Smart Sensors for IoT
Exercise 1 (20.09.2023)

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Problem 1 Sensors autonomy

Consider a sensor applied on the human body used to monitor the blood pressure, which uses $P_{op} = 1\,\text{mW}$ when on.

- If the node is powered with a LR44 button cell battery (capacity $C_{battery} = 150\,\text{mAh}$ and voltage $V_{battery} = 1.5\,\text{V}$), what is its lifetime?
- The power can be aggressively reduced by duty cycling the IoT node operation, alternating active tasks and long sleep periods as depicted in Fig. 1, with periodicity set by the wake-up cycle T.

  We consider $T = 100\,\text{ms}$ and a current consumption of $I_{sb} = 10\,\text{nA}$ in standby mode which is steered from the battery (we neglect the wake-up- and the sleep energy).

  - What would be an appropriate duty-cycle to extend the lifetime of the battery up to 2 years (17520 hours)?
  - What is the energy consumption during the active mode and sleep mode respectively?
- We now want to power the node, with the same duty cycle as the previous point, with the harvested thermal energy generated by the human body which we would store during one tenth of the sleep-mode time with an efficiency η of the 50%. What surface S would we need in order to harvest enough energy? (Refer to Table 1).

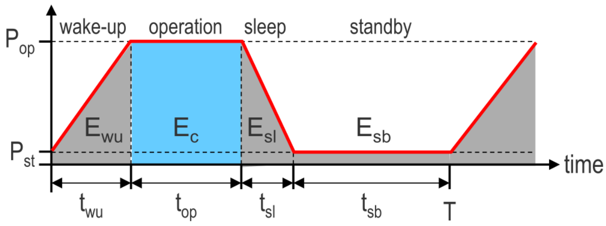
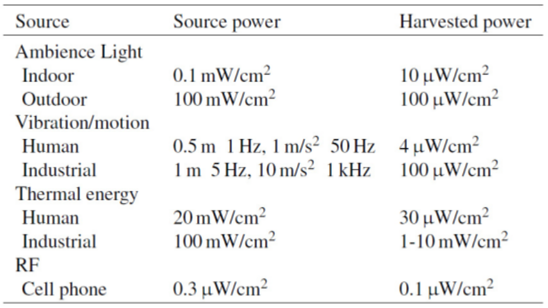


Figure 1: Scheme for alternating active tasks and long sleep periods.

Table 1: Available power from various energy sources.



Source	Source power	Harvested power
Ambience Light		
Indoor	0.1 mW/cm^2	10 µW/cm^2
Outdoor	100 mW/cm^2	100 µW/cm^2
Vibration/motion		
Human	0.5 m 1 Hz, 1 m/s^2 50 Hz	4 µW/cm^2
Industrial	1 m 5 Hz, 10 m/s^2 1 kHz	100 µW/cm^2
Thermal energy		
Human	20 mW/cm^2	30 µW/cm^2
Industrial	100 mW/cm^2	1-10 mW/cm^2
RF		
Cell phone	0.3 µW/cm^2	0.1 µW/cm^2

Problem 2 Duty cycled radio design

2.1 Defining a metric (Figure of Merit)

Let's assume an ultra-low-power (ULP) system which has to maintain a mean data rate of MDR [bps]. Let the time taken for this system to communicate K bits of data be T_d [s] $= K/MDR$. If the system employs a transmitter capable of a peak data rate of PDR [bps], then it can be duty cycled with a ratio $DC = MDR/PDR$. The packet rate of the system is given by R_p [packets/s] $= MDR/L$ where L is the length of each packet. The duration of each packet is then D_p [s] $= L/PDR$. If this radio consumes a peak power of P_p[W] while in operation, then the energy spent for communicating K bits of data is given by E_c [J] $= T_d \times R_p \times D_p \times P_p$ (communication energy). In addition, the static energy overhead in the radio is denoted as E_{oh} [J]. If the radio dissipates a power of P_{wu} (W) during wake-up, the overhead energy spent during each wake-up cycle will be E_{oh} [J] $= P_{wu} \times T_{wu}$, where T_{wu} [s] is the wake-up time of the radio (which is usually dominated by the frequency synthesizer wake up time). Subsequently, the energy wasted as overhead during the transmission of K data bits is $E_{oh,tot}$ [J] $= T_d \times R_p \times E_{oh}$. Then, the overall energy spent by the system for transmitting K bits of raw data is $E_{p,tot}$ [J] $= E_c + E_{oh,tot}$, which is the most important metric (Figure of Merit) for duty cycled radios.

2.2 Exercise

Let's assume a ULP radio communicating 10 kb/s on average. Now let the radio, used in the system, utilize a transmitter which has a peak operational power dissipation (P_p) of 5.4 mW and are capable of a peak data rate (PDR) of 2 Mb/s.

- In order to achieve the MDR of 10 kb/s, what duty-cycle ratio (DC) should the system use?
- Set the packet length L in bytes in order to get a packet duration D_p of 125 µs. Calculate then the packet rate R_p.
- If the data transmitted by the system is assumed to be $K = 10$ kb calculate the mean energy dissipated for communication E_c.

