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# Feasibility of Energy Harvesting in Industrial Automation Wireless Networks

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**Abstract:** The energy consumption of industrial wireless devices and the resulting requirement for battery changes is one of the limiting factors of this technology. In this paper, an overview over the special requirements of wireless systems with a focus on energy consumption is given. This is then matched against the possibilities provided by energy harvesting in an industrial environment in order to evaluate the feasibility of fully autonomous devices. Experimental results from the deployment of energy harvesting methods in a simulated process as well as results from an integrated autonomous temperature transmitter are given.

Keywords: Remote sensor data acquisition; Telecommunication-based automation systems

## 1. INTRODUCTION

In industrial automation in general and especially in the process industry, reliability is of paramount importance. The processes are planned (and financed) with a lifetime of 20 years or more in mind, and therefore the components which make up these systems must have a mean time to failure (MTTF) which is a lot longer and require little or no maintenance. Even though this is especially true for devices in control loops, it also holds for the sensors which are used for asset monitoring. If devices require more maintenance then their payback justifies, they will be turned off or ignored.

State of the art are wired devices which are connected to the control system via a simple 4–20 mA loop or a fieldbus like HART [1] or Profibus. With these devices, the energy required for the device is also supplied by a cable. Installing the required cabling and other communication related work can result in up to 90 % of the total device cost.

In recent years, wireless devices, especially sensors, have gained track in the process industry and are a promising option since they offer the possibility to decrease overall device cost by bringing down the effort required to install the device. However, as discussed above, if the reliability of the devices cannot satisfy the given standards or if the maintenance is too high, wireless devices will fail to deliver any form of benefit to the end user. As wireless devices are similar to wired devices from a measurement perspective, the difference in communication and energy supply has to be analyzed.

### *1.1 Related Work*

In Nenninger et al. [2010] the main outline of the energy problem for wireless devices is given. The paper focuses on the problem posed by the energy consumption which is given as a simplified model based on the measurement results of Adzan [2009] and shortcomings of batteries are discussed. Also, energy harvesting is proposed as a possible supply of energy to wireless industrial devices. In this paper we will refine this approach provide a more detailed discussion especially on our subsequent experimental verification of the proposed energy harvesting approach.

In Kim et al. [2008] the WirelessHART protocol is described in detail. This work, in combination with the HART 7 specifications, will serve as a starting point for the network-centric approach on energy consumption. In order to understand the developments in the protocol, Kahn et al. [2000] is a useful resource. A more recent overview is given in Willig [2008].

Several alternatives or modifications to standard protocols have been proposed, e.g. Niestoruk et al. [2009]. The aim of these works is to advance research and gain new insight which can be used in the design of future protocols. However we believe that standard compliant communication is a must for the industrial automation domain since the acceptance of a technology strongly requires devices from different manufacturers to integrate into the same network, see also Hübner et al. [2010].

For the different energy harvesting technologies there are several papers which go into detail on the inner workings of the harvester and the necessary power management. These works are necessary for a detailed understanding of the harvesters and will be cited along with suggestions for further reading when appropriate. However the contribution of this paper will focus on the applicability of these methods and tools to industrial automation.

[1] While HART is usually used in a master-slave configuration in order to have the 4–20 mA signal, the multidrop feature actually justifies referring to HART as a field*bus*.

## 2. REQUIREMENTS OF WIRELESS NETWORKS IN INDUSTRIAL AUTOMATION

### *2.1 Power Consumption of Embedded Devices*

In order to estimate the power required by an industrial device, it is helpful to consider the bare minimum power requirements of such a system. In Adzan [2009], a low-power optimized temperature sensor is presented, see also Figure 1.

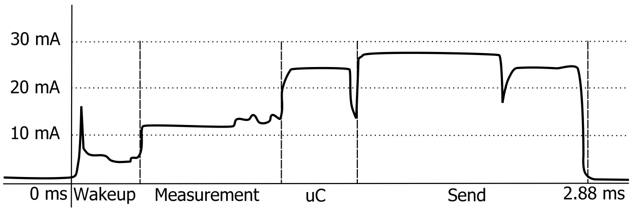


Fig. 1. Power consumption of a wireless temperature transmitter, which optimized for low power consumption from Adzan [2009]

Here, only the active power consumption of the device is shown as the power in standby is low. It can be seen from Figure 1 that the measurement, here implemented on-chip on the microcontroller, is short and not energy consuming.

