Performance Analysis of OOK Modulated Signals in the presence of ADC Quantization Noise

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***Abstract*—This paper investigates the word length requirement of an analog-to-digital (ADC) converter for coherent and non-coherent detection of On-Off Keying (OOK) schemes. The paper presents closed-form expressions for coherent and non-coherent detection in terms of bit error rate in the presence of quantization noise (QN) and additive white Gaussian noise (AWGN) channels. The analytical models show that for coherent as well as non-coherent demodulation of OOK schemes in AWGN channels and affected by QN, a 4-bit ADC is able to provide close to optimum performance. As OOK is popularly being employed in event-driven radios, we extend our analysis to these radios. Our analysis shows that for event-driven radios (also referred to as wakeup radios) a 4-bit ADC is able to provide close to optimum performance. Furthermore, in the paper all the analytical models are in close agreement with the simulation results.**

I. INTRODUCTION

On-Off Keying (OOK) is a modulation technique that has increasingly being used in energy constrained wireless applications where efficient design is required to minimize the power consumption and to extend the operation lifetime [1]–[3]. Non-coherent OOK provides a suitable compromise between power efficiency and receiver simplicity. However, the analysis with the analog-to-digital converter (ADC) quantization noise (QN) lags behind.

There is no clear indication in literature regarding what should be the word length of ADC and what will be the impact of the QN on the overall performance of the low-power system in which OOK is being employed. However, it is very well known that the power consumption of an ADC is directly related to the sampling frequency and is exponentially related to the ADC word-length [4], [5]. The focus of the paper, therefore, will be primarily on the word length of the ADC to ensure a low-power solution. As it is important not to over-design an ADC in a system with limited power budget.

In [6], an analytical expression for the probability of error is derived for orthogonal frequency division multiplexing (OFDM) systems based on the assumption that the QN is Gaussian distributed. This assumption is only valid for multi-carrier systems with large number of carriers and is, in general, not applicable to single carrier systems. In [7], [8], bit error rate expressions are derived assuming the ADC QN is uniformly distributed for M-ary pulse amplitude modulation (MPAM) and quadrature phase-shift keying (QPSK) modulation techniques. However, the analysis is specific to coherent detection of MPAM and QPSK detection and is not applicable for non-coherent OOK detection. It is also important to state that the performance of non-coherent OOK without the effect of QN has been extensively studied in literature, for instance [9], [10], and the references therein.

The major contributions of the paper are as follows. We derive the probability distribution function (PDF) for the signal which is non-coherently detected and experiences additive white Gaussian noise (AWGN) channel and ADC QN. For completion of the analysis and comparison we also derive the expression for coherently detected OOK signal. Based on these distribution functions we derive expressions for bit error rate (BER) for coherent and non-coherent OOK modulation schemes in the presence of ADC QN and AWGN channels, to provide quick methods to evaluate what word-length of ADC is sufficient for a low-power design. Furthermore, we also extend the analysis to event-driven radios (also referred to as wakeup radios) to determine the effect of QN on the system performance.

The rest of the paper is organized as follows: in Section II, we introduce the system model and quantization noise model. In Section III we present the performance analysis and derive analytical expressions for BER with coherent and non-coherent demodulation of OOK schemes in the presence of QN and AWGN channels, followed by results and discussion in Section IV. Lastly, we present the conclusions in Section V.

II. SYSTEM MODEL

Quantization is a process of mapping continuous signals onto a set of levels. The number of levels in the discrete set is determined by the number of bits N used and is given as [11]

$$\text{Number of quantization levels} = 2^N \tag{1}$$

Quantization levels are typically designed to be uniformly distributed from $[-V_s, V_s]$, which is the operating voltage of the data converter. As the levels are uniformly distributed the resolution of the converter is described in terms of its step size. The quantization error is defined as the difference between the quantized (discrete signal) and the original (continuous) signal. Typically the error signal is assumed to be random and uncorrelated (a valid assumption if the signal is spectrally rich with respect to the sampling frequency), and is therefore, modeled as a noisy source and the noise generated is termed as *quantization noise* (QN).

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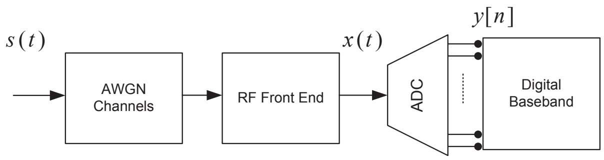

Fig. 1. Equivalent system model for a communication system under the influence of AWGN Channels and QN.

