

# Analysis of Circuit Noise and Non-ideal Filtering Impact on Energy Detection Based Ultra-Low-Power Radios Performance

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**Abstract**—With the coming of age of the Internet of Things (IoT), demand on ultra-low power radios will continue to boost tremendously. Circuit imperfections, especially in power hungry blocks, i.e. the local oscillators (LO) and band pass filters (BPFs), pose a real challenge for ultra-low power (ULP) radios designers considering their tight power budget. This paper presents an investigation on the effects of circuit non-idealities on the bit-error rate (BER) performance of On-off keying (OOK) and Gaussian Frequency-shift Keying (GFSK) energy detection based wakeup radios. In particular, this paper analyzes the impact of phase noise and frequency offset in the LO, BPFs bandwidth and roll-off, noise figure (NF) on ULP receivers’ performance. The paper contributes to the ongoing research in designing ULP wireless nodes by demonstrating the tradeoffs between these non-idealities and the receiver’s sensitivity level and selectivity and show some design guidelines for energy detection (ED) based ULP radios.

**Index Terms**— Phase Noise, Ring Oscillators, On-Chip BPF, Bit Error Rate, Low Power Radios, Wakeup Radios.

## I. INTRODUCTION

ENABLING ubiquitous receivers for IoT applications requires additional effort at both the system architecture and circuit design levels. The main challenge is to minimize the power consumption while still having an adequate sensitivity level in frequency congested spectrum, and using highly integrated solutions [1]. One increasingly popular approach to reduce the receiver’s power consumption is to use a mixer-first architecture. This is because RF low noise amplifiers (LNAs) power consumption is usually in the milliwatt range and hence they are avoided in ULP radios to save power [2]. As a result, the receiver power becomes dominated by the local oscillator (LO) [3]. Integrated solutions for interference rejection can also take a significant proportion of the receiver power, especially in the case of narrower channel bandwidths [4,5].

In practice, each of the receiver blocks show some degree of non-ideality. Optimizing the design of these blocks for closer to

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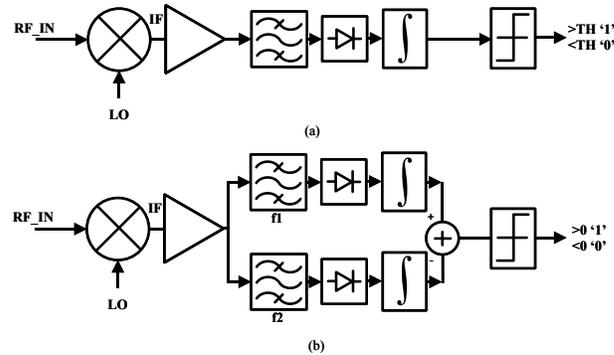


Fig. 1 Block Diagram of ED based mixer-first receiver for (a) OOK and (b) FSK

ideal performance can come at the expense of a higher power consumption, which represents a challenge for ULP receivers design. However, since certain blocks make up a higher proportion of the total power, this analysis is focused on exploring the design trade-offs for these blocks to facilitate the design of power efficient receivers for energy stringent applications.

In this paper, we analyze these circuits’ imperfections for two types of modulation schemes: On-Off-Keying (OOK) and Frequency-shift-keying (FSK). These are selected because they are the most commonly used in ULP receivers [6]. OOK can be very attractive when designing ULP radios due its simplicity. Also, FSK/GFSK are widely used nowadays in many existing communication standards. Simplified block diagrams for mixer-first energy detection (ED) based OOK and FSK radios used for this analysis are shown in Fig. 1.

The rest of the paper is organized as follows: Section II starts with a brief description about the non-idealities which will be analyzed in this paper. Section III presents the receiver model including the different sources of non-idealities. The implications of these imperfections are analyzed in Section IV. Finally, the conclusion is drawn in section V.

## II. BACKGROUND

This analysis addresses some non-idealities in the main power hungry blocks in ULP receivers. In this section, the

sources of these non-idealities within the scope of this paper are presented.

