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Energy optimisation of an OOK transmitter using high-order orthogonal modulation

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ABSTRACT

In this paper, we show that high-order orthogonal modulation can be used to optimize the power consumption of an energy efficient On-Off Keying (OOK) transmitter for short range wireless sensor applications. Our work is based on the characteristics of a high performance OOK modulator that completely turns off during the transmission of zeros and provides energies per bit in the picojoule range. We take into account the limitations of the circuit in terms of maximum modulation rate and constant output power. Based on a bit error rate performance analysis and a circuit energy model, we propose an original approach to find the energy optimal modulation order for a given range constraint.

When considering only the transmitter power consumption, a large improvement in energy per bit can be obtained by using this optimization. When considering a residual power consumption during the transmitter off state, an improvement is still obtained but is less important.

KEYWORDS

OOK; wireless sensors; energy efficiency; orthogonal modulation

1. Introduction

Wireless sensors (WS) find applications in various areas like home automation, health, safety, etc. For a large part of these applications, unidirectional communication is enough because only intermittent measurements need to be sent to the management system. In that case, it can be assumed that these devices are only composed of a sensing block associated to a transmitter block. Due to practical constraints, WS are expected to be powered by a limited energy source (battery or energy harvester) for a long period of time. The radio transmission is known to be the major energy consumer. So for energy constrained applications, the optimization of the transmission technique is crucial.

On-off keying (OOK) is the simplest form of amplitude-shift keying that represents digital data by the presence or absence of carrier. It has the advantage of more simple circuits

than more complex modulations. A good energy efficiency can be expected if the transmitter can be switched off during the transmission of zeros. Design of efficient OOK transmitters can be found in Daly, (Chee, Niknejad, & Rabaey, 2006; Chien et al., 2015; Daly & Chandrakasan, 2007; Jung et al., 2010; Raja, Chua, & Xu, 2012; Shirai et al., 2017; Yousefi et al., 2014) for VHF, UHF or K-Band.

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Especially, the transmitter proposed by Raja et al. (2012) provides an energy efficiency of 52 pJ/bit with a data rate equal to 10 Mbit/s. Due to the simplicity of the transmitter, the output power is constant and the circuit is matched to small range communications.

From the Shannon capacity theorem, we know that increasing energy efficiency implies sacrificing spectral efficiency (Proakis, 2008). It is also well known that this trade-off can be obtained by orthogonal modulations. Increasing the number of symbols reduces the energy per bit at the price of data rate decrease for a given bandwidth.

In this paper we propose to apply high-order orthogonal modulation to an efficient on-off keying transmitter and to study the optimization of the modulation. We show that these modulations can dramatically reduce the energy consumption of the transmitter. Taking into account the circuit characteristics, we propose an original approach to find the energy optimal modulation order for a given range constraint.

The paper is organized as follows. In section 2, we consider an energy efficient OOK transmitter and a circuit energy model based on a real device. Section 3 recalls the definition and performance of orthogonal modulation for non-coherent detection. Section 4 proposes the energy optimization of an OOK transmitter using orthogonal modulation. Section 5 provides numerical results. Finally a conclusion summarizes the obtained results.

2. OOK transmitter

An OOK transmitter is composed of an oscillator and a power amplifier (or buffer in the simplest case). When transmitting a bit 1, a sine wave generated by the oscillator is transmitted to the antenna through the amplifier. When transmitting a bit zero no signal is transmitted. To reduce the circuit energy consumption, it is important to shutdown the power supply of the circuit during the off state. But this operation is only possible if the start-up time of the oscillator is much lower than the bit duration.

As an example, we consider the 433-MHz OOK transmitter described by Raja et al. (2012). The circuit completely turns off the transmitter during the transmission of '0' and employs a speed up scheme to obtain high data rates and low wake up time. From the transmitter realistic parameters, the energy consumption per bit $E_{bit,OOK}$ can be derived as follows. Firstly, the circuit power consumption can be written as

$$P_{dc} = r_d P_h, \quad (1)$$

where r_d is the duty cycle of the message and P_h is the power consumption during the on state. In the data given by Raja et al. (2012), we have $P_{dc} = 518 \mu\text{W}$ for $r_d = 1/2$, so using equation (1), we can deduce $P_h = 1.036 \text{ mW}$.

