Minimization of Energy Consumption for OOK Transmitter Through Minimum Energy Coding

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Abstract
Energy consumption of Wireless Sensor Networks including On/Off keying (OOK) transmitter is important for short range transmission and long battery life time requirements. In order to improve the energy efficiency of an OOK transmitter, the Minimum Energy (ME) coding strategy is adopted in this paper. We first give the energy consumption model based on a real OOK transmitter, which has an energy efficiency of 52 pJ/bit by completely switching off the transmitter during the transmission of low bit ‘0’. Based on this energy consumption model, ME-Coding provides an energy efficiency of 30 pJ/bit for coding size $k = 3$. Moreover, larger coding size offers more significant improvement, at the sacrifice of spectral efficiency and transmission range. In this paper, we have also determined a closed-form solution for the optimal coding size for a given transmission range constraint.

Keywords Wireless sensor networks · Energy efficiency · OOK · Minimum energy coding

1 Introduction

Wireless Sensor Networks (WSNs), Molecular communication network and Tera-hertz communication nanonetwork have applications in diverse areas including military, health, industry, monitoring etc. There still remain many challenging issues in capacity, reliability, battery life and cost. It is critical to extend the operation life time of sensors in energy constrained applications with an unchangeable battery or other limited power supplies by energy harvesting [1–4].

The modulation scheme in physical layer is important for sensors to conserve energy. For a given bit error performance, many energy efficient modulations and coding strategies could be used to operate with low Signal to Noise Ratio (SNR), but most of them are often complex and their circuit power consumption is high.

Considering the transmit power and bandwidth efficiency, among various modulation techniques, the OOK modulation scheme is one of the most preferred choices for WSNs,
Wireless Body Networks (WBANs) or Wireless Nanosensor Networks (WNSNs). Besides, the time-spread OOK (TS-OOK) modulation with sub-picosecond-long Gauss pulse is currently the only modulation scheme in the terahertz frequency band [5-7], because of the circuit complexity and limited battery capacity. Most of recent researches [8-11] on WNSNs are based on OOK. Compared with M-PSK and M-FSK, OOK modulation has the best energy efficiency. M-PSK and FSK have better SNR performance and higher bandwidth efficiency at the cost of complexity in transmitter and receiver [12, 13]. Peng et al. [14] proposes to optimize energy consumption by using high-order orthogonal modulation. Cook et al. [15] presents FSK based transmitters with energy consumption about several nano Joule per bit. As OOK employs simple circuits in the transmitter and receiver, OOK based transmitter in [16-18] consume energy only about several pico Joule per bit. Therefore, it is an essential issue to find a transmitter which could be switched off during the transmission of bit '0'. [18] describes a realistic low power OOK transmitter used in our work, which could be completely switched off, including both the output buffer and the oscillator, when transmitting bit '0'.

Because the OOK transmitter consumes energy only when transmitting bit '1', the transmission energy could be saved by adopting low-weight coding [5, 6, 11]. The codeword's weight is the number of high bits contained in this codeword. These low-weight coding methods can be divided into two categories, according to error correction capability. Most of these schemes in [19-22] are not error correction code, and Minimum energy Channel coding (MEC) [10] provides error correction capability. The basic idea of a low-weight coding scheme, Minimum energy coding (ME) in [19], is mapping source words into codewords with least possible bit '1', that means transmitting as few high bits as possible to reduce the transmission energy consumption. Prakash et Gupta [20] propose to map $2^k - 1$ bits codewords to $k$-bit source words. Hence, there is no more than one high bit in the codeword of the corresponding codebook. This low-weight coding scheme is named Minimum Energy Coding (ME-Coding or PG). Other researchers use the constant weight codewords or variable-length low-weight codes (Superior lowest-weight coding [5]) to save energy by minimizing the average weight of codewords. Jornet et al. proposes Low-weight channel coding (LWC) [21] to prevent transmission error. Minimum transmission energy coding (MTE) [22] allows two consecutive high bits in the codewords to achieve lower bandwidth expansion. But these complex heuristic algorithms limits these application range.

So far, a general sensor node power consumption model [23] is widely used in the researches of energy efficiency WSNs. In our work, an energy consumption model based on a real physical circuit is adopted, which should be more accurate and practical.