### A. Bandpass Filters

The frequency spectrum which ULP radios operate in is shared with other transmitting devices, and hence, interference can degrade the receiver performance. On-chip higher order filtering of adjacent-channel signals can be very expensive in terms of power since it usually requires more stages, and higher-Q filters. This analysis aims to explore the implications of the filter bandwidth and order on the bit-error-rate (BER) performance and blocker rejection ratio of the receiver. The term “filter bandwidth” is defined as the 3-dB bandwidth throughout this analysis.

### B. LO

LC oscillators are used widely in transceiver design since they enjoy better frequency stability and low phase noise when compared with ring oscillators [7]. However, unlike ring oscillators, their power consumption doesn't scale with more advanced technology [8]. This led to more interest in using ring oscillators in ULP radio design to take advantage of technology scaling to minimize the power consumption. On the other hand, ring oscillators still suffer from lower frequency stability and higher phase noise which pose a challenge in lowering the power consumption. Since there is a clear trade-off between the oscillator power consumption and its phase noise [9], the impact of phase noise and LO frequency offset on energy detection receivers is analyzed in this paper to help minimizing the oscillator power consumption while still meeting the target specifications.

### C. Analog blocks along signal path

Since RF LNAs are usually avoided to achieve sub mW receivers, more attention has to be paid to the receiver noise figure (NF). The overall NF in mixer-first receivers is dominated by the mixer and the first intermediate-frequency (IF) stage given large enough gain is provided to the input signal. Low noise RF mixers, as the receiver's first stage, have been proposed in the literature [10]. However, they require more RF buffers to drive the multi-phase LO outputs which are part of the mixer design to reduce the NF, thus increasing power. This shows another clear trade-off between the power consumption and improving the gain/NF performance of the receiver. In section IV, the required  $E_b/N_0$  constant BER is demonstrated under multiple other circuit imperfections. This can provide a guidance to estimate the required NF for certain sensitivity target.

## III. RECEIVER MODELING

Fig.2 shows the model of an energy detection based ULP wakeup radio used in this analysis. First, the input RF signal is down converted to baseband frequency assuming ideal mixing with noisy oscillator. Then, the signal is amplified using ideal amplifier model. The signal is then filtered by non-ideal BPF. After that and using ideal blocks, the signal is rectified before integrating the energy over the symbol period. Finally, a 1-bit comparator is used to digitize the signal. The discrete time simulation is done in MATLAB with an oversampling ratio of 250. Blocks with imperfections that are not discussed in this

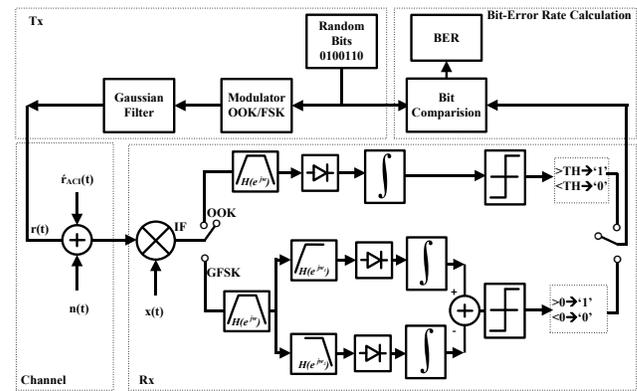


Fig.2 Block Diagram of the System Model used in this analysis for (a) OOK and (b) GFSK

paper are simulated with ideal models and are not within the scope of this paper.

The oscillator phase noise is modeled by shaping the noise in the frequency domain before converting the oversampled signal into the time domain. The phase noise shaping relative to the carrier is similar to what is shown in [11]. Phase noise values ranging from -80 dBc/Hz to -110 dBc/Hz at 1MHz offset are simulated. This range is representative of the phase noise change that could be achieved by moving from a ring oscillator to an LC oscillator. An LO frequency offset implies a shift in its center frequency from the one desired.

