An Analysis of Phase Noise Requirements for Ultra-Low-Power FSK Radios

Xing Chen, Hun-Seok Kim, David D. Wentzloff
University of Michigan, Ann Arbor, MI
{chenxing, hunseok, wentzlof}@umich.edu

***Abstract*—This paper presents an analysis of the influence of phase noise (PN) on FSK radios and derives the total PN requirement for a low power FSK link based on Bit Error Rate (BER) performance. A simple noise model is built, including phase noise and white noise from the AWGN channel, to analyze its influence on the BER of an ULP FSK RX. It shows that to achieve a 10^{-4} BER, the minimum PN requirement can be more relaxed than current synthesizer designs. The trade-off between PN, data rate, and frequency deviation of FSK modulation is also studied, showing how bandwidth can be traded for relaxed PN while maintaining the same spectral efficiency (bits/Hz). This result implies we could migrate from LC-VCOs to ring oscillators with a simple PLL for wireless communication using FSK and significantly reduce the power of radios. A chip was fabricated to test the accuracy of the model at different PN levels, showing agreement among theoretical analysis, simulations, and measurements.**

***Index Terms*— Phase Noise, FSK, Bit error rate, Ring oscillators, Radios, Body Area Networks.**

I. INTRODUCTION

Phase noise (PN) has always been a fundamental factor in the design of wireless communication systems. To meet the PN requirement, a relatively large amount of power is consumed in the local oscillator (LO), buffers, and RF frequency synthesizer. This is especially true for ultra-low power (ULP) radios, where the LO typically consumes 50%-80% of the total power. Some pulse modulations such as OOK allow us to design an ULP radio with a free running ring oscillator (RO) with relatively poor PN, or no oscillator at all. However, the low resilience of OOK to noise and interference limits the scaling of these radios for large numbers of personal area network nodes in IoT applications.

FSK is a good choice in ULP personal area network designs (e.g. Bluetooth) but the power consumption of FSK radios is at least 10x higher than radios based on OOK or PPM, because of the LO requirements. Fig. 1 shows the most recent publications on low power FSK receivers at frequencies above 400MHz, including BLE compliant radios [1]. It can be seen that all of them consume more than 100µW, and those with quadrature LOs where phase accuracy and noise are critical consume more than 1 mW, regardless of what sensitivity levels they are at. The PLL based quadrature receivers, which normally require a good phase noise specification, are built with low phase noise LC-VCOs and high performance PLLs, while energy-detection based receivers consuming closer to 100µW use envelop detector architectures, where PN is not a big concern. Using advanced CMOS processes, it is now possible to synthesize GHz ROs that consume <10µW. Leveraging these in ULP FSK receivers would dramatically reduce their power. Thus, it will be extremely helpful to clarify the relationship between the PN requirement and its influence on FSK and enable us to intrinsically save radio power.

FSK modulation and its BER performance has been well studied since modern communication systems came into use [2], [3], but mostly on analysis in AWGN channel noise. [4] analyzed the effect of circuit imperfections and found that phase noise effectively adds a higher noise floor and only affects the BER when the carrier-to-noise ratio is high. However, it doesn't include a quantitative analysis of how phase noise directly affects the BER and which FSK parameter has a more significant impact on the phase noise requirement of a radio system. This paper analyzes the direct relationship of PN in a TX-RX link, as well as the PN profile in free-running LOs and locked PLLs, to FSK parameters such as frequency deviation (FD) and data rate (DR), and then offers a PN boundary for a given BER requirement for FSK radios.