This paper investigates that the energy consumption of the efficient OOK transmitter described in [18] by adopting ME-Coding proposed in [20]. The main contributions of this paper are summarized as follows: firstly based on the ME-Coding OOK modulation, an energy model is proposed, and the energy consumption includes both the transmission and circuit based on a real transmitter; secondly, ME-Coding is used in the above model to significantly improve the energy consumption performance; thirdly the coding size $k$, an important factor, is analytically investigated in terms of the transmission range.

The rest of this paper is organized as follows. Section 2 shows the Bit Error Rate (BER) analysis of ME-Coding. Section 3 introduces the system model of a realistic OOK transmitter based on ME-Coding OOK modulation. Section 4 presents the numerical results of the energy consumption improvement by ME-Coding. Section 5 describes the coding size optimization problem and gives the optimal coding size in terms of the transmission range. The paper is concluded in Sect. 6.
2 BER of Minimum Energy Coding with Soft Decision

The simplest form of digital modulation scheme like OOK is a good choice because of its great energy efficiency in low data-rate wireless applications. ME-Coding can save energy by transmitting less number of low bits in the coded message. The basic idea is that every \( k \) bits of a source symbol is mapped into an \( n \)-bit (\( n = 2^k - 1 \)) codeword (standard form, \( ME[n, k] \)). Therefore, there are no more than one high bit in all codewords compared with the source symbols. The transmission energy consumption can be reduced by sacrificing the bandwidth efficiency. Then, a soft decision decoding scheme in [20, 24] is considered, the bit with the highest strength and larger than a threshold is decided as bit ‘1’ and the rest bits are decided as bit ‘0’.

As example, the codes for \( ME[3, 2] \) and \( ME[7, 3] \) are given in Table 1. The \( 2^k = n + 1 \) codewords are composed of blocks of \( n \) bits. In the codebook, there are one all zero codeword and the \( 2^k - 1 \) other codewords with only one high bit. In this paper, the elements of the codeword will be denoted as chips.

The bit error probability of OOK ME-Coding received through an Addition White Gaussian Noise (AWGN) channel is recalled [24, 25] as follows.

Denote \( P_{eS} \) and \( P_{eM} \) as the error probabilities of a low bit being received as a high bit and a high bit being received as a low bit, respectively. Using a threshold equal to \( A/2 \), where \( A \) is the amplitude of bit ‘1’, for a coherent receiver, \( P_{eS} \) and \( P_{eM} \) are given by

\[
P_{eS} = P_{eM} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{E_b}{4N_0}} \right)
\]

where \( \text{erfc}() \) is the complementary error function and \( \frac{E_b}{N_0} \) is the energy-to-noise power spectral density ratio.

In order to improve the performance of ME-Coding with hard-decision decoding without error recovery capability, soft decision process (code-by-code detection) is used. There are two situations to be considered

2.1 The Original Symbol is not All-Zeros

Denote \( P_{m0} \) the probability that codeword \( M_i \) is received as \( M_0 \) (all zero codeword), we have

| Table 1 Minimum-energy code table for \( k = 2 \) and \( 3 \) |
|-----------------|-----------------|-----------------|-----------------|
| Source bits  | Codeword | Source bits | Codeword |
| 00  | 000     | 000 | 00000000 |
| 01  | 001     | 001 | 00000001 |
| 10  | 010     | 010 | 00000100 |
| 11  | 100     | 011 | 00001000 |
| 10  | 010     | 011 | 00010000 |
| 11  | 110     | 011 | 01000000 |
| 11  | 111     | 100 | 10000000 |
The probability that codeword $M_i$ is received by a coherent receiver as another codeword $M_j$ except $M_0$ can be written.

\[ P_{m0} = P_e M (1 - P_e S)^{n-1} \]  

(2)

The probability that codeword $M_i$ is received by a coherent receiver as another codeword $M_j$ except $M_0$ can be written.

\[ P_{ij} = \int_{-\infty}^{\infty} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{x^2}{2\sigma^2} \right] \left[ \int_{-\infty}^{x} \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{r^2}{2\sigma^2} \right) dr \right]^{n-2} \]

(3)

\[ \int_{x}^{\infty} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -(r - A)^2 / 2\sigma^2 \right] dr \]

(4)

\[ P_e = \frac{1}{2} (P_{m0} + n P_{ij} + P_{0j}) \]  

