The energy benefit of level-crossing sampling including the actuator's energy consumption

Burkhard Hensel, Klaus Kabitzsch
Dresden University of Technology
Chair for Technical Information Systems, 01062 Dresden, Germany
Email: {burkhard.hensel, klaus.kabitzsch}@tu-dresden.de

***Abstract*—When using level-crossing (also called send-on-delta) sampling in control loops, messages can be saved compared to periodic sampling without degrading control performance. While it is clear that reducing messages improves also the energy efficiency of battery-powered sensor devices, this can be disadvantageous for the energy efficiency the actuator device.**

This paper addresses the question, under which conditions level-crossing sampling is also for the actuator device more energy-efficient than periodic sampling. It is shown that there is an optimum inter-sample interval. Methods for reaching this optimum by appropriate controller and transmission settings are given.

The theory is demonstrated using several known, standardized wireless network protocols.

I. Introduction

Level-crossing sampling as the most popular kind of nonuniform (not equidistant) sampling gains importance for networked control loops as it allows message reduction without loss of control performance [1]. Especially if energy consumption is critical because of the usage of automation devices powered by batteries or energy harvesting, this message reduction is advantageous. Several analyses about the benefit of level-crossing sampling have already been done (e. g. [1]–[3]). However, these articles focus on the reduction of the message rate and the sensors' energy consumption while it has not been considered whether level-crossing sampling is also profitable for the actuators' energy consumption. This is a relevant question if both devices (sensor and actuator) are battery powered, as it is often the case for electronically controlled room temperature control loops. The question to be answered by this paper is:

Under which conditions is level-crossing sampling more energy-efficient than periodic sampling?

Besides, some hints are given, how the minimal energy consumption can be reached without reduced control performance. At the end, several concrete examples of commercially available devices are considered.

Energy can also be saved by other methods, like reducing the transmission power, optimizing code, using more energy-efficient devices etc. [4], [5]. This is *not* content of this paper.

II. Assumptions

In this work it is assumed that there are two wireless devices, a sensor and an actuator, which work together. For several reasons, it is assumed that the controller is contained either in the sensor or in the actuator node:

- This simplifies the calculations.
- This is usual today, at least for room temperature control loops which are the probably most widespread application for the combination of level-crossing sampling and battery-powered actuators (compare [6]).
- This saves messages, energy, and costs for the otherwise necessary additional controller device including its installation.
- The results can also be applied if an additional controller device is used by separately analysing the transmission from the sensor to the controller and from the controller to the actuator, respectively.

If the controller is contained in the sensor device, the manipulated variable u is transmitted (e. g. valve opening), otherwise the controlled variable y (e. g. room temperature). Further it is assumed that sensor and actuator communicate *directly*, hence need no repeater or other devices for multi-hop communication.

In periodically sampled control loops, the sensor wakes up periodically with sampling period T_s, measures the controlled variable y and sends it (or the manipulated variable u if the controller is integrated in the sensor) to the actuator. The actuator device also wakes up periodically, listens until the message arrives and manipulates the actuator according to the manipulated variable. So both devices can sleep most time.

When using level-crossing sampling, also both devices wake up periodically, but a message is only sent if the variable to be sent has changed from the last sent value at least by a threshold Δ_{lc} [1], [6]. Mathematically formulated, the condition is

$$|y(t_n) - y(t_{n-1})| \geq \Delta_{lc} \tag{1}$$

or

$$|u(t_n) - u(t_{n-1})| \geq \Delta_{lc}, \tag{2}$$

respectively, where t_{n-1} and t_n are two subsequent time instances at which a message is sent. Therefore, level-crossing sampling is also called "send-on-delta sampling" [2], [3].

If *no* message arrives and the controller is integrated in the *actuator* device, the controller uses the last sent controlled variable value for computing the new manipulated variable. This leads to an only small error, because from the level-crossing condition (1) it can be concluded that the difference between the current controlled variable y_m and the value y_c used by the controller is small, i. e. smaller than Δ_{lc}. If *no* message arrives and the controller is integrated in the *sensor* device, the actuator position does not change. Also here, (2) ensures that the control performance difference to periodic

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transmission is only small. Because of this little difference, level-crossing sampling has also only little influence on the necessary actuator action (e. g. energy for adjusting a valve). If a critical time span without messages has elapsed, the actuator device should assume a communication breakdown (e. g. due to an empty battery of the sensor), bring the actuator into a safe state and try to resynchronize to the sensor.