The oversampled signal is then filtered by a Butterworth digital filter which is used to simulate the analog filter in ULP radios. Different practical filter bandwidths and orders are simulated to get better insight into how bandwidth trades off with ED ULP radios performance. Filters of orders: 1, 2 and 3 are simulated since higher orders would be a challenge to design in highly integrated ULP wake-up radios.

Additive white Gaussian noise (AWGN) is added to simulate the added noise by both the channel and the receiver blocks along the signal path. Theoretical optimum receivers for OOK and non-coherent FSK are already presented in the literature [12]. Since the goal of this analysis is to simulate a suboptimum energy detection based receivers including circuits' imperfections, a degradation in  $E_b/N_0$  is expected for a certain target BER.

The received signal  $r(t)$  is expressed as:

$$r(t) = Ae^{j(\omega_c + \omega_i)t} \quad (1)$$

where  $A$  is the signal peak amplitude,  $\omega_c$  is the carrier frequency,  $\omega_i$  represents the frequency modulation in the case of GFSK. The adjacent channel interference  $r_{ACI}$  has a similar form, but with a different amplitude and carrier frequency. The additive noise  $n(t)$  has a normal distribution which can be expressed as  $\mathcal{N}(0, \sigma^2)$ .

The LO signal  $x(t)$  can be expressed as:

$$x(t) = e^{j(\omega_0 + \varepsilon)t + \varphi(t)} \quad (2)$$

where  $\omega_0$  is the oscillating signal frequency,  $\varepsilon$  is the frequency offset and  $\varphi(t)$  which is a random variable representing the LO phase noise.

#### IV. ANALYSIS OF RECEIVER SENSITIVITY AND SELECTIVITY

In this section, the impact of the circuits' imperfections on the receiver sensitivity is analyzed first. Then, the analysis of their impact on selectivity is discussed later in this section.

##### A. Sensitivity Analysis

##### 1) Effect of Bandpass Filter Bandwidth and Order

The influence of the filter to signal bandwidths ratio  $BT_{\text{symbol}}$  and the filter order is presented in this subsection. The required  $E_b/N_0$  for constant BER of  $10^{-3}$  is used to compare the receiver performance with different filter specifications. The simulation results are shown in Fig.3 and Fig.4 for OOK and GFSK respectively. The two figures can be divided into two main regions. First, with  $BT_{\text{symbol}} \ll 1$ , part of desired signal energy is filtered which leads to a higher  $E_b/N_0$  requirement to achieve constant BER performance. On the other hand, in the second region, where  $BT_{\text{symbol}} \gg 1$ , the in-band noise dominates and higher order filters achieve optimum BER performance. For GFSK, and as shown in Fig.4, relaxed filters can degrade the receiver sensitivity performance compared with higher order filters. This is a result of leaked energy increasing with relaxed filters from the frequency representing the other bit. In general, it can be concluded from these two figures that there exist an optimum  $BT_{\text{symbol}}$  point which maximizes the receiver sensitivity for a given modulation specification. The optimum  $BT_{\text{symbol}}$  point doesn't depend strongly on the phase noise level, but it sets the minimum  $E_b/N_0$  for constant BER of  $10^{-3}$ . The optimum  $BT_{\text{symbol}}$  is 1 and 0.5 for OOK and GFSK, respectively. For the rest of this section, all simulations are based on the optimum  $BT_{\text{symbol}}$  of for modulation scheme.

##### 2) Effect of Oscillator Phase Noise and frequency offset

The impact of phase noise on the receiver performance can vary significantly based on many factors: i.e. filter to signal bandwidth ratio, filter order, and modulation characteristics. Based on Fig.3 and Fig.4, it can be observed that as the filter bandwidth becomes higher than the signal's, the receiver sensitivity penalty because of phase noise becomes less significant. This is attributed to phase noise spreading the signal energy over a wider bandwidth which requires a higher filter bandwidth for the same BER performance. In order to quantify phase noise impact for different filter orders and modulation characteristics, the required  $E_b/N_0$  for a BER of  $10^{-3}$  is simulated for each parameter.