(5)

2.2 The Original Symbol is All-Zeros

The event $M_0$ being received as $M_j$ occurs only when the $j$th bit changes to bit ’1’ and all the other $n - 1$ bits remain zero. Therefore for the coherent receiver, $P_{0j}$ is given by

\[ P_{0j} = \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{x} \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{r^2}{2\sigma^2} \right) dr \right]^{n-1} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -y^2 / 2\sigma^2 \right] dy \]

Therefore the total bit error rate of ME-Coding with soft-decision decoding[24] is given by

Assuming transmission over an AWGN channel, the bit error probabilities of different ME-Coding schemes can be calculated theoretically by Eq. (5), and compared with the simulation results. Figure 1 shows the improvement of bit error probability of ME-Coding with soft decision [19]. Compared to the uncoded OOK ($k = 1$), about 3 dB and 5 dB gains in SNR per bit can be obtained with ME[7,3] and ME[63,6] with soft decision respectively, for an error probability of $10^{-3}$. And ME[63,6] with soft decision obtain about 2 dB gain in SNR per bit compared with that of BPSK. With the purpose of increasing energy efficiency, these improvements can be used to reduce the transmit power corresponding to SNR. But the circuit power consumption should be also taken into account for the total energy budget.

3 Energy Consumption Model of a Realistic OOK Transmitter

The general energy consumption model of OOK is described in Figs. 2 and 3. The transmitter is composed of a local oscillator (LO) which generates the carrier wave. A switch transmits this signal through a filter to the power amplifier (PA) and the antenna if a high bit is sent. In case of low bit, no signal is transmitted. The receiver is composed of a low noise amplifier (LNA), a frequency transposition associated to a local oscillator and a coherent or more often a non coherent detector.
Fig. 1 BER performance of ME-Coding

Fig. 2 Transmitter circuit analog blocks

Fig. 3 Receiver circuit analog blocks
As OOK is simply in implementation both at the transmitter and receiver sides, it is a convenient modulation scheme for wireless communication. ME-Coding can be implemented using OOK with the advantage that the circuit power consumption when transmitting bit ‘0’ will be much lower than when transmitting bit ‘1’. An simply energy consumption model based on 433-MHz OOK transmitter described in [18] is proposed in this paper, which is specially adapted to ME-Coding using OOK modulation.

Figure 4 shows the block diagram of this low energy consumption OOK transmitter. During the transmission of bit ‘0’, the circuit is completely turns off. A speed up scheme is used to achieve low wake up times and high data rate. From parameters of the realistic transmitter in [18], the total power consumption is given by

$$ P_{dc} = r_d P_h $$

(6)

where $r_d$ is the duty cycle of the transmit message, $P_h$ is the average power during the ON state. These parameters can be deduced from the data given in [18]. We have : $P_{dc} = 518 \mu W$ for $r_d = 1/2$. By using (6), we deduce $P_h = 1.036 mW$.

For ME coding, the circuit power consumption during a large part of the symbol will be null. Using the circuit consumption model, the energy consumption per source bit can be derived as follows.

When the symbols have the same probability, the average duty cycle of $ME[n, k]$ is given by

$$ r_d = 1/2^k $$

(7)

Assuming a source bit rate $R_b$, the symbol duration is $T_s = k/R_b$ and the ON duration is $T_h = 1/R_c = k/(2^{k-1}R_b)$ with $R_c$ the chip rate. So, the total energy per bit is

$$ E_{b,tot} = P_{dc} T_s/k = P_h 2^k R_b = (2^k - 1)P_h/k2^k R_c $$

(8)

We can deduce that the total energy consumption per bit is a decreasing function of the chip rate $R_c$ from Eq. 8. For a given modulator, $R_c$ is limited (for example 10 Mb/s in the circuit described in [18]). If we denote this maximum chip rate by $R_{c, max}$, the maximum bit rate for $ME[n, k]$ is :

$$ R_{b, max} = kR_{c, max} / 2^k - 1 $$

(9)
Assuming that the bandwidth is approximately equal to the chip rate, the spectral efficiency can be written as

\[ \eta = \frac{R_{b,\text{max}}}{R_{c,\text{max}}} = \frac{k}{2^k - 1} \]  

Hence, the spectral efficiency is a decreasing function of \( k \). As expected, increasing \( k \), with the sacrifice of the spectral efficiency, reduces the total energy per bit (or of the bit rate if the chip rate is limited).