The communication on the other hand, requires most of the energy even though only sending a message is implemented here (more on details of the requirements for the protocol later). It is therefore clear that at least for simple measurement principles like an on-chip temperature measurement, the energy required for transmitting data is a key challenge.

With some reasonable assumptions on standby energy consumption and battery size, Nenninger et al. [2010] deducts the relationship between measurement interval and battery lifetime given in Figure 2.

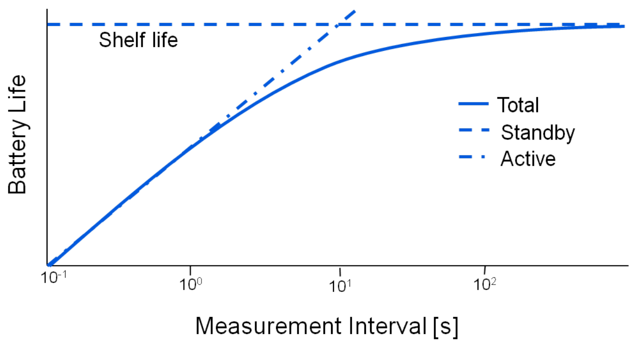


Fig. 2. Approximate battery life over the update rate of a power optimized wireless device on a double logarithmic scale, modified from Nenninger et al. [2010]

Even though this simplified model does not account for battery self-discharge, a more complex protocol and a more realistic estimate of the standby power consumed by the device under consideration, the battery life of such a senor is quite limited, even on an industrial $LiSOCl_2$ primary cell. In the following, we will analyze some of the requirements on communication and their effect on the power consumption of an industrial automation wireless sensor.

### *2.2 General Requirements for Communication*

As stated in Section 1, reliability is a key feature in industrial automation. While wired systems typically have a low bit error rate (BER) of $\leq 10^{-9}$, the typical BER of wireless systems is in the order of magnitude of $10^{-4}$. Since the packet error rate $p_{PER}$ for a packet of $l$ bytes on a channel with the BER $p_{BER}$ is

$$p_{PER} = 1 - (1 - p_{BER})^l \tag{1}$$

the BER has a strong influence on the probability of the correct transmission of a packet. Therefore the error detection mechanisms should be stronger in wireless communication compared to wired communication, for example through cyclic redundancy checks (CRC) or Reed-Solomon (RS) codes or Bose-Chaudhuri-Hocquenghem (BCH) codes. Although this increases the overhead of the protocol, the detection of a communication error is a requirement, even if the wireless nodes are used for monitoring only.

With the error detection covered by the methods just discussed, a mechanism to ensure timely data transmission even in challenging environments must be part of the wireless network. There are several options to have redundant communication, for example in time and space. Redundancy in time goes by the name of Automatic Repeat Request (ARQ) and has the sender of the message retransmit the message. This mechanism can be actively triggered by a missing "acknowledge" message, which is the most common implementation, or by a "not acknowledge" message. The main advantage of triggering on a missing acknowledgment is that in bad channels the "not acknowledge" can get lost as well in which case the message would not be retransmitted.

Having redundant communication on another frequency is possible as well, but is not explicitly practiced. However ARQ combined with frequency hopping can be interpreted to be an implementation of frequency and time redundant communication.

More interesting is the spatial decoupling of communication, which can be implemented in a so called mesh network, see also Figure 3. In this configuration, devices must not only communicate their own messages to the rest of the system, but at least some devices must also be able to route messages from other devices within the network. These devices are commonly called "child" devices [2].

From a reliability standpoint the mesh structure has the advantage that even if the link between two nodes is blocked, the message can still be delivered around this link. A practical use-case would be a truck blocking a device or a failure of a dedicated routing device. From a network perspective even the failure of devices can be tolerated, but of course there has to be some sort of fall-back strategy on the control system side to deal with this.

[2] The name can be a bit misleading since the parent → child relationship between nodes is only valid for on one given path and can be reversed for other paths in the same network.