For the following calculations, only the energy consumption of transmission-related actions is regarded. That means that constant (e. g. CPU/transceiver standby current, display) or periodic (e. g. wake-up, measuring, actuator movement) energy consumption parts as well as—in a long-term view—very rare actions (e. g. change of settings, display back light when pressing a button, initialization actions after battery changes) are not considered. The power in "sleep mode" is assumed to be constant or at least usable as a mean value over long time. All other powers are calculated as the *difference* to the "sleep" power so that the "sleep" power is always there (also if the devices are awake). The energy for the actuator movement is not equal for each period (because it depends on the control loop state) but can be averaged over long time. Further, as long as the control loop behaviour remains similar because of using a reasonably small threshold Δ_{lc}, it is hardly influenced by the transmission scheme.

III. Used symbols

Energy is written as E, power as P, time spans as T. The superscript marks whether the sensor s, actuator a or both (tot for total) are considered. The subscript defines more exact what is meant. For example, P^s_{sleep} is the power of the sensor when sleeping.

The energy portions which are necessary for one communication are combined to E^s_{comm} and E^a_{comm}, respectively. That allows to be independent of concrete transmission methods. The communication contains several tasks like creating a message (e. g. calculation of a CRC code or checksum), waking up the transceiver, sending a message, receiving a message and interpreting it (also checking a CRC code). Also sending and receiving an acknowledgement is included if provided by the network. *Not* included is the listening period before the communication as it depends on how long the last transmission was ago, what depends on the sampling scheme.

IV. Periodic transmission/sampling

As a simple starting point, periodic transmission is analysed. The mean communication power of the sensor is

$$P^s_{per} = \frac{E^s_{comm}}{T_s} \tag{3}$$

and the mean power of the actuator is

$$P^a_{per} = \frac{E^a_{drift} + E^a_{comm}}{T_s}. \tag{4}$$

The part E^a_{drift} results from the period when the actuator is listening before the message is transmitted. Due to inaccuracy of oscillators, the actuator must start listening a sufficiently long time before expecting the message. This time T_{drift} can be assumed as

$$T_{drift} \approx 2 \cdot p_{drift} \cdot T_s \tag{5}$$

where p_{drift} is the maximum drift (inaccuracy) of the oscillator, typically 20-60 ppm. The factor two comes from the worst-case assumption that the sensor clock goes maximum faster and the actuator clock maximum slower than ideal. This "idle listening" of the actuator can be avoided by polling the sensor by the actuator, but this only shifts the energy problems to the sensor. If listening needs more energy than sending (what is the case for many transceivers nowadays), it may be advantageous if the sensor wakes up T_{drift} before the next regular sampling time and sends the message repeatedly until the actuator wakes up and sends an acknowledgement, comparable to "preamble strobing" [7]. Unfortunately, this method leads to a more often occupied channel, thus more probable message collisions and perhaps even problems with maximum sending time regulations. Furthermore, it is not supported by currently popular wireless network technologies which try to minimize the network load (see section VII).

The overall power is

$$P^{tot}_{per} = P^s_{per} + P^a_{per} = \frac{E^a_{drift} + E^{tot}_{comm}}{T_s}. \tag{6}$$

The same equations hold for "roughly-periodic" sampling (used in some commercial protocols [8]) if the average sampling period is used.

V. Level-crossing transmission/sampling

In case of level-crossing sampling, several (here called n) sampling periods can elapse before the next message is sent. The mean energy consumption of the sensor for communication is

$$P^s_{lc} = \frac{E^s_{comm}}{n \cdot T_s} \tag{7}$$

and is the smaller, the larger n is, i. e. the less often it must send. Thus, level-crossing sampling is always more energy-efficient than periodic sampling from the sensor's point of view.