To simplify the design and obtain a low power consumption, the considered transmitter has a nonadjustable transmit power during the ON state, denoted by \( P_{\text{out}} \). The average transmitted energy per bit (a part of \( E_{b,\text{tot}} \)) can be expressed as

\[ E_{b,t} = \frac{P_{\text{out}}}{2^k R_b} \]  

Assuming a free space path loss and thermal noise, the received average bit energy to noise ratio [13] can be written as

\[ E_b = \frac{P_{\text{out}}}{2^k R_b} \left[ \frac{\lambda}{4\pi d} \right]^2 \frac{1}{M_g k_B T_0} \]  

where \( \lambda \) is the wavelength, \( d \) is the distance between the transmitter and receiver, \( M_g \) is a safety margin, \( T_0 \) is the temperature and \( k_B \) is the Boltzman constant.

The values of these parameters[18] are given in Table 2.

If \( E_b/N_o \) is given by a target bit error rate, then the transmission range can be deduced from (12) by replacing \( R_b \) by its maximal expression (9)

\[ d = \frac{\lambda}{4\pi} \sqrt{\frac{P_{\text{out}}(2^k - 1)}{k^2 M_g R_{c,\text{max}} k_B T_0 E_b}} \]  

We can see from this last expression that the transmission range is a decreasing function of \( k \).

| Parameter                     | Value                                      |
|-------------------------------|--------------------------------------------|
| The carrier wavelength        | \( \lambda = 0.693 \text{ cm} (f = 433 \text{ MHz}) \) |
| Nonadjustable transmit power  | \( P_{\text{out}} = -12.7 \text{ dBm} \)   |
| Average power (ON state)      | \( P_h = 1.036 \text{ mW} \)               |
| DC power                      | \( P_{dc} = 0.158 \text{ mW} \)            |
| Maximum chip rate             | \( R_{c,\text{max}} = 10 \text{ Mb/s} \)   |
| The safety margin             | \( M_g = 30 \text{ dB} \)                  |
| Boltzman’s constant           | \( k_B = 1.38 \times 10^{-23} \text{ Joules/K} \) |
| Temperature                   | \( T_0 = 300 \text{ K}, \) (room temperature) |
4 Numerical Results

From the proposed energy consumption model of the ME-Coding based on the realistic OOK transmitter, the energy consumption per bit can be further analyzed. Simulations parameters are given in Table 2.

The energy consumption per source bit of chip rate (8) is plotted in Fig. 5 as a monotonically decreasing function of $R_b$. So increasing the source bit rate can reduce the energy consumption per bit. In contrast, the energy consumption has a small value of 52 pJ/bit when the bite rate is 10 Mb/s for uncoded OOK. The ME-coding can be used to reduce the energy per bit of this circuit significantly, as shown in Fig. 5. Furthermore, the improvement of energy consumption performance is more notable when $k$ increases.

We also analyze the total energy consumption per source bit in terms of coding size $k$ as shown in Fig. 6 when the chip rate is 10 Mb/s. Decreasing total energy consumption need to increase the coding size. So a larger $k$ is preferred as the optimal coding size. For example, the energy consumptions per source bit are 30 pJ/bit and 17 pJ/bit for coding sizes $k = 3$ and $k = 6$ respectively, which is much smaller than the uncoded OOK ($k = 1$) 52 pJ/bit. However, the improvement is more important for small range of $k$.

5 Optimization of the Coding Size for a Given Transmission Range

Because the transmission area is limited in lots of applications in WSNS or WBANS, it is crucial to find the minimum values of the circuit energy when transmission range is given. According to (11) and (13), increasing the coding size decreases not only the average transmitted energy per bit but also the range of the transmitter, with a fixed
output power of this circuit. That means $k$ should be as large as possible in order to have a greater energy efficiency and transmission range.