In the usual case, the bits one and zero have the same probability and the duty cycle is half. The total energy per bit can be written

$$E_{bit,OOK} = \frac{P_h}{2R}, \quad (2)$$

where R is the bit rate. For $R = 10 \text{ Mbit} / \text{s}$, we get $E_{\text{bit},\text{OOK}} = 52 \text{ pJ/bit}$.

3. Orthogonal modulation

As stated in the introduction, an improvement of the energy efficiency at the price of the spectral efficiency can be obtained using high-order orthogonal modulations. We consider this type of modulation defined in figure 1 and by the following $M = 2^k$ symbols, where k is the number of bits per symbol

$$s_n(t) = 1_{[t_1, t_2]} \cos(2\pi f_0 t + \phi_n), n \in [1, M], \quad (3)$$

where $1_{[t_1, t_2]}$ is the index function, t_c is the pulse duration and f_0 is the carrier frequency. The phase ϕ_n is random because we assume that the transmitter oscillator is switched on and off during each symbol.

Figure 1. On-Off orthogonal modulation.

Due to the presence of this random phase, it is not possible to use a coherent receiver. In the case of a non-coherent detector, the bit error rate of orthogonal modulation, is given by Proakis (2008) as

$$P_{eb} = \frac{1}{2} \frac{M}{M-1} \sum_{n=1}^{M-1} C_M^n \frac{(-1)^{n+1}}{n+1} e^{-\frac{nk}{n+1} \frac{E_b}{2N_0}}. \quad (4)$$

In the next section, it will be necessary to express the required E_b / N_0 as a function of a target P_{eb} . As it is difficult to inverse equation (4), we propose an approximation of the bit error probability given by the following expression:

$$P_{eb} \simeq \frac{2^k}{4} e^{-k \frac{E_b}{2N_0}}. \quad (5)$$

As seen in figure 2, the proposed expression provides good approximations for P_{eb} under 10^{-3} and k between 1 and 8.

Figure 2. Probability of a bit error for noncoherent detection of orthogonal modulation, exact (dash line) and approximation (symbol).

We can then deduce the expression of the signal to noise ratio (SNR) per bit as a function of the target bit error rate

$$\frac{E_b}{N_0} \simeq 2 \left[\ln(2) - \frac{1}{k} \ln(4P_{eb}) \right], \quad (6)$$

which is obviously a decreasing function of k .

Orthogonal modulation based on OOK can be compared with Minimum Energy (ME) which optimizes energy by minimizing the number of ones which are present in the coded message. Every block of k bits is mapped into a $2^k - 1$ bit codeword. The BER performance of minimum coding is studied in Tang et al. (2005) and Peng et al. (2014) for unknown source statistic. Orthogonal modulation outperforms ME coding in term of required SNR. For example

for $k = 6$ and for a BER equal to 10^{-4} , a SNR per bit of 7 dB is required for non-coherent soft-decoding ME coding and 5.5 dB for non-coherent orthogonal modulation.

4. Energy optimization

With the previously defined OOK transmitter, the total energy per bit using orthogonal modulation can be written

$$E_{btot,k} = \frac{P_h}{2^k R}. \quad (7)$$

From this equation, it is obvious that increasing k or increasing the bit rate R can reduce the energy per bit. But, to obtain realistic results, the limitations of the circuits must be considered.

The first limitation deals with the bit rate which is bounded by the maximum modulation rate of the OOK transmitter and the minimum 1 pulse duration t_{cmin} . From this limitation, the maximum bit rate for an orthogonal modulation using 2^k symbols is

$$R_{max} = \frac{k}{2^k t_{cmin}}. \quad (8)$$

This equation illustrates that when increasing the number of symbols, the bit rate must be reduced to take into account the limited bandwidth of the circuit (represented by $1/t_{cmin}$).

Replacing (8) in (7), we get a new expression of the total energy per bit

$$E_{btot,k} = \frac{P_h t_{cmin}}{k}. \quad (9)$$

This expression is a decreasing function of k .

In a more realistic scenario, the control circuits of the modulator should also be considered. Assuming a power consumption P_c during the transmission of zero, the total energy per bit can be written

$$E_{btot,k} = \frac{P_h t_{cmin} + P_c t_{cmin} (2^k - 1)}{k}. \quad (10)$$

This new expression of $E_{btot,k}$ is a convex function of k and the optimal value of k , minimizing the total energy, can be easily obtained by zeroing the derivative (proof in appendice)

$$k_{E_{min}} = \frac{1 + W_L \left(\frac{P_h / P_c - 1}{e} \right)}{\ln 2}, \quad (11)$$

where W_L denotes the Lambert function. This equation shows that $k_{E_{min}}$ depends only on the ratio of the on and off power consumptions P_h / P_c .