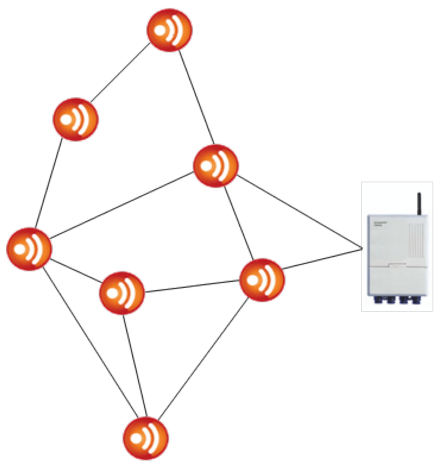

Fig. 3. Example of a mesh network

### 2.3 Power Aspects of Wireless Mesh Networking

Mesh networking not only affects the reliability of the network communication, but also the power aspects. From Figure 1 and the discussion in Subsection 2.1 it is clear that the main part of the power consumption in active mode comes from the wireless part of the device. Since mesh networking increases the number of links of devices and therefore the transmissions between the devices, it also increases the active power consumption of a device roughly proportional to the number of additional transmission. The number of additional transmissions depends on details of the network topology and routing algorithms employed, see also Datta and Gopinath [2006], Niestoruk et al. [2009], Song et al. [2007], Song et al. [2008].

In order to be able to deal with other constraints in the network topology like end-to-end response times, it is reasonable to assume that each device should have 3 children. This assumes that there are no bottlenecks in the network topology. In this respect, a configuration of the mesh network as shown in Figure 3 should be avoided since two nodes have to forward all messages to the gateway. This is of course only true if all devices devices have the same energy budget. A solution for this problem can be the insertion of dedicated line-powered routing devices or in the case of WirelessHART the use of so called adapters. The main purpose of the adapters is to make the (digital) HART data available over the wireless network while not interfering with the 4–20 mA loop which can still be used for control. These adapters can be powered either by a battery pack or from the existing 4–20 mA loop. In case they are powered by the loop, they make very good repeaters, since they are not energy limited. In contrast to battery powered devices, which are energy limited (at least until the battery is exchanged), line powered devices are power limited. In case of a dedicated power supply connection, for example 24 VDC, this is not problem. However if the power is taken from a 4–20 mA loop which also supplies the main device, the maximum power the device can draw poses a problem although $E = \int_{t=0}^{\infty} P dt$ does not converge.

## 3. ENERGY HARVESTING

### 3.1 Overview

In plants in the process industry, there are few places where measurements have to be taken and energy is in short supply; however the energy is usually not in a form which can be used to power a sensor. Typical forms of energy present include light, flow, vibration, and heat. The conversion of these energy forms to electricity is referred to as *energy scavenging* or *energy harvesting*. In the following discussion we will mainly focus on vibration and temperature differences since “harvesting” from sunlight is trivial given the current proliferation of solar cells and has been part of industrial offerings for years, for example in flow meters for the water industry or totalizers in the oil and gas field. Converting flow to electricity in an energy harvesting context is still a challenge since the available technologies used for example in the generators in power plants do not scale well to the milliwatt range.

### 3.2 Vibration

Although electrical motors are optimized for very little vibration through their construction and installation, the interaction with the process, for example a pump, results in vibration which lends itself to energy harvesting. Figure 4 shows the vibrtion spectrum which was recorded on the motor of a pump in an industrial process rig.

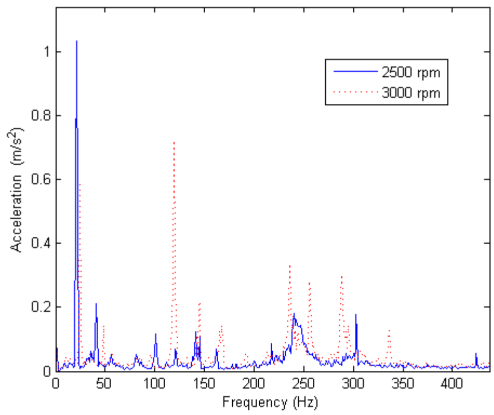


Fig. 4. Spectrum of a 37 kW electrical motor driving a pump for 2500 rpm and 3000 rpm

In the example given in Figure 4 there is a clear difference between the spectra at 2500 rpm and at 3000 rpm. The shift of the peaks is due to the fact that the motor was connected to a variable frequency drive which modulated the frequency of the input voltage for the motor. The peak, which is at 50 Hz for the 3000 rpm spectrum can be found at $2500/3000 \cdot 50 = 41.6$ Hz in the 2500 rpm spectrum. When compared with the bandwidth of a typical vibration harvester as shown in Figure 5, one can see that even slight variations in the rpm of the motor can lead to significant decrease of power on the harvester.

