ÉNERGIE ET RADIOSCIENCES

Modulation Scaling for Energy Efficiency

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Abstract *The energy consumption of wireless communicating devices as well as their autonomy are two important factors in energy constrained system such as Wireless Sensor Networks (WSNs). The spectral efficiency is another important metric. The main goal is to study the trade-off between the energy consumption of the system and it's spectral efficiency when varying system parameters. In this paper, an uncoded system using M-ary Quadrature Amplitude Modulation (M-QAM) in which the spectral efficiency is assumed proportional to its bandwidth efficiency is used. In order to find the balance between spectral and energy requirements, the considered system parameters are studied. First, a general and comprehensive power model for both transmitter and receiver is developed. Next, by considering Additive White Gaussian Noise (AWGN) channel for point-to-point communication, the total energy consumption is evaluated. A new approximation for the Bit Error Rate (BER) is adopted. Then, the effect of communication distance, bandwidth and circuit power consumption on the optimum spectral efficiency is studied. For a fixed BER, we demonstrate that for each of those parameters, an optimum spectral efficiency can be found.*

1 Introduction

As the number of communicating objects is increasing, the energy consumption of these different devices become more and more relevant [1]. With the actual demand in high data rate, excessive power usage becomes a critical issue for such network. Therefore, finding the right trade-off between performance in terms of data rate and energy consumption is an important problem. The main criteria are the energy consumption per bit and the spectral efficiency. In this context, most studies is to focus on optimizing modulation performance for WSN in order to minimize energy consumption [2, 3]. The authors analyzed the constellation optimization for some modulations in both coded and uncoded systems. It has been shown that the optimum constellation size can save energy. Some other extended works [4–6] proposed to study other types of modulation schemes. For short range communication, the transmitter (TX) power amplifier (PA) is not the unique component to consider in the total power dissipation. Besides TX and receiver (RX) RF front end, digital signal processing (DSP) (modulation scheme, channel coding, etc.) should be considered in the system optimization in terms of energy consumption. Most of these works use a fixed energy model which is a linear model considering transmitting power and a fixed RF power [2, 7] neglecting the digital part. Recently many works [8, 9] have demonstrated that this model is not always sufficient and the digital part must be considered. these works usually use a classical approximation to estimate the signal-to-noise ratio per bit (SNR). In this paper, we extend the work done in previous studies : we propose a complete power model for the system and we use a more accurate expression to estimate the BER.

The reminder of this paper is organized as follows. In Section 2, a theoretical study highlights our motivations. System description and energy model are provided in Section 3. Spectrum and energy efficiency trade-off is derived in Section 4. Numerical results are presented in Section 5. Finally, Section 6 concludes the paper.

2 Theoretical investigation and motivation

The fundamental relation between the spectral efficiency b in bit/s/Hz and the received energy per bit E_b is given by Shannon's formula over AWGN channel [10]

$$b = \log_2\left(1 + b\frac{E_b}{N_0}\right) \tag{1}$$

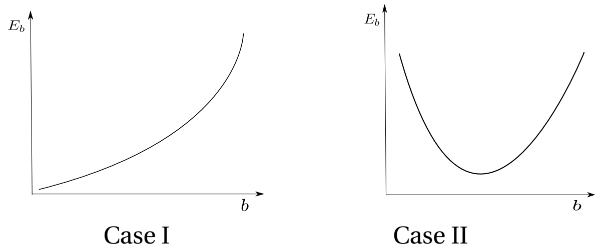

FIGURE 1 – Tradeoff between energy E_b and spectrum efficiency b for transmitted power model (case I) and the system power model (case II).