If such an system employs a PLL-based[1] radio for its radio, then the system will have a long wake up time owing to the Crystal Oscillator (XO) (typically $T_w = 1$ ms) and a high start up power dissipation (P_{st}) of around 1 mW which worsens the $E_{p,tot}$. After this startup time, the XO usually uses 100 µW

- Would the power consumption improve if the XO is permanently left on? Why?
- What if the XO is duty-cycled?

Let's consider the XO permanently on and in addition to this, assuming a best case PLL settling time of around 20 µs, the energy overhead due to the PLL will be around 4.3 µJ. This is shown in Fig. 2 which graphically explains the aforementioned energy dissipation calculations.

- What is the total energy dissipated considering also the XO startup when transmitting 10 kb of data?
- If the system uses a 3 V CR2032 button cell battery (225 mAh) as its power source, what would be (in days) its lifetime?

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[1] A phase-locked loop or phase lock loop (PLL) is a control system that generates an output signal whose phase is related to the phase of an input signal. Phase-locked loops are widely employed in radio, telecommunications, computers and other electronic applications and can be used to generate a stable frequency at multiples of an input frequency (in this case the input frequency is given by the crystal oscillator).

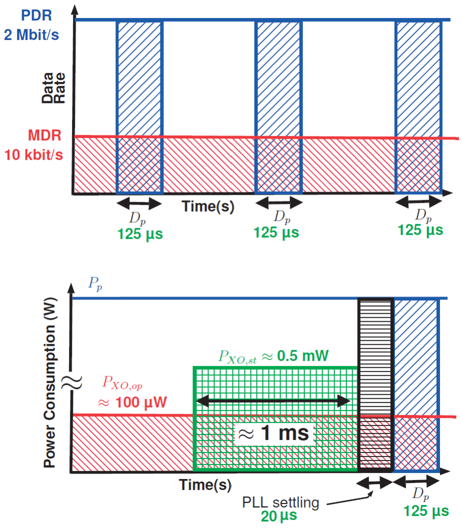

Figure 2: PLL-based Transmitter duty cycling showing the various sources of energy dissipation in a duty cycled system - Multi-packet communication (top) and Single packet communication with crystal oscillator startup overhead (bottom). (A phase-locked loop (PLL) is an integrated circuit used to generate a clock signal).

Solutions to Exercise 1 (20.09.2023)

Problem 1 Sensors autonomy

Consider a sensor applied on the human body used to monitor the blood pressure, which uses $P_{op} = 1\,\text{mW}$ when on.

- If the node is powered with a LR44 button cell battery (capacity $C_{battery} = 150\,\text{mAh}$ and voltage $V_{battery} = 1.5\,\text{V}$), what is its lifetime?

The energy given by the battery is:

$$E_{battery} = C_{battery} \cdot V_{battery} = 150\,\text{mAh} \cdot 1.5\,\text{V} = 225\,\text{mWh}. \tag{1}$$

The battery lifetime can then be calculated as:

$$t_{lifetime} = E_{battery}/P_{op} = 225\,\text{h} = 9.375\,\text{days}. \tag{2}$$

- The power can be aggressively reduced by duty cycling the IoT node operation, alternating active tasks and long sleep periods as depicted in Fig. 1, with periodicity set by the wake-up cycle T.

  We consider $T = 100\,\text{ms}$ and a current consumption of $I_{sb} = 10\,\text{nA}$ in standby mode which is steered from the battery (we neglect the wake-up- and the sleep energy).
  - What would be an appropriate duty-cycle to extend the lifetime of the battery up to 2 years (17520 hours)?
  - What is the energy consumption during the active mode and sleep mode respectively?

We have first to calculate the average power as:

$$P_{avg} = P_{op} \cdot \frac{t_{op}}{T} + P_{sb} \cdot \frac{t_{sb}}{T} = P_{op} \cdot D + P_{sb} \cdot (1 - D), \tag{3}$$

where D is the duty-cycle expressed in decimals.

The standby power is given as:

$$P_{sb} = I_{sb} \cdot V_{battery} = 15\,\text{nW}. \tag{4}$$

Similarly to (2), we define the lifetime as:

$$t_{lifetime} = E_{battery}/P_{avg} = \frac{E_{battery}}{P_{op} \cdot D + P_{sb} \cdot (1 - D)}, \tag{5}$$

from which

$$D = \frac{E_{battery} - P_{sb} \cdot t_{lifetime}}{t_{lifetime} \cdot (P_{op} - P_{sb})} = 0.0128 = 1.28\%. \tag{6}$$

The energy consumed during the operation and standby time are respectively:

$$E_{op} = P_{op} \cdot t_{op} = P_{op} \cdot D \cdot T = 1.28\,\mu\text{J} \qquad E_{sb} = P_{sb} \cdot t_{sb} = P_{sb} \cdot (1 - D) \cdot T = 1.48\,\text{nJ}. \tag{7}$$

- We now want to power the node, with the same duty cycle as the previous point, with the harvested thermal energy generated by the human body which we would store during one tenth of the sleep-mode time with an efficiency η of the 50%. What surface S would we need in order to harvest enough energy? (Refer to Table 1).