The second limitation concerns the maximum output power P_{out} . As the transmitted symbol energy is $P_{out} \times t_{cmin}$ and we have k bits per symbol, the transmitted energy per bit can be written

$$E_b = \frac{P_{out} \times t_{cmin}}{k}. \quad (12)$$

Assuming a path loss $\left(\frac{4\pi d}{\lambda}\right)^2$, a noise power spectral density $k_b T$ and a link margin M_g , where λ is the carrier wave length, d is the distance, k_b is the Boltzmann constant and T the temperature in Kelvin, we can write

$$\frac{E_b}{N_0} = \frac{P_{out} \times t_{cmin}}{k} \left(\frac{\lambda}{4\pi d}\right)^2 \frac{1}{M_g k_b T}. \quad (13)$$

From this expression, the maximum range of the device can be deduced

$$d = \frac{\lambda}{4\pi} \sqrt{\frac{P_{out} t_{cmin}}{M_g k k_b T \frac{E_b}{N_0}}}. \quad (14)$$

By replacing (6) in (14) we get

$$d = \frac{\lambda}{4\pi} \sqrt{\frac{P_{out} t_{cmin}}{M_g k_b T (2k \ln(2) - 2 \ln(4P_{eb}))}}. \quad (15)$$

We note that if k increases, the transmission range is reduced. Solving for k , we can also express the value of k for a range d_{min} as

$$k_{d_{min}} = \frac{P_{out} t_{cmin} \left(\frac{\lambda}{4\pi d_{min}}\right)^2 \frac{1}{M_g k_b T} + 2 \ln(4P_{eb})}{2 \ln(2)}. \quad (16)$$

In a lot of applications the area of transmission is limited (for example to a room) and it can be interesting to optimize the circuit energy for a given transmission range d_{min} .

This problem can be written

$$\min_k E_{btot,k} \quad s.t. \quad d \geq d_{min}. \quad (17)$$

As the range is a decreasing function of k and $E_{btot,k}$ is a convex function, the problem which is illustrated in figure 3, can be solved in two steps. Firstly determine $k_{d_{min}}$ for the target range using equation (16). Then determine $k_{E_{min}}$ using equation (11).

- If $k_{d_{min}} < k_{E_{min}}$, the range for $k_{E_{min}}$ is less than d_{min} because we are in the decreasing part of $E_{btot,k}$. The constraint is active and the solution is $k_{d_{min}}$. For example, this situation is obtained for $d_{min} = 16$ m in the figure 3. The optimal value is $k_{d_{min}} = 3$.

- In the other case, the solution is $k_{E_{min}}$. The constraint is not active because we are in the increasing part of $E_{btot,k}$. This situation is obtained for $d_{min} = 14$ m in the figure 3. We have

$k_{d_{min}} = 6$ and $k_{E_{min}} = 5$. The solution is $k_{E_{min}} = 5$.

Figure 3. Illustration of solving problem (17). E_{bitot} (square) and d (o) as a function of k .

Increasing the number of bits per symbol k can be interesting in terms of energy optimization but the price to pay is the decrease of spectrum efficiency. This effect can be evaluated using a simple scenario. Assume M_s sensors communicating with an access point in a limited area (a house for example). Assume that each sensor send K bits every T_t seconds (These K bits include the frame header and the payload). Using a modulation with k bits per symbol, the K bits can be transmitted using N_s symbols

$$N_s = \lceil \frac{K}{k} \rceil, \quad (18)$$

where $\lceil x \rceil$ denotes the ceiling function. The frame duration T_f , to transmit the N_s symbols, can be expressed as:

$$T_f = T_{cmin} 2^k N_s \quad (19)$$

Assuming that the sensors are not synchronized, the probability that the $M_s - 1$ other sensors transmit during the first sensor transmission can be written

$$P_{collision} = \frac{T_{cmin}}{T_t} 2^k \lceil \frac{K}{k} \rceil N_s (M_s - 1). \quad (20)$$

This probability is a growing function of k but it must be noticed that, in practical applications, the ratio T_{cmin} / T_f is very small so that $P_{collision}$ remains very low. This remark will be illustrated at the end of the next section.