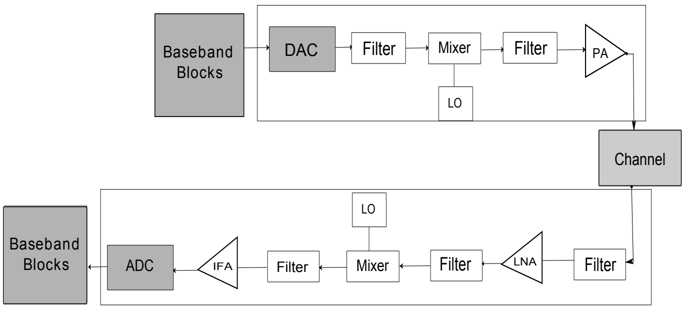

FIGURE 2 – Communication link model with block diagram of transmitter and receiver hardware.

where N_0 is the power spectral density of complex noise. This relation can be expressed differently as

$$E_b = N_0 \cdot \frac{2^b - 1}{b} \tag{2}$$

This equation illustrates the fundamental relation between energy and spectral efficiency which deserves careful study [1, 11]. The result shows only the limit case without considering practical modulation and coding and also it considers only the received power related to the transmit power P_t without counting for the circuit overhead. Furthermore, practical modulation may result in high BER due to smaller minimum distance separating constellation points. Moreover, as the circuit energy will be included, the penalty in terms of circuit processing cost can be large. This is illustrated in Fig. 1 in which we compare the two possible cases. The case I corresponds to the transmitted power model where only P_t is considered. The case II corresponds to the system power model where P_t plus an extra circuit power are considered.

3 System and energy model

In a sensor node, energy is consumed mainly for communication. We assume a generic transmitter and receiver as shown in Fig. 2. At the transmitter, the baseband signal is converted to an analog signal by the digital-to-analog converter (DAC), filtered by the reconstruction filter, modulated by the mixer, filtered again and finally amplified by the power amplifier (PA). On the receiver side, the reverse processing is performed from the low noise amplifier (LNA) to the baseband blocks after the analog-to-digital converter (ADC).

3.1 Power consumption model

The overall consumed power by the communication process consists in the power consumed by the RF blocks as well as the baseband blocks of the transceiver. The power consumption of the power amplifier depends on the transmit power, while the DAC, the ADC and the baseband blocks power consumption scales with bandwidth [12]. Therefore, we estimate the overall power as following

$$P_{tot} = P_{pa} + P_{RP} \tag{3}$$

— Power amplifier power P_{pa} : composed of the transmitted power P_t and the amplifier circuit power $P_{amp} = \beta P_t$, where $\beta = \frac{\xi}{\psi} - 1$, with ψ is the PA drain efficiency and ξ is the peak-to-average-power-ratio (PAPR) [2], i.e.

$$P_{pa} = P_t + P_{amp} = (1+\beta) P_t = \frac{\xi}{\psi} P_t \tag{4}$$

— Processing power P_{RP} : composed of the RF power and the baseband power.

— The RF power contains the constant part P_c and the bandwidth dependent part, ϑ_t and ϑ_r are respectively the power coefficients of the DAC and the ADC. Hence, $P_{RF} = P_c + \vartheta_t B + \vartheta_r B$.

— The baseband power consumption, *excluding* the FEC decoder, is linearly dependent on bandwidth, ε_t and ε_r are respectively the power coefficient of transmitter and receiver. Hence, $P_{BB} = \varepsilon_t B + \varepsilon_r B$.

Finally, our general power model is given by

$$P_{tot} = \frac{\xi}{\psi} P_t + \varepsilon B + P_c \tag{5}$$

where $\varepsilon = \vartheta_t + \vartheta_r + \varepsilon_t + \varepsilon_r$. ξ depends on the modulation scheme. For M-QAM modulation $\xi = \frac{3(\sqrt{M}-1)}{(\sqrt{M}+1)}$ and $P_c = 2\left(P_{mix} + P_{syn} + P_{filt}\right) + P_{IFA} + P_{LNA} + c_{fa} + c_{fd}$ (c_{fd} and c_{fa} are the DAC and ADC fixed power consumption constants).