A binary sequence can be transmitted using OOK signaling. To transmit a binary 1, a signal ($s(t)$) is transmitted in a time interval of duration T_s; whereas to transmit a binary 0, no signal is transmitted during T_s. The distinction of Mark (transmission of binary 1) and Space (transmission of binary 0) from the received composite signal envelope ($x(t)$) is based on the comparison at the sampling instant against a threshold (β). Coherent and non-coherent detection of OOK at the receiver is very well studied in the literature and we refer the reader to [9], [10] and the references therein.

An equivalent system model for a communication system under the influence of AWGN and QN is shown in Figure 1. The real baseband signal (y) which is effected by AWGN noise and ADC QN is $y = s + n + u = x + u$, where n represents the AWGN with zero mean and variance $\sigma^2 = N_0/2$ and N_0 is single-sided noise power spectral density, u represents the additive QN. The combined random variable x, represents the composite signal that can vary from being only noise (as in the case of Space) to signal plus noise (as in the case of Mark). The average signal-to-ratio (SNR) is defined as $\bar{\gamma} = A_s^2/2\sigma^2$, where A_s is the amplitude of the desired signal. It is assumed that the signal is uniformly distributed across the quantization levels over the range $[-V_s, V_s]$ to ensure that no clipping occurs. QN u is additive and uniformly distributed between $[-V_s/2^N, V_s/2^N]$ and the associated PDF can be given as [11]

$$f_U(u) = \begin{cases} \frac{2^{N-1}}{V_s} & \frac{-V_s}{2^N} \leq u \leq \frac{V_s}{2^N} \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

it's variance (σ_u^2) is related to N (where N is the number of bits used (1)) as

$$\sigma_u^2 = \frac{V_s^2}{(3 \cdot 2^{2N})}. \tag{3}$$

In the subsequent subsections we present the performance for coherent and non-coherent demodulation of OOK and analyze the effect of QN on the overall performance of the system.

III. Performance Analysis

The performance analysis is parsed on the basis of the demodulation technique being adopted, i.e., coherent or non-coherent demodulation. Firstly, the performance of a system without QN is analyzed, followed by the analysis for a system with QN.

A. Coherent and Non-Coherent Demodulation without QN

The performance of OOK modulation, is dependent on the probability of Mark (P_M) and Space (P_S) error, which effects the overall probability of error P_e as:

$$P_e = \frac{1}{2}(P_M + P_S), \tag{4}$$

where in the case of coherent demodulation [10]

$$\begin{aligned} P_S &= \frac{1}{2}\text{erfc}\left(\frac{\beta}{\sqrt{2\sigma^2}}\right) \\ P_M &= \frac{1}{2}\text{erfc}\left(\frac{A_s - \beta}{\sqrt{2\sigma^2}}\right), \end{aligned} \tag{5}$$

where β is the decision threshold and in case of coherent demodulation is chosen to be $\beta = A_s/2$. For the case of non-coherent demodulation P_M and P_S can be given as [9], [10]

$$\begin{aligned} P_S &= \exp\left(\frac{-\beta^2}{2\sigma^2}\right) \\ P_M &= 1 - \text{Q}\left(\sqrt{2\bar{\gamma}}, \frac{\beta}{\sigma}\right), \end{aligned} \tag{6}$$

where $\bar{\gamma} = A_s/2\sigma^2$ is the average SNR, $Q(\cdot)$ is the Marcum-Q function and the optimal $\beta = \sigma(1 + \frac{\ln(2\pi\bar{\gamma})}{2\bar{\gamma}})\sqrt{\bar{\gamma}/2}$. The asymptotic error rate behavior of non-coherent OOK without QN has been discussed extensively in literature and we refer the reader to [9], and the references therein.

Throughout the paper, the ideal performance, as given by (4), (5) and (4), (6) for coherent and non-coherent detection, respectively, will be compared with a system being effected by QN using optimal threshold values.

B. Coherent Demodulation with QN

In order to derive the P_e (4) of the system in case of coherent OOK modulation AWGN and QN, the combined PDF describing the real baseband signal y for Space and Mark is required.