Assuming an application where the range of the transmitter must be at least $d_{\text{min}}$, we want to find $k$ that satisfies this constraint, and at the same time, minimizes the energy per bit consumed by the transmitter. This problem can be formulated as

$$\min_k E_{b,\text{tot}}(k) \quad \text{s.t.} \quad d \geq d_{\text{min}}$$

Since the energy consumption and transmission range are both decreasing functions of the coding size $k$, the optimization solution is to find $k$ from the following Eq. combining (12):

$$2^k r_0(k) = 2^k \frac{E_b}{N_o} = \left( \frac{\lambda}{4\pi d_{\text{min}}} \right)^2 \frac{P_{\text{out}}}{MR_b k_b T_0}$$

in which $r_0$ is a function of $k$ for a given BER. As shown in [24], the bit error probability of OOK based ME-Coding received through an AWGN channel by a soft decision coherent receiver is given by (5), which is too complex to be used in (14). Therefore, we try to find a simple function to approximate the bit error probability (Fig. 7).

Figure 1 shows the ground truth [25] of energy per bit to noise ratio ($\frac{E_b}{N_o}$) for different bit error rates. According to the characteristics of these values, we propose to approximate values of energy per bit by the following simple function:

$$r_0(k) = \frac{a}{k + b}$$

where $a$ and $b$ can be obtained for different values of BER, through Least Squares LS algorithm, their values are given in Table 3.
The relative root-mean-square errors of the approximation are 2.4% (BER $10^{-3}$), 2.11% (BER $10^{-4}$), 2.07% (BER $10^{-5}$), 1.03% (BER $10^{-6}$), respectively.

According to the approximation (16) and (15), (14) can be rewritten as:

$$2^k \left( \frac{a}{k+b} \right) \leq \left( \frac{\lambda}{4\pi d_{\text{min}}} \right)^2 \frac{P_{\text{out}}}{M g R_b k B T_0}$$

which can be solved for $k$:

$$k \leq -\frac{1}{\ln 2} W_L \left( -\ln 2 a 2^{-b} \left( \frac{4\pi d_{\text{min}}}{\lambda} \right)^2 \frac{M g R_b k B T_0}{P_{\text{out}}} \right) - b$$

where $W_L(x)$ is the Lambert function.

A comparison between the transmission ranges obtained by the ground truth of $r_0$ (mark points) and by the approximation in Eq. (16) (solid lines) can be given in Fig. 8 respectively, for a given $k$. This figure indicates that the approximation accurately predict the results which provides a closed-form solution (18) for the optimization problem (15).

Assuming two given transmission distances $d_{\text{min}}$ of 5 m and 10 m with $BER = 10^{-5}$ in Table 3, the coding sizes calculated by (18) are 5.6 and 2.95 respectively. Therefore the optimal coding sizes $k_o$ are 5 (ME[31,5]) and 2 (ME[3,2]) respectively. Besides, Table 3 also presents the energy consumption per bit $E_{k_o}$ of the optimal coding size $k_o$ and the energy reduction with respect to the uncoded OOK: $E_R = E_{k_o}/E_1$. For small transmission ranges, the coding size can be increased to provide an important energy reduction.

Because finding $k$ from (13) is core to the optimization problem. Figure 9 provides the obtained results for different values of the target bit error rate. The optimal $k$ increases when the distance decreases and the bit error rate increases. For each value of $P_{e^c}$, a

![Fig. 7 Signal to noise ratio $r_0$ versus coding size $k$](image-url)
minimum range is obtained when the optimal $k$ reach 1. For example the range is limited to $11m$ for $P_e = 10^{-4}$.

Figure 10 shows the total energy per bit of the transmitter for optimal $k$. The last figure shows that the optimization of the code length allows reducing the total energy per bit to very low values for a given maximum range.

### 6 Conclusion

In this paper, an application of ME-Coding to a realistic OOK circuit is studied, this transmitter turns off during the transmission of low bit. An OOK matched energy consumption model is proposed. Then we described an energy model based on this efficient circuit. The simulation results indicate that the energy consumption per bit can be reduced to 30 pJ/bit using ME-Coding (coding size $k = 3$). This energy consumption is better than that of...
uncoded OOK, which is 52 pJ/bit in high data rate (10 Mbps). Moreover, the improvement will be more significant when $k$ increases. However, the output power of the circuit is a fixed value, increasing the coding size will reduce the energy consumption and the transmission distance at the same time. Therefore, a closed-form solution has been found to
determine the optimal minimum coding size for a given transmission range. Even our work is based on a specific transmitter, it can be easily adapted to other OOK based transmitters.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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