3.2 Scenario and energy parameters

We assume that the transmitter needs to communicate L bits of information at a given deadline divided in three operating modes $T_{on} + T_{tr} + T_{sp}$. The working mode occupies the time T_{on} where the circuit is on and consumes the power P_{tot}. The sleeping mode occupies the time T_{sp} where the circuit is in sleep mode. The power corresponding to this sleeping mode is negligible compared to P_{tot} and we put it to 0. The last mode is the transition mode where the circuit switches from sleep mode to working mode or vice-versa. This transition mode occupies the time T_{tr} and consumes P_{syn} (mainly the power consumed by the frequency synthetizers) for each up or down switch and each synthetizer. The total energy required to transmit the L bits is then $P_{tot}T_{on} + 2P_{syn}T_{tr}$. Now the energy consumption per bit is given by

$$E_{bt} = \frac{P_{tot}T_{on} + 2P_{syn}T_{tr}}{L} \tag{6}$$

We consider M-QAM uncoded modulation in AWGN channel, where $M = 2^b$, b is the number of bits per symbol. The spectral efficiency of the system, given by the modulation order, is linked to other system parameters by [2] $b = \frac{L}{BT_{on}}$.

4 Spectrum and energy efficiency trade-off

As established in the previous section, for a variable rate system, the energy per bit can be written as

$$\begin{aligned} E_{bt} &= \frac{\left(\frac{\xi}{\psi}P_t + \varepsilon B + P_c\right)T_{on} + 2P_{syn}T_{tr}}{L} \\ &= \frac{\xi}{\psi}P_t\frac{T_{on}}{L} + (\varepsilon B + P_c)\frac{T_{on}}{L} + 2P_{syn}\frac{T_{tr}}{L} \end{aligned} \tag{7}$$

The SNR per bit is $\gamma = \frac{P_r}{BN_0N_f b}$, where P_r is the received signal power and N_f represents the receiver noise figure. On the other hand, the transmit power P_t can be obtained by $P_t = P_rG_d = \gamma BN_0N_f bG_d$, where G_d is the power gain factor $G_d = G_1 d^k M_l$, with G_1 the gain factor at $d = 1$ m, $G_1 = \frac{(4\pi)^2}{\lambda^2 G_t G_r}$, where λ is the carrier wavelength, G_t and G_r represent the antennas gain and M_l is the link margin compensating the hardware process variations and other additive background noises. Finally, (7) is rewritten as

$$E_{bt} = \frac{\xi}{\psi}N_0N_fM_lG_1d^k\gamma + \frac{\varepsilon + P_c/B}{b} + 2P_{syn}\frac{T_{tr}}{L} \tag{8}$$

The SNR per bit γ depends on the target BER. The upper bound of the BER (P_b) of M-QAM in the AWGN channel is given by [13]

$$P_b \le \frac{4}{b}\left(1 - 2^{-b/2}\right)Q\left(\sqrt{\frac{3b\gamma}{2^b - 1}}\right) \tag{9}$$

To estimate the SNR as a function of BER, many works have been yield [14, 15] to make the result more accurate. A well-known approximation is based on the Chernoff-bound which has the advantage of being simple and invertible so that the SNR can be easily expressed in a closed-form. The approximation of P_b is then [7]

$$P_b \approx \frac{4}{b}\left(1 - 2^{-b/2}\right)\exp^{-\left(\frac{3b\gamma}{2(2^b-1)}\right)} \tag{10}$$