The energy used by the sensors is $E_{tot} = E_{op} + E_{sb} \approx E_{op} = 1.28\,\mu\text{J}$, therefore we need to harvest an energy greater than this each cycle. This energy needs to be collected during the non-operating phase, therefore during a time $t_{sb} = (1 - D)T$. To be on the safe side, let us consider tenfold the required energy:

$$E_{harv} = \frac{1}{10} \cdot t_{sb} \cdot \eta \cdot \textit{Harvested Power} \cdot S, \tag{8}$$

from which the minimum required surface in order to get the required energy is:

$$S = \frac{10 \cdot E_{harv}}{t_{sb} \cdot \eta \cdot \textit{Harvested Power}} = 8.6\,\text{cm}^2. \tag{9}$$

Problem 2 Duty cycled radio design

2.1 Exercise

Let's assume a ULP radio communicating 10 kb/s on average. Now let the radio used in the system utilize a transmitter which has a peak operational power dissipation (P_p) of 5.4 mW and are capable of a peak data rate (PDR) of 2 Mb/s.

- In order o achieve the MDR of 10 kb/s, what duty-cycle ratio (DC) should the system use?

$$DC = \frac{MDR}{PDR} = \frac{10\,\text{kb/s}}{2\,\text{Mb/s}} = 0.5\% \tag{10}$$

- Set the packet length L in bytes in order to get a packet duration D_p of 125 µs. Calculate then the packet rate R_p.

$$D_p = \frac{L}{PDR} \Rightarrow L = D_p \times PDR = 125\,\mu\text{s} \times 2\,\text{Mb/s} = 250\,\text{b} = 32\,\text{bytes} \tag{11a}$$

$$R_p = \frac{MDR}{L} = \frac{10\,\text{kb/s}}{250\,\text{b}} = 40\,\text{packets/s} \tag{11b}$$

- If the data transmitted by the system is assumed to be $K = 10\,\text{kb}$ calculate the mean energy dissipated for communication E_c.

$$T_d = \frac{K}{MDR} = \frac{10\,\mathrm{kb}}{10\,\mathrm{kb/s}} = 1\,\mathrm{s} \tag{12a}$$

$$E_c = T_d \times R_p \times D_p \times P_p = 1\,\mathrm{s} \times 40\,\mathrm{packets/s} \times 125\,\mathrm{\mu s} \times 5.4\,\mathrm{mW} = 27\,\mathrm{\mu J} \tag{12b}$$

If such an system employs a PLL-based radio for its radio, then the system will have a long wake up time owing to the XO (typically $T_w = 1\,\mathrm{ms}$) and a high start up power dissipation (P_{st}) of around $1\,\mathrm{mW}$ which worsens the $E_{p,tot}$. After this startup time, the XO usually uses $50 - 100\,\mathrm{\mu W}$

- Would the power consumption improve if the XO is permanently left on? Why?
- What if the XO is duty-cycled?

Regarding to the energy overhead, due to its long startup time, the XO is usually left permanently ON during which time it consumes $P_{XO} = 100\,\mathrm{\mu W}$ of power. Therefore the energy overhead for the transmission of 10 kb of data is

$$E_{oh,tot} = P_{XO} \cdot T_d = 100\,\mathrm{\mu J}, \tag{13}$$

which is higher than the energy spent to communicate.

Even if duty cycling of the XO along with the TX is pursued (and this is not really feasible as the startup time is too slow), based on the 1 ms startup time and 0.5 mW power, the energy overhead is 20 µJ for 40 packets/s by applying (12).

Let's consider the XO permanently on and in addition to this, assuming a best case PLL settling time of around 20 µs, the energy overhead due to the PLL will be around 4.3 µJ. This is shown in Fig. 2 which graphically explains the aforementioned energy dissipation calculations.

- What is the total energy dissipated considering also the XO startup (once) when transmitting 10 kb of data?

$$\begin{aligned} E_{p,tot} = E_c + E_{oh,tot} &= E_c + E_{oh,PLL} + E_{XO,st} + E_{XO,op} \\ &\approx 27\,\mathrm{\mu J} + 4.3\,\mathrm{\mu J} + 0.5\,\mathrm{\mu J} + 100\,\mathrm{\mu J} = 131.8\,\mathrm{\mu J} \end{aligned} \tag{14}$$

- If the system uses a 3 V CR2032 button cell battery (225 mAh) as its power source, what would be (in days) its lifetime?

Since the XO is started up only once, its energy dissipation can be neglected in order to calculate the battery life time, therefore the considered total energy $E_{p,tot}$ is 131.3 µJ, which translates into a power load P_{tot} of 131.3 µW.

The battery can provide $3\,\mathrm{V} \times 225\,\mathrm{mAh} = 675\,\mathrm{mWh}$, which (with and ideal efficiency) can sustain the system for $675\,\mathrm{mWh}/131.3\,\mathrm{\mu W} = 5140\,\mathrm{h} \approx 214\,\mathrm{days}$.