The performance of OOK receivers under phase noise is shown in Fig.5. Phase noise levels as high as -80 dBc/Hz at 1MHz offset can be tolerated without any major sacrifice with respect to the receiver sensitivity. This implies that the LO power can be significantly reduced by relaxing its phase noise while having the same receiver sensitivity.

Fig.6 shows the phase noise impact on a GFSK receiver assuming a modulation index of 0.5 as required in the Bluetooth Low Energy (BLE) specifications. Unlike in OOK, phase noise has a much stronger impact on BER performance. Fig.7 demonstrates that increasing the modulation index can significantly push the limits to phase noise levels higher than -80 dBc/Hz at 1MHz offset. In that case, receivers using GFSK with relaxed low power ring oscillators and modulation index of 1 can be used since they tolerate a phase noise of -77 dBc/Hz

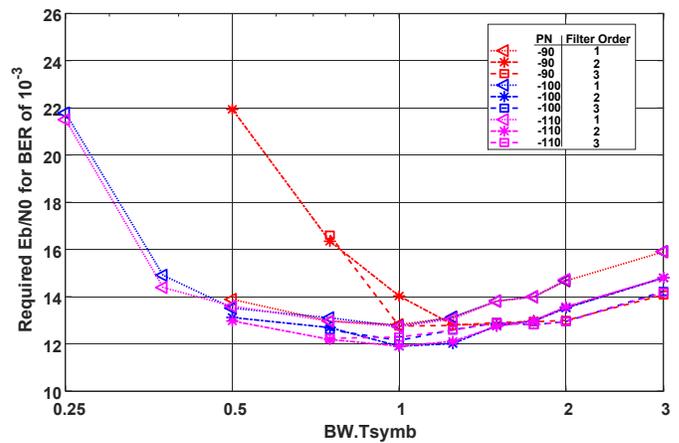


Fig.3  $BT_{\text{symbol}}$  impact on OOK performance for different Phase Noise Levels at 1MHz offset (dBc/Hz) and Filter Orders

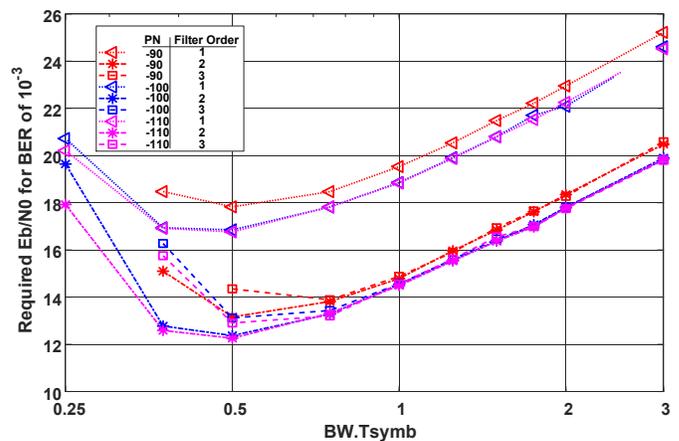


Fig.4  $BT_{\text{symbol}}$  impact on GFSK performance for different Phase Noise Levels at 1MHz offset (dBc/Hz) and Filter Orders

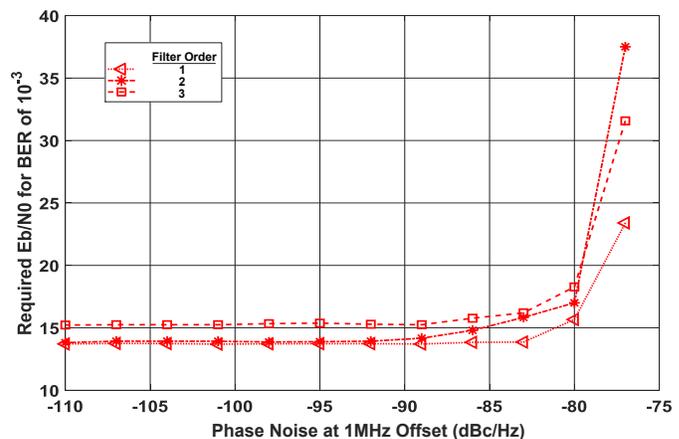


Fig.5 Impact of Phase noise on OOK performance for different Filter Orders

at 1MHz with less than 3 dB sensitivity penalty compared with higher power LC oscillators. The reason higher modulation index helps in relaxing the phase noise specification is that it corresponds to higher frequency deviation for GFSK, and hence can tolerate more signal spreading caused by LO phase noise. However, this means lower frequency spectral efficiency.