The PDF at the receiver for transmission of Space x_s in coherent demodulation can be given as [10] (for better comprehension we would use subscript s and m for Space and Mark designation, respectively).

$$f_{X_s}(x_s) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{x_s^2}{2\sigma^2}\right), \tag{7}$$

and the combined PDF with QN and AWGN can be evaluated using (2) and (7) as

$$\begin{aligned} f_Y(y) &= \int_{-\infty}^{\infty} f_{X_s}(y-u) f_U(u) \mathrm{d}u \\ &= \frac{1}{2b\sqrt{2\pi\sigma^2}} \int_{-b}^{b} \exp\left(-\frac{(y-u)^2}{2\sigma^2}\right) \mathrm{d}u \\ &= \frac{1}{4b}\left[\text{erf}\left(\frac{b-y}{\sqrt{2\sigma^2}}\right) + \text{erf}\left(\frac{b+y}{\sqrt{2\sigma^2}}\right)\right], \end{aligned} \tag{8}$$

where $b = \frac{V_s}{2^N}$ and erf is the error function. In [7], [8], (8) has also been reported for MPAM and QPSK signal constellations.

Now using (8) we can derive P_S with respect to the decision threshold β as,

$$
\begin{aligned}
P_S(y>\beta) &= \int_{\beta}^{\infty} \frac{1}{4b}\left[\operatorname{erf}\left(\frac{b-y}{\sqrt{2\sigma^2}}\right)+\operatorname{erf}\left(\frac{b+y}{\sqrt{2\sigma^2}}\right)\right]\mathrm{d}y \\
&= \frac{1}{4b}\Bigg[e^{\frac{-(b+\beta)^2}{2\sigma^2}}\left\{\sqrt{\frac{2}{\pi}}\sigma(-1+e^{\frac{2b\beta}{\sigma^2}})\right\}+ \\
&\quad \Bigg\{2b+(b-\beta)\operatorname{erf}(\frac{b-\beta}{\sqrt{2\sigma^2}})- \\
&\quad (b+\beta)\operatorname{erf}(\frac{b+\beta}{\sqrt{2\sigma^2}})\Bigg\}\Bigg]. \qquad (9)
\end{aligned}
$$

Similarly, the PDF at the receiver for transmission of Mark in coherent demodulation x_m can be given as [10]

$$
f_{X_m}(x_m)=\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(x_m-A_s)^2}{2\sigma^2}\right), \qquad (10)
$$

and the combined PDF with QN can be evaluated using (2) and (10) as

$$
\begin{aligned}
f_Y(y) &= \int_{-\infty}^{\infty} f_{X_m}(y-u)f_U(u)\mathrm{d}u \\
&= \frac{1}{4b}\left[\operatorname{erf}\left(\frac{b+A_s-z}{\sqrt{2\sigma^2}}\right)+\operatorname{erf}\left(\frac{b-A_s+z}{\sqrt{2\sigma^2}}\right)\right]. \qquad (11)
\end{aligned}
$$

Using (11), we can derive P_M as (12). As P_M and P_S are equi-probable the overall P_e is given by (4).

C. Non-Coherent Demodulation with QN

The non-coherent demodulation of OOK leads to a power efficient design [3]. In order to evaluate the system performance of non-coherent OOK demodulation with QN and AWGN, we firstly derive the PDF of the received signal with QN and AWGN which is non-coherently demodulated.

The PDF at the receiver for transmission of Space employing non-coherent demodulation x_s can be given as [9], [10]

$$
f_{X_s}(x_s)=\frac{x_s}{\sigma^2}e^{\frac{-x_s^2}{2\sigma^2}}, \qquad (13)
$$

and the combined PDF with QN and AWGN can be evaluated using (2) and (13) as

$$
\begin{aligned}
f_Y(y) &= \int_{-\infty}^{\infty} f_Y(y-u)f_U(u)\mathrm{d}u \\
&= \frac{1}{2b}\left\{\exp\left(\frac{-(b-y)^2}{2\sigma^2}\right)-\exp\left(\frac{-(b+y)^2}{2\sigma^2}\right)\right\}, \qquad (14)
\end{aligned}
$$

and P_S can be derived as

$$
\begin{aligned}
P_S &= \int_{\beta}^{\infty}\frac{\exp\left(\frac{-(b-y)^2}{2\sigma^2}\right)-\exp\left(\frac{-(b+y)^2}{2\sigma^2}\right)}{2b}\mathrm{d}y \\
&= \frac{\sqrt{\frac{\pi}{2}}\sigma\left(\operatorname{erf}\left(\frac{b-\beta}{\sqrt{2}\sigma}\right)+\operatorname{erf}\left(\frac{b+\beta}{\sqrt{2}\sigma}\right)\right)}{2b}. \qquad (15)
\end{aligned}
$$