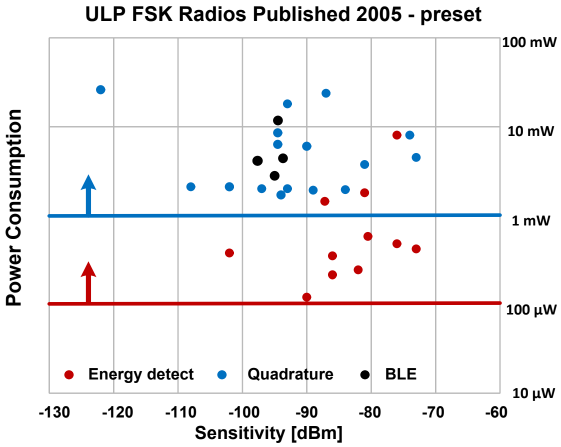

Fig. 1 Power consumption vs sensitivity of recent publications on ULP FSK receivers

This paper is organized as follows. Section II analyzes the PN effects on real time frequency variation. Section III offers a unified noise model and analyzes the PN vs BER influence through a simple FSK receiver assuming a matched filter implementation. Section IV compares the simulated results from the proposed model to measurement results at 2 different PN levels and verifies its accuracy. Finally, in section V, conclusion is drawn and a consideration of circuit choice and FSK modulation choice for ultra-low-power design is given.

II. PHASE NOISE ANALYSIS AND ITS EFFECTS TO FREQUENCY VARIATION

In order to clarify the relationship between PN (phase noise) and frequency deviation in FSK, it's necessary to find out the relation between PN and real time frequency variation. The real time frequency variation is related to period jitter but must be treated as a random process, and cannot be directly inverted. Period jitter is the standard deviation of the normally distributed clock period around its mean value. Assume on average the clock has a period of T and thus a frequency of $F = 1/T$, and due to phase noise, at a random point in time, the instantaneous relationship between period and frequency is:

$$\mathrm{T} + \Delta\mathrm{t} = \frac{1}{\mathrm{F} + \Delta\mathrm{f}} \qquad (1)$$

Which can be rewritten as:

$$1 + \frac{\Delta\mathrm{t}}{\mathrm{T}} = \frac{1}{1 + \frac{\Delta f}{F}} \approx 1 - \frac{\Delta f}{F} \qquad (2)$$

For RF frequency synthesizers, the center frequency is much larger than its frequency variations, thus by using the Taylor expansion, the relation can be further simplified as:

$$\Delta f \approx -F^2 \Delta t \qquad (3)$$

This indicates that frequency variation changes in the same way as period jitter. The frequency over time of a free running RO is measured using a Tektronix MDO4000C and shows that the distribution of frequency is Gaussian and that its standard deviation scales up with center frequency. This also implies that frequency variation and period jitter are ergodic and their time average is the same as the average over frequency or period space when there is no frequency drift.

The relationship of phase noise to period jitter has been well studied in [5]-[8] and the link between jitter to phase noise is:

$$\sigma_\tau^2 = \int_0^\infty S_\tau(f)df = \int_0^\infty \frac{S_\phi(f)sin^2\left(\frac{\pi f}{f_0}\right)}{(\pi f_0)^2}df \qquad (4)$$

Where $S_\tau(f)$ and $S_\phi(f)$ are the power spectral densities (PSDs) of jitter and random phase, respectively. When neglecting the influence of flicker noise, it could be further simplified as:

$$L(f) = \frac{\sigma_\tau^2 f_0^3}{f^2} \qquad (5)$$

Where $L(f)$ is the PN PSD. With the approximation from period jitter to real time frequency variation, the link between phase noise and frequency variation is:

$$L(f) \approx \frac{\sigma_f^2}{f_0 f^2} \qquad (6)$$

This result shows that whenever the frequency variation of an oscillator is doubled, the phase noise will increase by 6dB.

III. SYSTEM MODEL AND VERIFICATION

In order to verify the analysis of the phase noise influence on frequency variations and its impact on FSK parameters such as frequency deviation (FD) and data rate (DR), a simple TX - phase noise - RX model is built. White noise in circuits can either affect the phase noise or increase the noise floor while the AWGN channel noise only affects the noise floor. It is more straightforward to model the total additive noise together when designing a communication link, as shown in Fig. 2.