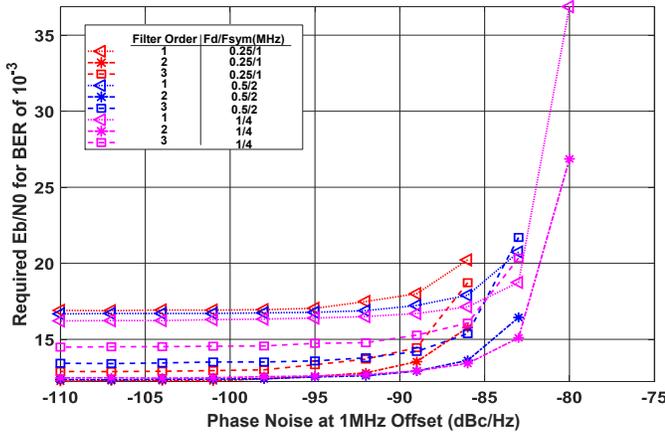


Fig.6 Impact of Phase noise on GFSK performance for different Filter Orders and Frequency Deviations with Modulation Index =0.5

Besides LO frequency stability, which can be quantified by its phase noise, LO frequency accuracy will also affect the receiver sensitivity. Fig.8 shows the impact of LO offset in terms of the excessive required  $E_b/N_0$  for constant BER of  $10^{-3}$  for OOK. The performance degradation is a function of the frequency offset over filter bandwidth ratio. For GFSK, Fig.9 shows that LO offset impact depends on the frequency offset over frequency deviation ratio. In both modulation schemes, relaxed filters help tolerate more offset in the LO frequency. This can result in a major power reduction in the LO calibration power budget. When lower GFSK modulation indexes are used, i.e.  $\ll 1$ , the LO offset specification become much stricter, which is a similar conclusion to what was found with respect to phase noise. When phase noise is considered in addition to frequency offset, OOK outperforms GFSK as shown in Fig.8 and Fig.9. This higher sensitivity to LO imperfections in GFSK is a results of it relying on comparing the energy of two frequency bands that can shift with any change in LO frequency.

### 3) Effect of Noise Figure

The maximum receiver noise figure to achieve a certain target sensitivity can be calculated for a given  $BT_{\text{sym}}$  product, phase noise level, and filter order based on the required  $E_b/N_0$  presented in this section. The maximum receiver  $NF_{\text{max}}$  is given by:

$$NF_{\text{max}}(\text{dB}) = S_n(\text{dBm}) - (-174(\text{dBm/Hz})) - \frac{E_b}{N_0}(\text{dB}) + 10 \log_{10}(T_{\text{sym}}) \quad (3)$$

where  $S_n$  is the target sensitivity in dBm, and  $-174 \text{ dBm/Hz}$  is the thermal power density at room temperature. Based on Eq.3, any improvement in the NF of the receiver will relax required  $E_b/N_0$  for certain target receiver sensitivity.