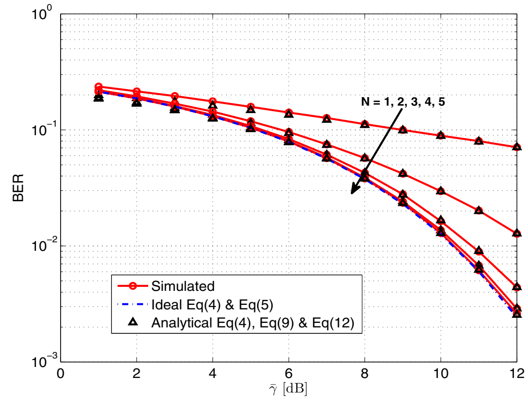

Fig. 2. Average probability of error P_e for OOK modulation with coherent detection in AWGN channels for different values of N. The direction of arrow shows the increasing value of N.

Similarly, the PDF at the receiver for transmission of Mark employing non-coherent demodulation x_m can be given as [9], [10]

$$
f_{X_m}(x_m)=\frac{x_m}{\sigma^2}\exp\left(-\frac{x_m^2+A_s^2}{2\sigma^2}\right)I_0\left(\frac{x_mA_s}{\sigma^2}\right), \qquad (16)
$$

and the combined PDF with QN can be evaluated using (2), (16) and the identity $I_0(v)=1/\pi\int_0^{\pi}\exp(v\cos(\theta))\mathrm{d}\theta$. We can evaluate P_M as (17), which can be efficiently evaluated using numerical methods.

In section IV, we will elaborate on the overall system performance and compare the presented analytical models with simulation results.

IV. Results and Discussion

In this section we present the impact of the ADC quantization on the system performance in terms of BER. The results are parsed on the basis of the demodulation method. It is important to reiterate the assumptions, i.e., we assume that no clipping occurs and the quantization levels are uniformly distributed over the full-scale range of the ADC and the channel is AWGN.

In this section we also take wakeup radios (also referred to as event-driven radio) as an example of a system employing non-coherent OOK modulation and we study the impact of the QN on the overall system performance.

A. Coherent Demodulation with QN

Figure 2 shows the BER performance of the OOK system in AWGN channels with coherent detection as a function of the SNR ($\bar{\gamma}$) and with varying values of the number of ADC bits N. The analytical results from (9) and (12), are in close agreement with the simulation results. Furthermore, we also see that in the case of coherent OOK modulation a 4-bit ADC with optimal threshold is able to provide close to optimum performance.

$$
\begin{aligned}
P_M(y<\beta) \;=\;& \frac{1}{4b}\Bigg\{ e^{-\frac{b^2+2b\beta+A_s^2+\beta^2}{2\sigma^2}} \left((b-A_s+\beta)e^{\frac{b^2+2b\beta+A_s^2+\beta^2}{2\sigma^2}} \mathrm{erf}\left(\frac{b-A_s+\beta}{\sqrt{2\sigma^2}}\right) + \sqrt{\frac{2}{\pi}}\sigma\left(e^{\frac{A_s(b+\beta)}{\sigma^2}} - e^{\frac{2b(A_s+\beta)+\beta^2}{2\sigma^2}}\right)\right) \\
& + (A_s-b)\mathrm{erf}\left(\frac{b-A_s}{\sqrt{2}\sigma}\right) - (b+A_s-\beta)\mathrm{erf}\left(\frac{b+A_s-\beta}{\sqrt{2}\sigma}\right) + (b+A_s)\mathrm{erf}\left(\frac{b+A_s}{\sqrt{2\sigma^2}}\right) + \\
& \sqrt{\frac{2}{\pi}}\sigma\left(e^{-\frac{(b+A_s)^2}{2\sigma^2}} - e^{-\frac{(b+A_s-\beta)^2}{2\sigma^2}}\right)\Bigg\} \qquad (12)
\end{aligned}
$$

