation to examine the accuracy of the proposed models.

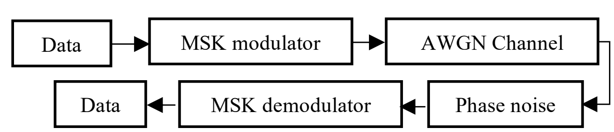

Figure 3. The presentation of the simulation model for the MSK modulation with Phase noise block in Simulink

BER graphs are used to demonstrate the results. The precision of the BER graph depends on the number of transmitted bits. The Monte-Carlo [17] method is a common technique for estimating the BER of a communication system. The number of required data symbols to achieve the desired accuracy is [18]:

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$$N \approx \frac{1}{\sigma_n^2 p_e} \quad (3)$$

σ_n^2 is the normalized variance of the estimation error and P_e is the desired bit error rate. The small value of BER requires a considerable number of transmitted symbols. Otherwise, the estimation variation shall be significant when the error is too small. For example, $N \approx 100/p_e$ is needed while counting 100 errors for $\sigma = 0.1$. Therefore, at least 10^8 bits are needed to study a system with BER of 10^{-6}.

The BER was calculated by comparing the received and the transmitted signals. Fig. 4 presents the BER result with no additive phase noise in comparison with the theoretical BER graph of the MSK modulation. From this figure, the reliability of simulation models can be justified. The BER result from the proposed simulation method follows precisely the theoretical curve of the BER of the MSK modulation. To calculate the BER with higher precision, we need to transmit and process more bits, which will increase the time of calculation significantly. The difference between the two graphs of BER at the very low BER value is due to this issue.

IV. Simulation Results

The BER graphs at different phase noise levels were traced for different values of the bit energy over the noise variance (E_b/N_0) to study the effect of phase noise on the efficiency of the communication systems in terms of BER for the MSK modulation. In each run of the simulation, E_b/N_0 varied from 1 to10 dB for a constant level of phase noise. In Fig. 5, the BER for different values of Phase Noise Level (PNL) from -96 to -80 dBc/Hz are presented. These results are compared with the BER for the MSK modulation in theory. By varying the phase noise level from -96 dBc/Hz up to -80 dBc/Hz, the bit error rate varies from almost the theoretical BER (for -96dBc/Hz) to the weakest BER result (at -80 dBc/Hz). The effect of phase noise on the MSK modulator is negligible for PNL equal or below -90 dBc/Hz,.

It is possible to simulate the phase noise effect for a specific RF component. In this case, a set of different phase noise levels are attributed to different frequencies. This information usually comes with the RF component datasheet. The precision of the simulation increases by having more data about the component phase noise level at different frequencies.

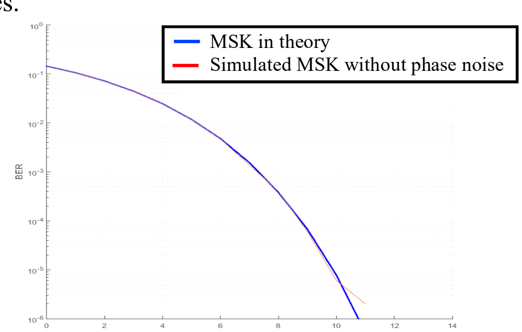

Figure 4. BER of the MSK modulation in theory (blue) compared with simulation result without phase noise (red)

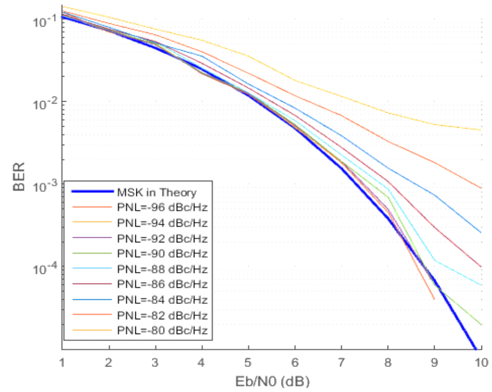

Figure 5. Phase noise effect on the MSK modulator, PNL from -96 to -80 dBc/Hz

Here, we consider the phase noise level for ADF-7021-V, which is a standard RF transceiver. The frequency offset were: [10Hz, 100Hz, 1000Hz] and the corresponding phase noise level for these frequencies were: [-71.5, -82, -92.5] dBc/Hz. Fig. 6 presents the result of the simulation in the presence of phase noise (in yellow) and without phase noise (in orange), in comparison with the theoretical BER for the MSK modulation (in blue).