5. Numerical results

With the previous expressions, we can evaluate, as an example, the OOK transmitter proposed by Raja et al. (2012) implementing OOK orthogonal modulation. The used numerical parameters are given in the table 1.

Table 1. Parameters for the numerical analysis.

Parameter	Value	Unit
P_h	1.036	mW
t_{cmin}	0.1	μ s
P_c	0,1 or 10	μ W
P_{out}	-12.7	dBm
k_b	1.38×10^{-23}	$J.K^{-1}$
T	300	K
Mg	30	dB
λ	0.69	m

Figure 4. Total energy per bit versus bit per symbol, (o) $P_c = 1 \mu\text{W}$, (x) $P_c = 0 \mu\text{W}$.

We first analyze the total energy per bit using formula (10) with $P_c = 0 \mu\text{W}$ (figure 4). It can be shown that the total energy per bit of 52 pJ/bit for OOK modulation can be reduced to 35 pJ/bit for orthogonal modulation with $k = 3$ and to 17.5 pJ/bit for $k = 6$, which represent an energy reduction of respectively 32 % and 66 % compared to the OOK transmitter presented in Raja et al. (2012).

When taking into account the power consumption of the other circuits, we consider $P_c = 1 \mu\text{W}$. This small value represents the power consumption of a microcontroller in shutdown mode waiting a timer to wake up. It can be shown in figure 4 that the total energy firstly decreases with k to a minimum value and then increases. This is due to the influence of P_c which becomes predominant when the symbol duration is large.

For the given parameters, the minimum energy is obtained for $k = 8$ which is in agreement with formula (11) which provides $k_{Emin} = 7.78$. The obtained optimal total energy per bit is 16 pJ/bit representing an energy reduction of 69 % compared to the OOK transmitter presented in Raja et al. (2012).

Figure 5. Transmission range as a function of k .

The output power of the OOK transmitter is limited to -12.7 dBm. For that reason, the considered device is only matched to small range communication. Using formulas (6) and (14) the figure 5 provides the transmitter range for $P_{eb} = 10^{-4}$ and $P_{eb} = 10^{-3}$. Obviously the range decreases when k increases or the target P_{eb} decreases. This figure shows also Monte Carlo simulation results which are in good accordance with analytic results.

The parameter k can now be optimized to obtain a given range d_{min} . When $P_c = 0 \mu\text{W}$, the solution is provided by equation (16) saturating the minimum value to 2. The obtained results, for $P_{eb} = 10^{-3}$ are plotted in figure 6 as a function of d_{min} . The optimal k decreases with the distance. When a value of 2 is reached it must be noticed that the range cannot be obtained. So considering the particular device and our propagation model, the range is limited to 17 m. Finally, the total energy per bit can be largely reduced by optimizing k for a given range. For example, for a range less than 10 m, the total energy can be reduced to about 5 pJ/bit, i.e. 10 times less than in OOK.

When P_c is no more zero, the procedure described at the end of the part 4 must be used to find the optimal k for a given maximum range. Figures 7 illustrates the obtained results for $P_c = 1 \mu\text{W}$ ($P_h / P_c \approx 1000$). In the first case, for distances less than 14 meters, the optimal k is now constant equal to 8. A larger value of k would increase the total energy per bit due to the influence of P_c . The total energy per bit can be reduced from 52 pJ/bit in OOK to 16 pJ/bit in orthogonal modulation with a maximum range equal to 14 m.

Figure 6. Optimal k (o) and bit energy (square) as a function of the distance.

Figure 7. Optimal k (o) and total energy per bit (square) versus distance with $P_c = 1 \mu\text{W}$ (

$P_h / P_c \approx 1000$).

Finally, to illustrate the influence of the number of sensors, we consider the simple scenario given at the end of the previous section. The number of sensors is $M = 20$. The number of bits transmitted by each sensor is $K = 16$ and the transmitting period is $T_t = 1s$. Using expression (20), the probability of collision is plotted in figure 8 as the function of k . As already noticed, the probability of collision increases with k but remains low when the transmission period is much larger than t_{cmin} .

Figure 8. Probability of collision, equation (20) (dash line) and Monte-Carlo simulation (*).