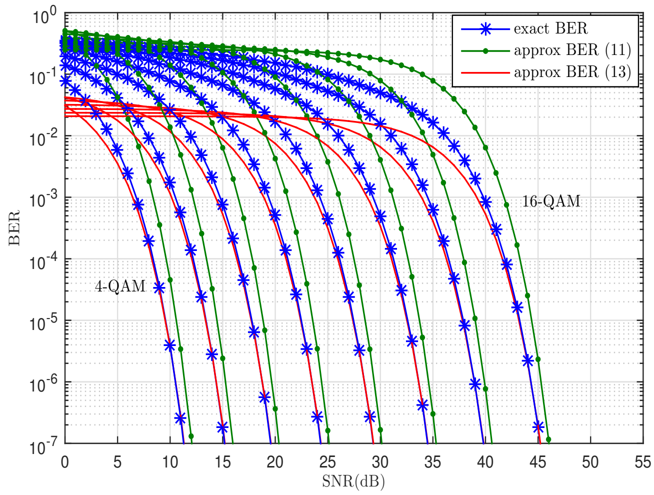

FIGURE 3 – Comparison between different BER approximation with the exact one

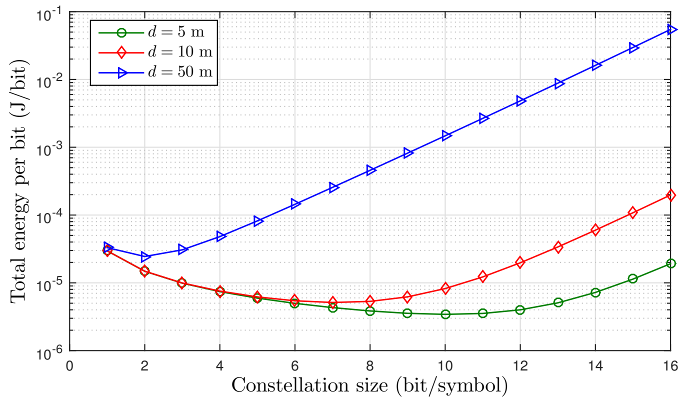

FIGURE 4 – Effect of distance on the optimum modulation order of M-QAM

The Q-function approximation is usually obtained via the complementary error function erfc. A tighter approximation can be found in [15] $\mathrm{erfc}(x) \approx \frac{1}{6}e^{-x^2} + \frac{1}{2}e^{\frac{-4}{3}x^2}$. For large values of x , the first part is dominant, then the approximation becomes $\mathrm{erfc}(x) \approx \frac{1}{6}e^{-x^2}$. Thus the Q-function is approximated as

$$Q(x) = \frac{1}{2}\mathrm{erfc}\left(\frac{x}{\sqrt{2}}\right) \approx \frac{1}{12}e^{\frac{-x^2}{2}} \tag{11}$$

finally, the BER approximation is

$$P_b \approx \frac{1}{3b}\left(1-2^{-b/2}\right)\exp^{-\left(\frac{3b\gamma}{2(2^b-1)}\right)} \tag{12}$$

Fig. 3 shows the difference between the mostly used approximate BER (10) and our proposed approximation (12). It can be shown that this latter is closer to the exact BER [16] for a BER lower than 10^{-3}. Then by approximating the bound as an equality, the total energy per bit is then expressed as

$$E_{bt} = \frac{2}{3}\frac{\xi}{\psi}N_0N_fM_lG_1d^k\frac{(2^b-1)}{b}\ln\left(\frac{\left(1-2^{\frac{-b}{2}}\right)}{3bP_b}\right) + \frac{\varepsilon+P_c/B}{b} + 2P_{syn}\frac{T_{tr}}{L} \tag{13}$$

We can see that the first term in (13) is monotonically increasing function of b for each value of P_b, d and k, while the second term is monotonically decreasing function of b and L which is independent of d and k. The optimization problem is to determine the optimum $b \in [2, b_{max}]$ ($b_{max} = L/B(T_{on})_{min}$) subject to $d > 0$, such that E_{bt} is minimized. For this purpose we have two scenarios based on the distance d :

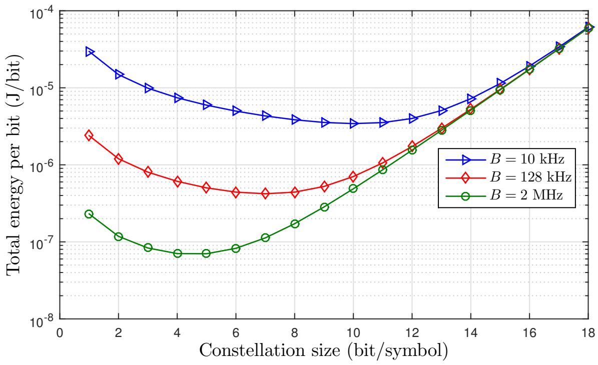

FIGURE 5 – Impact of bandwidth variation ($d = 5$ m)