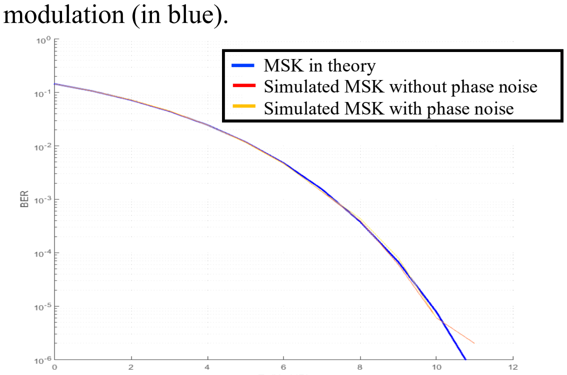

Figure 6. Simulated effect of phase noise on ADF7021 transceiver (without phase noise (red) and with Phase noise (orange))

The simulation results with and without phase noise are almost the same. As we can see, the phase noise does not have a significant impact on the BER of the MSK modulation.

These results should be compared with the phase noise level of other RF components. Tables I, II and III present the phase noise level for a standard RF transceiver, a mixer and a synthesizer, respectively. From these tables, we can note the maximum phase noise level of presented components and compare their phase noise level with the simulation results. The highest phase noise level in these tables is equal to -106 dBc/Hz for Si4464 at 460 MHz with ±10 kHz offset.

Respecting the simulation results, we conclude that the impact of the phase noise on the MSK modulator is negligible. This conclusion is proven with experimental tests for the transmission of a very noisy signal (SNR≈0.3dB). The results of experimental tests were published in [7].

TABLE I. PHASE NOISE LEVEL FOR A GIVEN RF TRANSCEIVER

Device number	Fabricant	Description	Frequency bands	Receiver Sensitivity	Phase noise in 460 MHz (dBc/Hz)	Phase noise in 169 MHz (dBc/Hz)
Si4464	Silicon Labs	high-performance, low-current transceivers	from 119 to 1050 MHz	–126 dBm at 500 bit/s	±10 kHz offset: -106 ±100 kHz offset:-110 ±1 MHz offset: -123	±10 kHz offset: -111 ±100 kHz offset:-116 ±1 MHz offset: -135

TABLE II. PHASE NOISE LEVEL FOR A GIVEN RF SYNTHESIZER

Device number	Fabricant	Description	Frequency bands	RF1 Phase Noise (dBc/Hz)	IF Phase Noise (dBc/Hz)
Si4123	Silicon Labs	Dual-band RF synthesizer with integrated VCO	RF1: 900 MHz to 1.8 GHz IF: 62.5 to 1000 MHz	100 KHz offset: -110 1 MHz offset: -132	100 KHz offset: -117 1 MHz offset: -134

TABLE III. PHASE NOISE LEVEL FOR A GIVEN RF MIXER

Device number	Fabricant	Description	LO Frequency	Phase noise level (dBc/Hz)
ADRF6655	Analog Devices	High dynamic range active mixer with integrated PLL and VCO.	1330 MHz	±100 kHz offset:-114 ±1 MHz offset: -138

V. CONCLUSION

LPWAN, as a novel communication paradigm, has been investigated as a solution which improves the communication range while enhancing power efficiency. These parameters can be enhanced by increasing the sensitivity of the receiver. Any variation in the frequency stability of the local oscillator has an impact on synchronization. In this article, the effect of phase noise was studied on the MSK modulator. The results of the simulation model were first compared to the theoretical result to verify the reliability of the proposed model. Various phase noise levels were analyzed and the results were compared with standard RF components. BER was used to compare the effect of phase noise for different signal energy levels. The simulation model was customized to study a specific RF transceiver (ADF7021).

By comparing the phase noise level for standard RF components and the simulation results, we can conclude that the effect of phase noise on the MSK modulator is negligible. Performing the TSA method during experimental tests on a very noisy signal (SNR around 0.3dB) presents the same results.

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