Because of the oscillator drift, the listening time of the actuator device has to be increased after each sampling period without transmission. Additionally, if no message is sent, it must be listened not only before the expected transmission time instance but also after it for the same time span because it is possible that the sensor clock is slower than the actuator clock. So, i periods after the last transmission the listening time T^a_{list} (if no message is sent) must be

$$T^a_{list} = 2 \cdot i \cdot T_{drift}. \tag{8}$$

If a message is sent, then the expectation for the listening time is only the half of T^a_{list} because after getting the message, the actuator device can switch off the receiver. The mean power of the actuator device is

$$\begin{aligned} P^a_{lc} &= \frac{\sum_{i=1}^{n-1} \left(2 \cdot i \cdot E^a_{drift}\right) + n \cdot E^a_{drift} + E^a_{comm}}{n \cdot T_s} \\ &= \frac{n \cdot E^a_{drift} + \frac{1}{n} \cdot E^a_{comm}}{T_s}. \end{aligned} \tag{9}$$

The sum of both powers is

$$P^{tot}_{lc} = P^s_{lc} + P^a_{lc} = \frac{n \cdot E^a_{drift} + \frac{1}{n} \cdot E^{tot}_{comm}}{T_s}. \tag{10}$$

Both, energy consumption of the actuator (9) and energy consumption of both nodes together (10), are a similar function of n. It is the sum of a hyperbolic part—energy is saved if no communication is necessary—and a linear part—more energy for listening due to synchronisation problems is necessary. This is shown graphically in Fig. 1. So, there must exist a global minimum at some n.

The minimum can be got by finding the root of the deviation

$$\frac{\mathrm{d}P_{lc}^{tot}}{\mathrm{d}t} = \frac{E_{drift}^{a}}{T_s} - \frac{E_{comm}^{tot}}{T_s} \cdot \frac{1}{n^2}. \tag{11}$$

This optimum n is

$$n_{opt}^{tot} = \sqrt{\frac{E_{comm}^{tot}}{E_{drift}^{a}}}. \tag{12}$$

Analogously can be found

$$n_{opt}^{a} = \sqrt{\frac{E_{comm}^{a}}{E_{drift}^{a}}}. \tag{13}$$

The value n is only realizable for integers, so the practical minimum $\tilde{n}_{opt}^{tot}$ is one of the both integers next to the theoretical n_{opt}^{tot}. The minimum can be found by computing both powers and taking the n with lower power consumption.

Besides, this transmission scheme contains also the periodic case for $n = 1$. That means that level-crossing sampling is only useful, if the minimum energy is reached for $n > 1$, i. e. $\tilde{n}_{opt}^{tot} > 1$. This can be checked as follows. P_{lc}^{tot} must be smaller for $n = 2$ than for $n = 1$.

$$\begin{aligned}
\frac{\frac{1}{2} \cdot E_{comm}^{tot} + 2 \cdot E_{drift}^{a}}{T_s} &< \frac{E_{comm}^{tot} + E_{drift}^{a}}{T_s} \\
E_{drift}^{a} &< \frac{1}{2} \cdot E_{comm}^{tot} \qquad (14)\\
T_{drift} \cdot P_{drift}^{a} &< \frac{1}{2} \cdot E_{comm}^{tot} \qquad (15)\\
2 \cdot p_{drift} \cdot T_s \cdot P_{drift}^{a} &< \frac{1}{2} \cdot E_{comm}^{tot}
\end{aligned}$$

From that, the maximum sampling time T_s what fulfils the condition can be computed:

$$T_{s,max}^{tot} = \frac{E_{comm}^{tot}}{4 \cdot p_{drift} \cdot P_{drift}^{a}}. \tag{16}$$

Analogously:

$$T_{s,max}^{a} = \frac{E_{comm}^{a}}{4 \cdot p_{drift} \cdot P_{drift}^{a}} < T_{s,max}^{tot}. \tag{17}$$

That means, that the range of possible T_s where level-crossing sampling is more efficient for the actuator is a subset of the range for both nodes together. This is reasonable, because for the sensor level-crossing sampling is always of benefit.