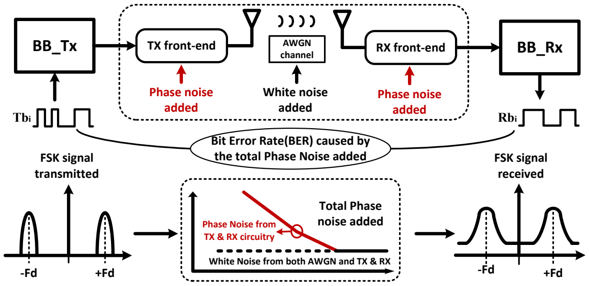

Fig. 2 TX-Phase Noise-RX model for BER analysis in FSK

Transmitted data are directly FSK modulated and sent to the noisy circuits and channel, where phase noise is added mostly from the local oscillators (LO), and the noise floor is increased by both. Then the noisy signal is sent to the RX baseband for demodulation and the BER is calculated. This will offer a direct relationship between just LO phase noise and BER. We assume a representative FSK receiver implementation with a digital phase discriminator and frequency domain matched filter as shown in Fig. 3.

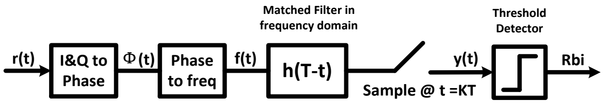

Fig. 3 Matched filter receiver for FSK

Noting that phase noise will be independently added together from both TX and RX, so from the design prospective, the phase noise specifications for each radio could either be set from the model with a 3 dB margin, if the same synthesizer is used for both, or that one (e.g. TX in a sensor node) be directly set from this model if the other one, say RX in the base-station, has a much better PN performance.

The simulation results of PN vs BER at different FSK FD and DR are shown below. Fig. 4 shows the phase noise added with different phase noise levels while the noise floor is kept the same at -110dBm, which is the same noise floor when capturing measured data with a MDO4000C spectrum analyzer. The phase noise is shaped by a simple type I order I PLL with a 1MHz BW to suppress flicker noise, thus the noise has a -10dB/dec rolloff in band and -20dB/dec rolloff out of band. The phase noise levels @ 1MHz offset are sampled as the X-axis for the PN vs BER plot. Fig. 5 shows how the BER changes with the FSK FD when the PN are kept the same for different traces. It shows that whenever the FSK frequency deviation is doubled, the phase noise requirement could be relaxed by 6dB to achieve the same BER, which agrees with previous analysis on phase noise over frequency variation. Meanwhile, if DR is doubled, as shown in Fig. 6, phase noise should be 3dB better to achieve the same BER. The reason is that when doubling the data rate, energy per bit will be halved and thus the total in band noise has to be reduced by 3dB to maintain the same E_b/N_0. The result is e.g. by increasing both the FSK frequency deviation (signal bandwidth) and the data rate by a factor of 2, the spectral efficiency remains constant (bits/Hz) however the PN specification is relaxed by 3dB, as shown in Fig. 7. This result favors wider bandwidth, higher datarate FSK for enabling ULP receivers using ROs.

It also shows that with a commercial standard such as Bluetooth Low Energy (BLE), in order to achieve a BER smaller than 10^{-4}, the total phase noise requirement is nearly 20dB higher than what is typically reported. For example, BLE 4.2 with a 1MSym/s DR and 250kHz FD only needs a simple type I PLL and a low power RO with -84dBc/Hz phase noise @ 1MHz (with some margin) to meet the BER requirement; compared to typical implementations of better than -105dBc/Hz @ 1MHz. For the newly released BLE 5.0 in high data rate mode (2x the FD and DR of BLE 4.2), the phase noise requirement is relaxed by another 3dB.

IV. MEASUREMENT VS SIMULATION

To verify the accuracy of the system model, more cases are simulated and 2 reference measurement tests are executed. A VSG is used to verify the case for very good phase noise performance and a fabricated chip with a free running RO is use to verify the case for very poor phase noise performance (but much lower power consumption). Fig. 8 shows the influence of both FSK FD and DR on the phase noise requirement. As can be seen for both cases, for a large range of phase noise levels, when FD is doubled, the phase noise requirement can be relaxed by 6dB. But for the influence of data rate, when phase noise is good, doubling DR will require more than a 3dB phase noise improvement.