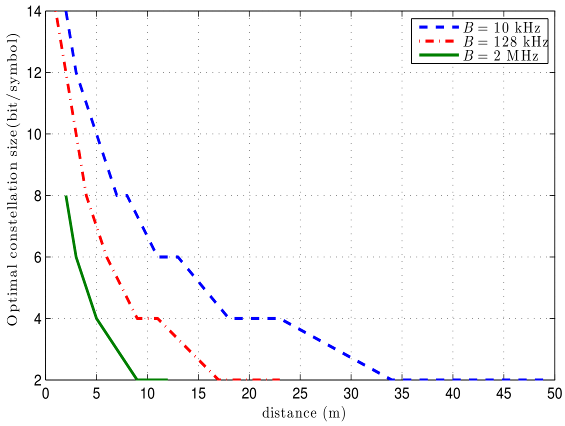

FIGURE 6 – Optimal constellation size as function of distances for different bandwidths

- For large values of d where the first term in (13) is dominant, the objective function E_{bt} is a monotonically increasing function of b and is minimized at $b = 2$, equivalent to 4-QAM scheme ;
- In the case of a small distance d. We have two cases : for small values of b, the energy is decreasing function of b as the circuit consumption dominates and for large values of b the energy is an increasing function of b due to the larger transmitting power.

4.1 The circuit power factor impact

Let α the circuit power factor that defines the variation in power consumption of the circuits part of the system from it's actual state ($\alpha = 1$) to an other state ($\alpha \neq 1$). Thus the associated energy is expressed as

$$E_{bt} = \frac{2}{3}\frac{\xi}{\psi} N_0 N_f M_l G_1 d^k \frac{(2^b - 1)}{b} \ln\left(\frac{\left(1 - 2^{\frac{-b}{2}}\right)}{3bP_b}\right) + \alpha \cdot \left(\frac{\varepsilon + P_c/B}{b} + 2P_{syn}\frac{T_{tr}}{L}\right) \tag{14}$$

By introducing α, we aim to study the impact of a possible variation in the circuit power variation of the system on our

TABLE 1 – System parameters

f_c	2.4 GHz	P_{syn}	50 mW
B	10 kHz	P_{mix}	30.3 mW
P_b	10^{-3}	P_{IFA}	3 mW
$N_0/2$	−174 dBm/Hz	P_{filt}, P_{filr}	2.5 mW
P_{LNA}	20 mW	ψ	0.35
k	3.5	T_{tr}	5 µs
G_1	30 dB	L	2 kbits
M_l	40 dB	N_f	10 dB

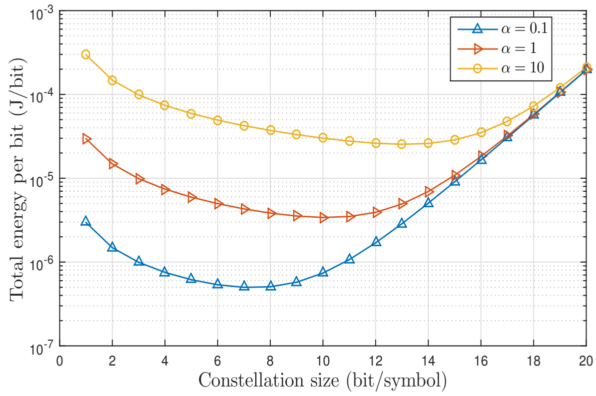

FIGURE 7 – Effect of circuit factor (α) on energy and b variation (d = 5 m)