As n depends on the measured signal and is thus not constant, it is also interesting, for which range of n level-crossing sampling is more efficient than periodic sampling. It must be fulfilled:

$$\begin{aligned}
P_{lc}^{tot} &< P_{per}^{tot} \\
n \cdot E_{drift}^{a} + \frac{1}{n} \cdot E_{comm}^{tot} &< E_{drift}^{a} + E_{comm}^{tot} \\
n^2 \cdot E_{drift}^{a} + E_{comm}^{tot} &< n \cdot \left(E_{drift}^{a} + E_{comm}^{tot}\right)
\end{aligned}$$

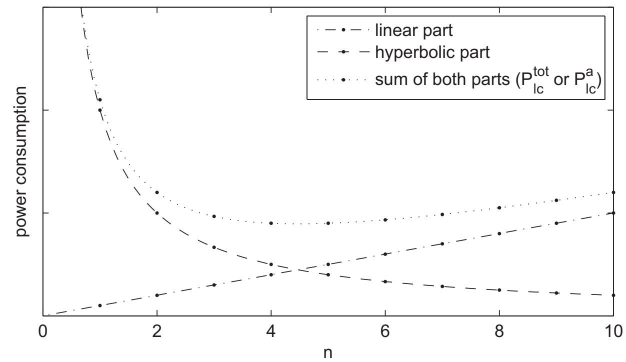

Fig. 1. Example for the power consumption P_{lc}^{tot} or P_{lc}^{a} as a function of n. Note that the function is only defined for integer n and the minimum depends on several influences, see (12) and (13).

$$n^2 \cdot E_{drift}^{a} - n \cdot \left(E_{drift}^{a} + E_{comm}^{tot}\right) + E_{comm}^{tot} < 0 \tag{18}$$

The roots of this quadratic equation deliver the bounds of the range where level-crossing sampling is better than periodic sampling:

$$\begin{aligned}
n_{min}^{tot} &= 1 \qquad (19)\\
n_{max}^{tot} &= \frac{E_{comm}^{tot}}{E_{drift}^{a}} \qquad (20)
\end{aligned}$$

and short

$$1 < n < \frac{E_{comm}^{tot}}{E_{drift}^{a}}. \tag{21}$$

This condition can only be fulfilled for integer n if

$$E_{comm}^{tot} > 2 \cdot E_{drift}^{a} \tag{22}$$

what matches to (14).

The more exact the oscillators are, the more beneficial is level-crossing sampling. In the case that the oscillators are perfect (there is no drift), n_{opt}^{tot} approaches infinity.

The lower the energy consumption of the receiver (actuator) is compared to the energy consumption of the transmitter (sensor), the more advantageous is level-crossing sampling. It is worth noting that for the transmitter power there is a lower limit, because the sending power must be so high that the power at the receiver is larger than the noise. On the other hand, the power of the receiver is not limited because it only depends on the current consumption of the used electronic devices and has no influence on the transmission itself. This leads to the assumption that in future the receiver power will be reduced more and more while the transmitter power cannot be reduced under a given level. Then, level-crossing sampling becomes increasingly profitable.

VI. Optimization of the Energy Efficiency

The value of n depends on what is going on in the control loop, but should be as close as possible to $\tilde{n}_{opt}^{tot}$.

So first, it should be avoided that n is larger than $\tilde{n}_{opt}^{tot}$. This can simply be reached by sending a message after

$$T_{max} = \tilde{n}_{opt}^{tot} \cdot T_s \tag{23}$$

also if the level-crossing condition is not fulfilled.

Avoiding that n is lower then $\tilde{n}_{opt}^{tot}$ is more difficult, because increasing the minimum inter-sample interval is semantically equivalent to increasing the sampling period and will result in degradation of control quality. However, it can be concluded that:

The inter-sample interval should be as high as possible if control performance is not degraded and T_{max} avoids that the inter-sample interval becomes too long.