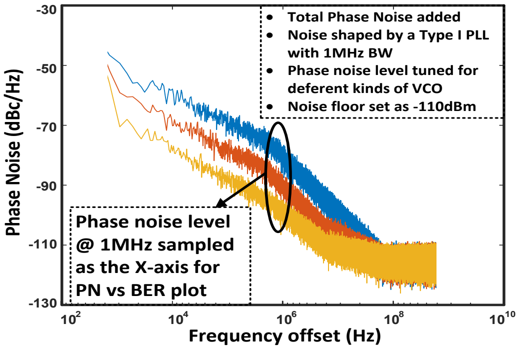

Fig. 4 Total phase noises at different levels for simulation

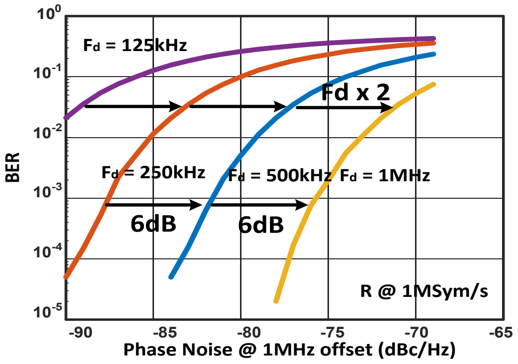

Fig. 5 BER vs PN for different frequency deviations

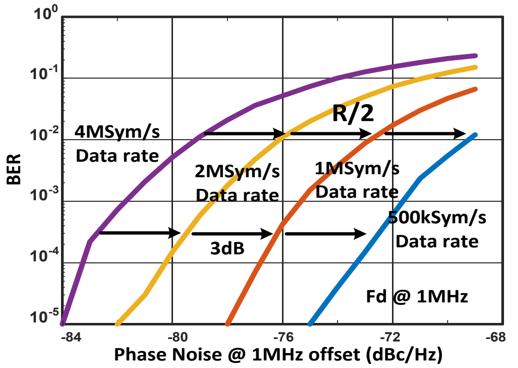

Fig. 6 BER vs PN for different data rates

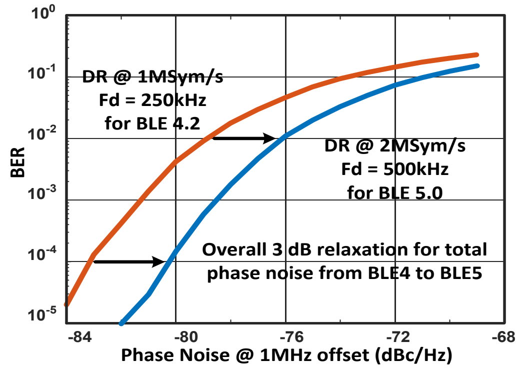

Fig. 7 BER vs PN comparison for Bluetooth Low Energy applications

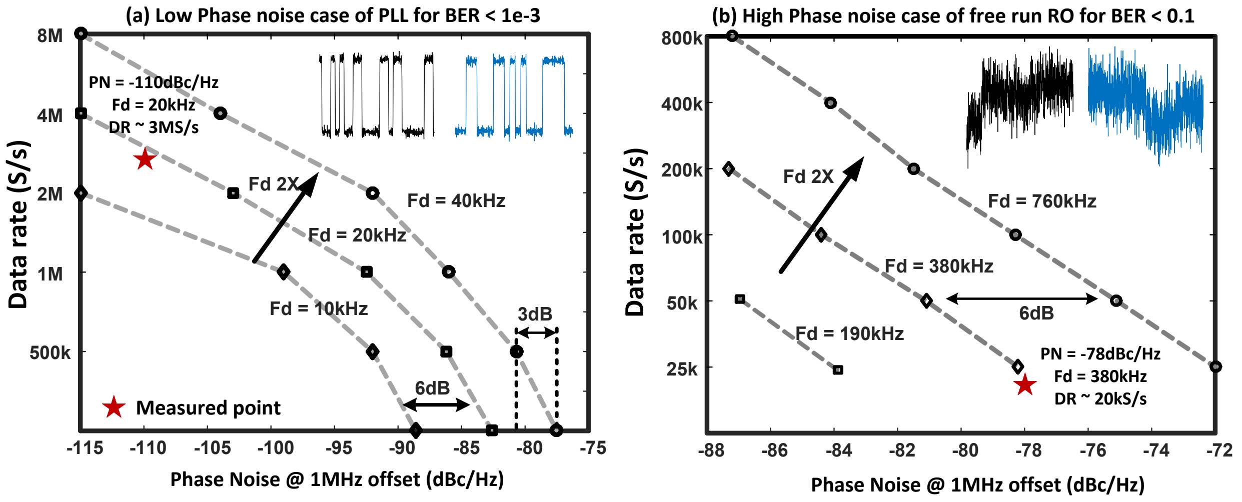

Fig. 8. FSK FD & DR influence to PN and comparison between simulated and measured results (a) Low phase noise case, and (b) high phase noise case

This can be explained by white noise falling into the bandwidth of the baseband filter when the PN is low, which will affect E_b/N_o, and a 3dB improvement in PN isn't enough to counter the loss of the bit energy. This also agrees with [4].

For the measurements of the low PN case, an AWG and VSG are used to generate the noisy FSK signal in RF and a mixed domain scope is used to capture the data for demodulation. The phase noise in simulation is set to the same level and noise shape but with the noise floor raised up to -110dBm. Since the PN of a VSG is too good and not tunable, extremely narrow FSK deviations are used to test the model. For the high phase noise case, the chip with a free running RO, which has a PN of -78dBc/Hz @ 1MHz offset, is tested, and compared to simulated results based on a free run RO phase noise shaping. The FD of the RO is fixed at 390 kHz. Decent agreement between simulation and measurement is achieved; measured (top left in black) and modeled (top right in blue) frequency vs time signals at the 2 different PN levels are also shown for visual comparison.

V. CONCLUSION

The direct relation between phase noise in a TX-RX link and FSK parameters are analyzed. Excellent agreements among theory, simulation and measurement are achieved. The presented noise model can be practically used to define phase noise specifications for FSK radio systems. Moreover, the phase noise requirements are found