6. Conclusion

Energy efficient OOK transmitter for short range wireless sensor applications can be improved by using high order orthogonal modulation. An optimization scheme has been proposed using bit error rate performance analysis associated to circuit energy model. It allows to find the number of symbols which provides the minimum energy per bit for a target maximum range. A large improvement in energy per bit can be obtained if the power consumption during the off state is very small or null. Increasing the number of symbols of orthogonal modulation increases the symbol duration and then the channel occupancy. We showed that this effect has little impact in a simple multi-user scenario.

Orthogonal modulation associated to efficient OOK transmitter provides an energy efficient solution for short range wireless sensors. However, to obtain the maximal efficiency, effort must be done on the circuit design to reduce the power consumption when the transmitter is off.

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Appendix A. Proof of the expression of optimal k

Proof of the expression of optimal k (11): zeroing the derivative of (10) with respects to k we get

$$2^k (k \ln(2) - 1) = P_h / P_c - 1. \quad (\text{A1})$$

Let $w = k \ln(2) - 1$ we can write equation (A1) as

$$w 2^{\frac{w+1}{\ln(2)}} = w e^{w+1} = P_h / P_c - 1. \quad (\text{A2})$$

Using the definition of the Lambert function, we get

$$w = W_L \left(\frac{P_h / P_c - 1}{e} \right). \quad (\text{A3})$$

Thus replacing the expression of w

$$k_{opt} = \frac{1 + W_L \left(\frac{P_h / P_c - 1}{e} \right)}{\ln 2}. \quad (\text{A4})$$

The second derivative of (10) is

$$\frac{P_c t_{cmin}}{k^3} \left[2^k (k^2 \ln(2) - 2k \ln(2) + 2) + 2 \left(\frac{P_h}{P_c} - 1 \right) \right], \quad (\text{A5})$$

which is always positive for $k \geq 0$ because $P_h > P_c$ and $k^2 \ln(2) - 2k \ln(2) + 2 > 1$. So $E_{btot,k}$ is a convex function of k for $k \geq 0$.

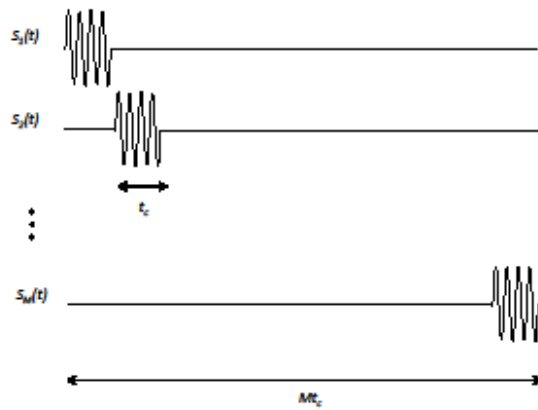


Figure 1. On-Off orthogonal modulation.

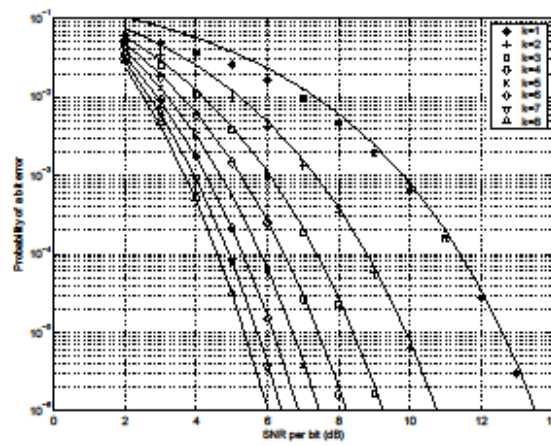


Figure 2. Probability of a bit error for noncoherent detection of orthogonal modulation, exact (dash line) and approximation (symbol).

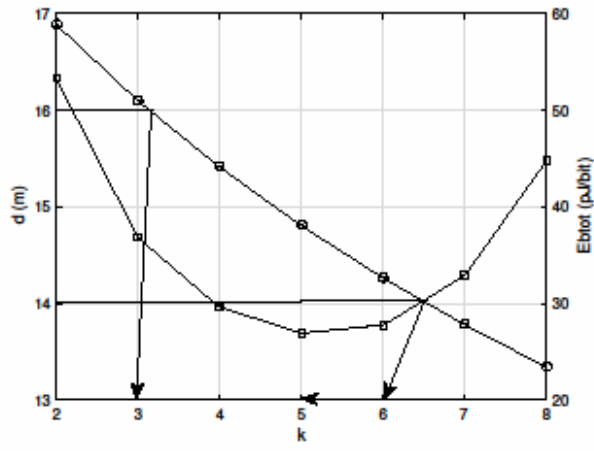


Figure 3. Illustration of solving problem (17). E_{tot} (square) and d (o) as a function of k .