$$
\begin{aligned}
P_M &= \int_0^\beta f_Y(y)\mathrm{d}y \\
&= \frac{-1}{2b\pi}\int_0^\beta\int_0^\pi\int_{y+b}^{y-b}\frac{z}{\sigma^2}\exp\left(\frac{-(z^2+A_s^2-2zA_s\cos(\theta))}{2\sigma^2}\right)\mathrm{d}z\mathrm{d}\theta\mathrm{d}y \\
&= \int_0^\beta\int_0^\pi \frac{-1}{2b\pi\sigma\sqrt{(-A_s\cos(\theta)+b+y)^2}\sqrt{(A_s\cos(\theta)+b-y)^2}}\Bigg\{\sqrt{2\pi}(-A_s)\cos(\theta)(-A_s\cos(\theta)+b+y) \\
& \sqrt{(A_s\cos(\theta)+b-y)^2}e^{\frac{A_s^2\cos^2(\theta)-2A_sy\cos(\theta)+b^2+y^2}{\sigma^2}}\mathrm{erf}\left(\frac{\sqrt{(-A_s\cos(\theta)+b+y)^2}}{\sqrt{2}\sigma}\right) - \sqrt{(-A_s\cos(\theta)+b+y)^2} \\
& e^{-\frac{2A_sy\cos(\theta)}{\sigma^2}}\left(\sqrt{2\pi}A_s\cos(\theta)(A\cos(\theta)+b-y)e^{\frac{A^2\cos^2(\theta)+b^2+y^2}{\sigma^2}}\mathrm{erf}\left(\frac{\sqrt{(A_s\cos(\theta)+b-y)^2}}{\sqrt{2}\sigma}\right)+\right. \\
& \left. 2\sigma\sqrt{(A_s\cos(\theta)+b-y)^2}e^{\frac{2A_sy\cos(\theta)}{\sigma^2}}\left(e^{\frac{(-A_s\cos(\theta)+b+y)^2}{2\sigma^2}} - e^{\frac{(A_s\cos(\theta)+b-y)^2}{2\sigma^2}}\right)\right)\Bigg\} \\
& \exp\left(-\frac{A_s^2\cos^2(\theta)+A_s^2-4A_sy\cos(\theta)+2\left(b^2+y^2\right)}{2\sigma^2}\right)\mathrm{d}\theta\mathrm{d}y \qquad (17)
\end{aligned}
$$

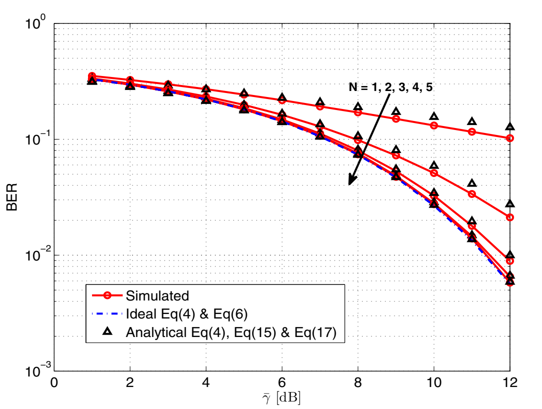

Fig. 3. Average probability of error P_e for OOK modulation with non-coherent detection in AWGN channels with QN for different values of N. The direction of arrow shows the increasing value of N.

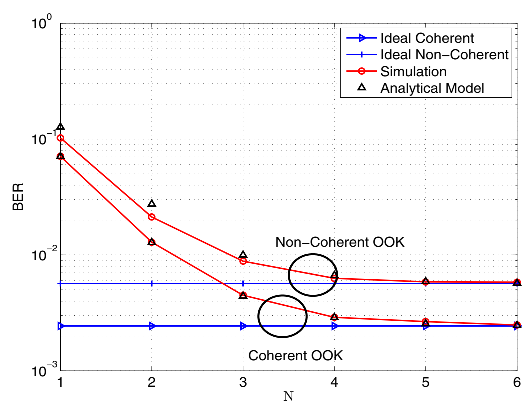

Fig. 4. Average probability of error P_e for OOK modulation for coherent and non-coherent detection in AWGN channels with QN for different values of N at $\bar{\gamma} = 12$ dB.

B. Non-coherent Demodulation with QN

Non-coherent demodulation is an important detection scheme as it is used in many simple radio designs, e.g., in wakeup radios [1], [2]. In Figure 3 it is obvious that also in the case of non-coherent demodulation of OOK, a 4-bit ADC is able to provide close to optimum performance. Furthermore, the analytical results from (15) and (17) are also in close agreement with the simulation results as shown in Figure 3.