### B. Selectivity Analysis

The second important measure of the receiver performance is the receiver selectivity. In this analysis, that is quantified by simulating the signal to interference ratio (SIR) at different blocker frequency offsets from the desired signal. The blocker has the BLE modulation characteristics. Fig.10 and Fig.11 show the SIR for OOK and GFSK respectively. These results imply

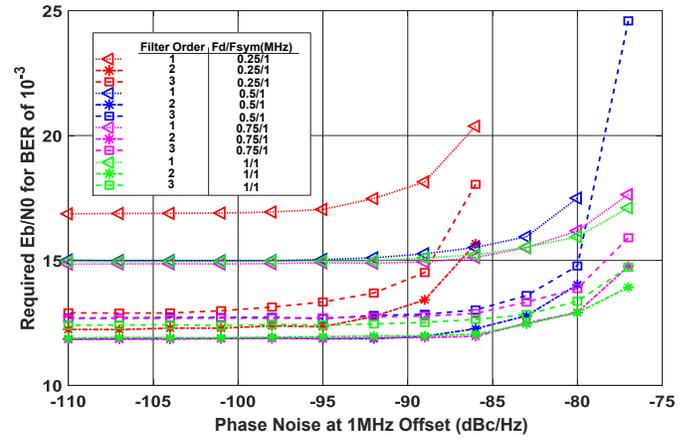


Fig.7 Impact of Phase noise on GFSK performance for different Filter Orders and Modulation Indexes

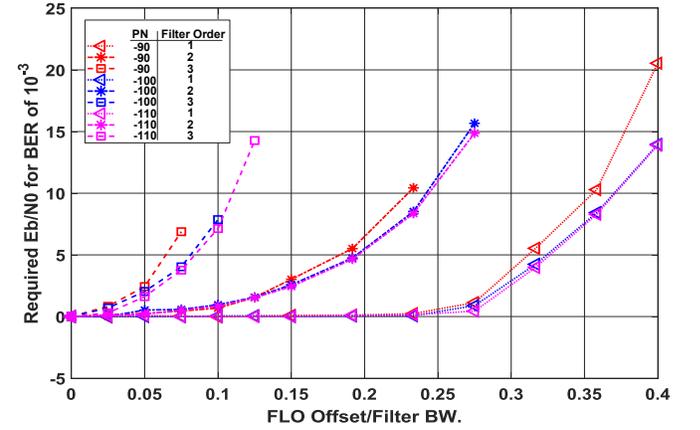


Fig.8 Impact of LO Offset on OOK performance for Phase noise Levels at 1MHz offset (dBc/Hz) and Filter Orders

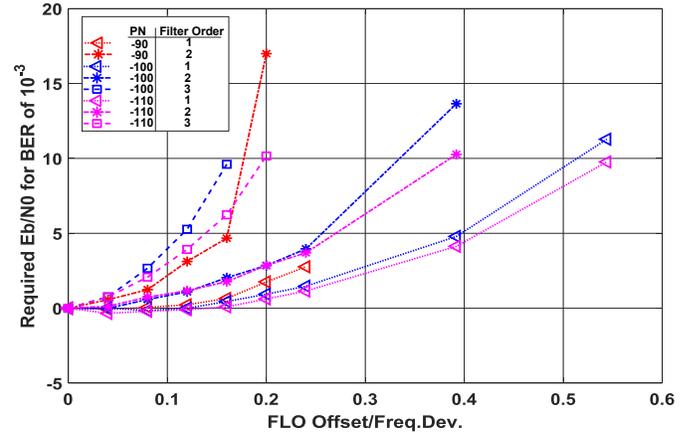


Fig.9 Impact of LO Offset on GFSK performance for Phase noise Levels at 1MHz offset (dBc/Hz) and Filter Orders

that the filter order and the phase noise level have an impact on the blocker rejection performance of the receiver. When the Bluetooth-low-energy standard is used, the channel bandwidth is 2MHz and hence, both figures show the first five adjacent channels.

When comparing the SIR levels of GFSK receivers in Fig.11 with the interference performance in the BLE 5.0 standard also shown in Fig.11, only a higher order filter with low phase noise level can meet the blocker performance specified in the