to be much more relaxed compared to current designs. This will allow us to design FSK radios, especially transmitters, with much more freedom and utilize the noisy but much lower power ring oscillators. On the other hand, a 2 times increase in FSK frequency deviation will offer 6dB relaxation on phase noise requirement, while a doubled data rate will only require an extra 3dB when the noise out of the band is effectively filtered. Thus for ULP FSK radio designs, a 'wider' but 'faster' FSK modulation is preferred over the 'narrower' but 'slower' one.

REFERENCES

[1] Ultra Low Power Radio Survey. [Online]. Available: http://www.eecs.umich.edu/wics/low_power_radio_survey.html

[2] R. Pawula, "On the Theory of Error Rates for Narrow-Band Digital FM," in IEEE Transactions on Communications, vol. 29, no. 11, pp. 1634-1643, Nov 1981.

[3] R. F. Pawula, "Refinements to the theory of error rates for narrow-band digital FM," in IEEE Transactions on Communications, vol. 36, no. 4, pp. 509-513, Apr 1988.

[4] M. Lont, D. Milosevic, G. Dolmans and A. H. M. van Roermund, "Implications of I/Q Imbalance, Phase Noise and Noise Figure for SNR and BER of FSK Receivers," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 8, pp. 2187-2198, Aug 2013.

[5] A. A. Abidi, "Phase Noise and Jitter in CMOS Ring Oscillators," in IEEE Journal of Solid-State Circuits, vol. 41, no. 8, pp. 1803-1816, Aug 2006.

[6] T. C. Weigandt, Beomsup Kim and P. R. Gray, "Analysis of timing jitter in CMOS ring oscillators," Proceedings of IEEE International Symposium on Circuits and Systems - ISCAS '94, London, 1994, pp. 27-30 vol.4.

[7] C. Samori, A. L. Lacaita, A. Zanchi and F. Pizzolato, "Experimental verification of the link between timing jitter and phase noise," in Electronics Letters, vol. 34, no. 21, pp. 2024-2025, 15 Oct 1998.

[8] F. Herzel and B. Razavi, "A study of oscillator jitter due to supply and substrate noise," in IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing, vol. 46, no. 1, pp. 56-62, Jan 1999.