The results of the preceding subsections are summarized in Figure 4. Figure 4 shows the performance for coherent and non-coherent detection of OOK schemes in AWGN channels with QN at $\bar{\gamma} = 12$ dB. A 4-bit ADC is able to provide close

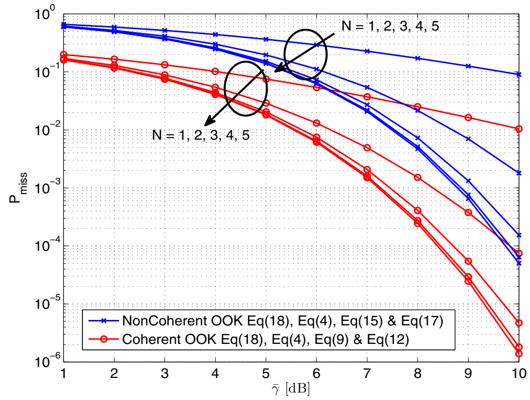

Fig. 5. Average probability of miss detection P_{miss} for OOK modulation with coherent and non-coherent detection in AWGN channels for different values of N. The address packet length is 16 with a Hamming distance of $d_m = 4$ chosen as a decision criterion. The direction of arrows show the increasing value of N.

to optimum performance for coherent as well as non-coherent detection schemes. For instance, for coherent detection the optimal BER value at $\bar{\gamma} = 12$ dB is 2.4×10^{-3}, and with a 4-bit ADC the BER performance is 2.8×10^{-3} which is very close to the optimum, whereas for a 5-bit ADC the BER performance is 2.5×10^{-3}, leading to a negligible gain in terms of BER but has a severe impact in terms of power consumption.

C. Wakeup Radio Example

Wakeup radio [1]–[3], is one of the prime candidates in which non-coherent OOK modulation is being employed. Wakeup radio, is able to considerably extend the life-time of a main radio by taking over the role of continuous channel monitoring. The performance of the wakeup radio can be evaluated in terms of probability of miss detection P_{miss} (i.e., the error in detecting the correct wakeup address and generating no wakeup signal) and, the probability of false alarm P_{false} (i.e., the error in detecting a wrong address as correct address and wrongly generating a wakeup signal). The Hamming distance between the address fields of a packet can be used to distinguish the wrong addresses from the correct. P_{miss} and P_{false} are packet error rate performance indicators. For further information on wakeup radios we refer the reader to [1], [2] and the references therein.

To analyze the performance of wakeup radio, we take as an example P_{miss} and evaluate the effect of QN on it. For a given Hamming distance criterion (d_m) and for an address length of L, P_{miss} can be given as:

$$P_{miss} = \sum_{k=d_m+1}^{L} \binom{L}{k} (1 - P_e)^{(L-k)} P_e^k, \tag{18}$$

where P_e for the coherent case can be evaluated using (4), (9) and (12); whereas for the non-coherent case, it can be evaluated using (4), (15) and (17).

Figure 5 shows the performance of the wakeup radio in the presence of QN and AWGN channels under the assumptions that the address packet length is $L = 16$ and the Hamming decision criterion is $d_m = 4$. From Figure 5 it is clear that a 4-bit ADC is able to provide a close to optimum performance and the gain achieved from using a 5-bit ADC is negligible. The result is consistent with the previous analysis in preceding sections.

The power consumption of an ADC is exponentially related to its effective number of bits. Therefore, it is important to reiterate that over-designing an ADC in a system with a limited power budget could lead to more power consumption without any significant gain in terms of performance.

V. Conclusions

In this paper we have derived analytical models for coherent and non-coherent demodulation of OOK schemes with QN and AWGN channels. We show that for coherent as well as non-coherent detection of OOK schemes a 4-bit ADC can provide close to optimum performance. For instance, for coherent detection the optimal BER value at $\bar{\gamma} = 12$ dB is 2.4×10^{-3}, and with a 4-bit ADC the BER performance is 2.8×10^{-3}. Furthermore, also in the case of a wakeup radio a 4-bit ADC is able to provide close to optimum performance. Moreover, we also show that the analytical models derived for coherent and non-coherent demodulation of OOK in the presence of QN and AWGN are in close agreement with the simulation results.

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