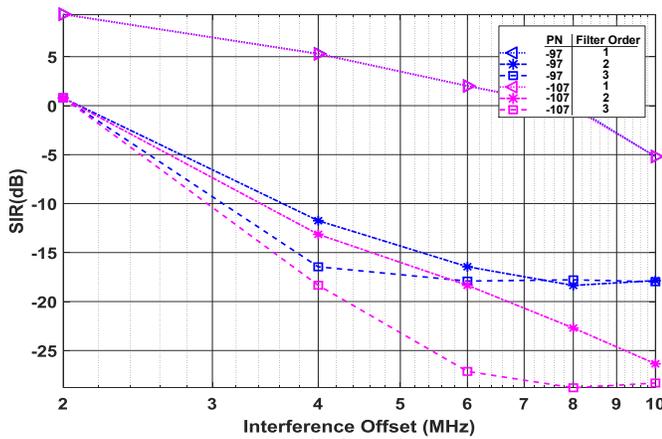


Fig.10 SIR for OOK receivers with different Phase noise Levels at 1MHz offset (dBc/Hz) and Filter Orders

standard. With existing integrated CMOS solutions, this presents a challenge in the design of ULP receivers since such solutions have a power consumption that starts in the order of hundreds of microwatts [13]. Moreover, when designing filters with sharper roll-off to improve the blocker rejection performance, other factors become more critical, such as LO offset. As a result, the overall power consumption can increase significantly. Although off-chip filtering could be used, it's not an attractive option when considering IoT applications where highly integrated solutions are essential.

## V. CONCLUSION

In this paper, an analysis of some critical circuit imperfections and their impact on ULP receivers is presented. First, for a given modulation specification there exists an optimum  $BT_{sym}$  that maximizes the receiver sensitivity. For instance, the optimum bandwidth for ED based OOK receivers is the same as its input signal data rate. Designing an LO with a phase noise better than a certain limit makes little to no impact on ED based receivers' sensitivity. The phase noise limit is a function of the modulation specification and filter order. For example, for GFSK, the LO phase noise can be relaxed to -85 dBc/Hz, which can be achieved using a low power ring oscillator, by increasing modulation index to 1 while maintaining the same sensitivity performance. Because of the trade-off between phase noise and power, this will result in substantial power savings.

For selectivity, when designing the filter roll-off, a trade-off exists between the receiver SIR performance and its power consumption. Also, this analysis showed that highly integrated ED based ULP radio architectures suffer from weak blocker rejection and still cannot meet popular wireless communication standards tailored for lowering the power consumption like Bluetooth-low-energy. To meet the demand of future radios designed for IoT applications, more innovation is needed in both system and circuit levels to overcome this challenge. In particular, new wake-up oriented wireless communication standards which can tolerate higher blocker power will bridge the gap between the existing ULP radios and communication standards. One option to achieve such relaxed blocker performance would be to invert the current standard from repeatedly transmitting advertising packets, which lead to a

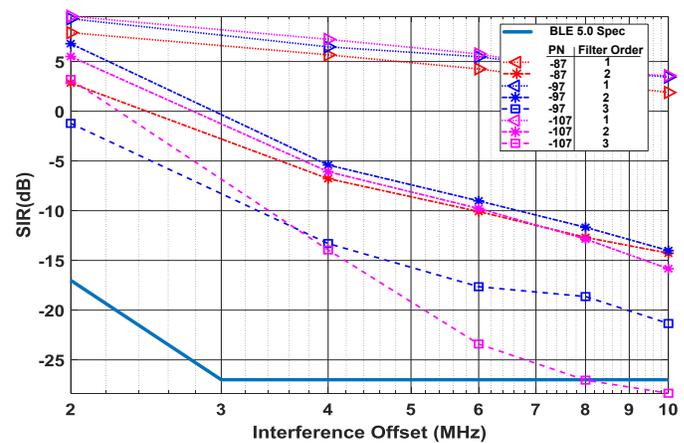


Fig.11 SIR for GFSK receivers with different Phase noise Levels at 1MHz offset (dBc/Hz) and Filter Orders

more congested spectrum, to listening and checking for pre-define wake-up message.

To conclude, ED based ULP receivers, by using the appropriate modulation characteristics and the optimum filter bandwidth, can achieve high sensitivity in the presence of LO imperfections. However, they suffer from worse than typical interference performance specified in common wireless communication standards. The interference performance can be improved at the expense of higher power consumption.

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