This fits also to former works like [6], [9] which did not take into account the energy efficiency of the actuator. Besides, n cannot be smaller than 1 and thus level-crossing sampling can never be worse than periodic sampling when n is below $\tilde{n}_{opt}^{tot}$.

n can be increased by raising Δ_s, but this will result in control performance degradation. Instead, suitable controller settings should avoid oscillations and hence level-crossings and messages [9].

VII. Examples

The theoretical results are now applied to known wireless network technologies. Three important standardized networks are considered here. Unfortunately, only few details can be given for space reasons.

A. ISO/IEC 14543-3-10

ISO/IEC 14543-3-10 is the standard according to the lower three OSI layers of the EnOcean radio protocol. In the calculations here, a total length of 1.25 ms for one message ("subtelegram") is assumed. Up to three identical subtelegrams are sent in a time window of 40 ms to compensate message collisions. It is allowed to decrease this number. According to [10], the transmitter mode of an EnOcean Dolphin chip needs P_{send}^{s}=42.1 mW and P_{rec}^{a}=49.3 mW. So, $E_{comm}^{s}\approx$158.0 µJ (three messages), $E_{comm}^{a}\approx$ 61.7 µJ (one message), $E_{comm}^{tot}\approx$ 219.6 µJ.

The energy for creating and interpreting the message is neglected here. For understanding that, it should be noted that even 1 % of E_{comm}^{tot} is enough to let the internal processor run for 330 µs what are 5,280 clock cycles and should be enough for a lot of calculations.

For applying level-crossing sampling with benefit, (15) must hold. This means that T_{drift} must be lower than 2.23 ms. Further, (16) must hold. Since the most exact timer in the Dolphin chip has an accuracy of p_{drift}=40 ppm, the maximum sampling period is $T_{s,max}^{tot}\approx$27.8 s. If only one message is transmitted, the maximum sampling period is even shorter. This means that level-crossing sampling using these devices is not useful for temperature control (because sampling time is a few minutes), if the energy efficiency of the actuator is important.

B. IEEE 802.15.4

The standard IEEE 802.15.4 describes the two lower OSI layers of another protocol. On top of these two layers, several protocols like ZigBee, 6LoWPAN, and Wireless HART exist. The message has a duration of 512 µs and the acknowledgement a duration of 352 µs. According to the MAC layer standardization, a device must wait for a random time between 0 and 2.24 ms before sending a message, thus on average 1.12 ms. The receiver must be listening for this duration as the random time is not known.

For calculating with real values, the documentation of the ZigBee device "deRFmega128-22A002" by the vendor dresden elektronik is used what contains an Atmel ATmega128RFA1 as processor and transceiver. The energy for sending a message and receiving an acknowledge is $E_{comm}^{s}\approx$21.3 µJ; the energy for waiting the mean random time, receiving the message, and sending the acknowledgement is $E_{comm}^{a}\approx$45.7 µJ. The sum is $E_{comm}^{tot}\approx$67.0 µJ. The maximum sampling period $T_{s,max}^{tot}$ for which level-crossing sampling is advantageous is thus 12.41 s, due to the short messages. So, also here, level-crossing sampling only profitable for applications with very short sampling rates (like constant light control), if the actuator's energy consumption is of interest.

C. EN 50090-5-3

KNX-RF is the wireless version of the bus protocol KNX and is standardized in EN 50090-5-3. The overall length of one message is at least 12.7 ms. Acknowledgements are not used, but messages can be repeated to decrease the probability for message losses.

Using a Semtech SX1211 for transmission, E_{comm}^{s} is 666.6 µJ, E_{comm}^{a} is 80.0 µJ, and E_{comm}^{tot} is 746.5 µJ. Based on these values and a timer accuracy of 60 ppm, the maximum sampling time $T_{s,max}^{tot}$ is 493.7 s=8.2 min, due to the low receiver energy consumption and the long messages. As sampling times are usually shorter than 8.2 min (also for room temperature control), level-crossing sampling is very useful using that kind of device. For example, if the sampling time is 3 min, T_{drift} is 21.6 ms, E_{drift}^{a} is 136.1 µJ, n_{max}^{tot} is 5.49, and n_{opt}^{tot} is 2.34.

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