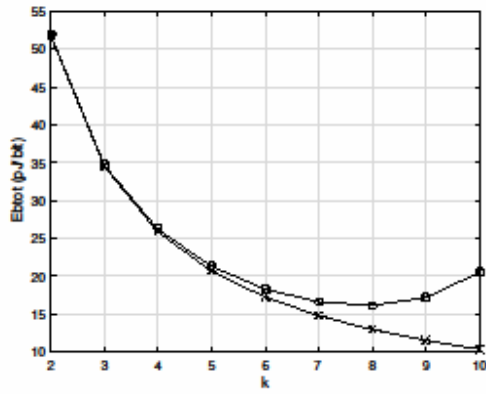


Figure 4. Total energy per bit versus bit per symbol, (o) $P_c = 1 \mu W$, (x) $P_c = 0 \mu W$.

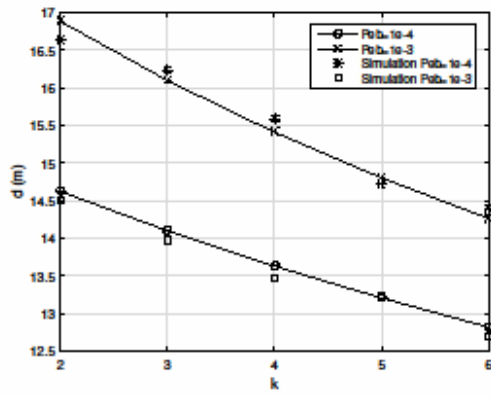


Figure 5. Transmission range as a function of k .

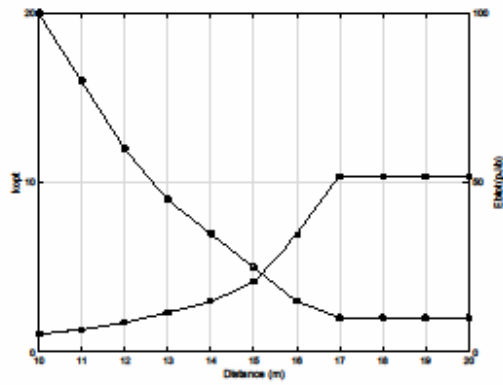


Figure 6. Optimal k (o) and bit energy (square) as a function of the distance.

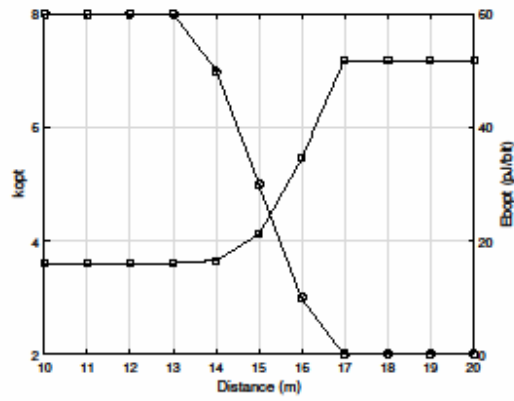


Figure 7. Optimal k (o) and total energy per bit (square) versus distance with $P_c = 1 \mu\text{W}$ ($P_h/P_c \approx 1000$).

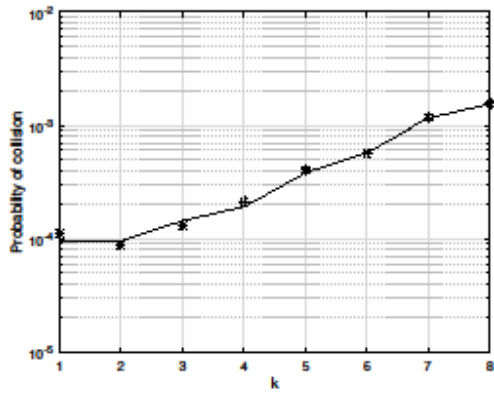


Figure 8. Probability of collision, equation (20) (dash line) and Monte-Carlo simulation (*).