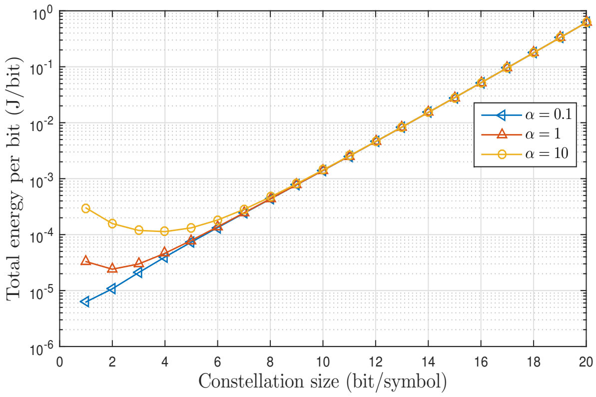

FIGURE 8 – Effect of circuit factor (α) on energy and b variation (d = 50 m)

results. Thus, an increase in the circuits consumption ($\alpha > 1$) or a decrease ($0 < \alpha < 1$) could result in a new optimum spectral efficiency value.

5 Numerical results

Table 1 summarize the different parameters used. The other power model coefficients are : $c_{\text{fd}} = 0.0615$ W and $c_{\text{fa}} = 0.0378$ W [2] . The other coefficients have the same unit in W/Hz : $\varepsilon_t = 4.09 \times 10^{-9}$, $\varepsilon_r = 1.62 \times 10^{-9}$ [17], $\vartheta_t = 2.16 \times 10^{-10}$, $\vartheta_r = 7.56 \times 10^{-8}$ [2] . We use a simple search algorithm to find the optimal constellation size.
Fig. 4 presents the total energy for M-QAM modulation for different distances. As shown in Fig. 4, as the transmission distance increases, the total energy increases as well and the optimal constellation size approaches M = 4 as expected. Thus, for long distance, 4-QAM is preferred. For medium and short distances, bandwidth efficient modulation schemes that leads to shorter on time will have an advantage. Consequently, the circuit energy shouldn't be ignored mainly for short range communication. In Fig. 5 the effect of increasing the constellation size of M-QAM for different operating bandwidth can be observed. The figure relates the total energy per bit to the spectrum efficiency (that we consider equal to the bandwidth efficiency of the modulation) and the modulation bandwidth. An increase in the bandwidth minimizes the total energy which is due to the shorter on time. We note that as the bandwidth increases, the optimum constellation size decreases. Indeed, the transmission energy will dominate the circuit energy, hence the minimal constellation size will save energy.
Fig. 6 plots the optimal constellation size over distance for each bandwidth allocation. We note that the optimal modulation reduces as the distance increases since the circuit energy becomes dominant for higher distances. It appears here a threshold distance from which the optimal constellation size still equal to the minimum value i.e $b_{min} = 2$. This distance depends on the bandwidth allocation and it informs about the optimization range in which the optimal b is higher than b_{min}. This distance is inversely proportional to the bandwidth. Fig. 7 and Fig. 8 represent the total energy per bit as a function of b for d = 5 m and d = 50 m respectively. As compared to the actual circuit consumption ($\alpha = 1$), the increase in circuit consumption ($\alpha = 10$) or the decrease ($\alpha = 0.1$) can vary the optimal constellation size from a large value to a smaller one. We note that for a large distance (d = 50), the optimal b is less sensitive to circuit power consumption for ($\alpha = 0.1$ and $\alpha = 1$). A larger optimal b appears for a circuit consumption equal to 10 times the actual consumption.

6 Conclusion

In this work we investigated the problem of balancing energy and spectrum efficiency for energy constrained systems. We conclude that considering circuit energy is essential for selecting system parameter mainly for short range communicating system. Using a general power model, we estimated the total energy using a more accurate SNR expression. We have evaluated the total energy per bit which is linked to the modulation order. Based on that, we studied the effect of varying the distance, the bandwidth and the circuits power consumption. Those parameters are shown to have an impact on the choice of the optimum constellation size. As a result, optimum energy-spectral efficient operating point can be set.

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