If the speed of the motor is fixed, then available harvesters can be adjusted by the manufacturer rather easily. Therefore, motors with a constant speed can prove to be a

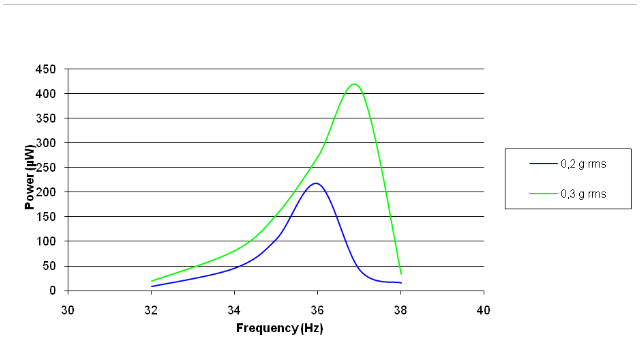


Fig. 5. Power over frequency of a commercial vibration harvesting setup at different amplitudes.

reliable source of energy. There are vibration harvesters available on the market which are based on the inductive harvesting principle. This corresponds to conventional generators and can be seen as rather robust.

The fact that the harvesters are only effective at a certain speed raises the question how to deal with situations when there is not enough power available or even no power at all due to a different speed of the motor or the motor even standing still. The first option is to use the harvester only for powering sensors which are not required in cases when there is no or not enough power available. In the case of a vibration harvester this might be a vibration monitor which is used for the early detection of faults. Since the cannot provide data during standstill of the motor, the harvester can be used to provide energy to the sensor.

In case the harvester is used to power other sensors, this behavior might not be acceptable. Especially in a scenario where the wireless sensors are used in control loops, the reliability of the energy source is a must. Therefore a suitable backup strategy has to be in place. As discussed in Nenninger et al. [2010], most energy storage mechanism have some sort of shortcoming, be it charging cycles or lifetime under extreme temperatures. Therefore this backup strategy has to be chosen carefully in order to match the requirements of the harvester, the sensor, and the requirements of the plant.

### *3.3 Temperature Gradient*

Another promising technique is to harvest energy from the temperature difference between the process and the ambient air. Using Peltier elements based on the Seebeck effect, thermo-electric generators (TEGs) can convert the temperature difference between a hot and a cold side to electrical energy. Ideally the heat flux over the TEGs is small enough as to not influence the process it harvests from [3]. TEGs are composed of p-n couples of semiconductors, silicon or BiTe, which are in parallel thermally and in series electrically. On the one hand this implies that the area significantly influences the power which can be harvested. On the other it shows that the voltage provided by the TEGs grows proportionally to the number of p-n couples.

[3] Despite the low conversion efficiency of TEGs of around or below 10 %, the power drawn from the process is in the order of magnitude of tens of milliwatts. For normal industrial processes this should not be a problem.

Modern thin film technology allows for the production of new thermo-electric generators which are not only an order of magnitude smaller (down to 10 $mm^2$) but also feature more p-n couples which increases the output voltage and allows for more efficient DC/DC conversion, see Nurnus [2009]. With this technology it is possible to fit the harvester into existing process connections.

The power provided by TEGs increases approximately with the square of the temperature difference on the hot and the cold side and only saturates at levels which are not relevant for simple wireless sensors. This means that care has to be taken not to isolate either side of the TEG.

Evaluation kits for both micro TEGs and regular TEGs exist readily on the market. These kits are able to power small sensor boards as for example the one used by Adzan [2009]. However they provide the TEG with almost direct thermal contact to the hot and cold thermal reservoirs. While this is of course ideal to demonstrate the possibilities of TEGs, it is rarely encountered in industrial applications. Therefore the adaption of the TEGs to industrial requirements is a major challenge.

Just like the vibration monitor has its *natural partner* in the vibration harvester the temperature sensor is the natural partner of the thermal gradient harvester. In contrast to vibration monitors which are primarily used for wear detection on bearings, temperature sensors should be active during plant startup and shutdown. Also the temperature is a less predictable source of energy which requires a good buffering strategy. The problem of bridging the gaps in energy provided by the harvester is therefore much more pronounced with temperature gradient harvesting than it is for example with solar.

## 4. RESULTS AND DISCUSSION

In order to evaluate the feasibility of an energy harvesting based industrial wireless sensor, a proof of concept device as shown in Figure 6 was built and tested in a simulated industrial environment.

Fig. 6. Proof of concept of an energy harvesting based industrial temperature transmitter

In order to show the readiness for industrial applications, the measurement principle is based on a standard Pt100 sensor which available for wired transmitters today. Also for the housing materials which are in use in industrial applications today were used, especially for all parts of the sensor which are in direct physical contact with the process. As a protocol, wirelessHART was chosen since, as discussed above, the protocol has a large influence on the power requirements of the device. As a consequence the device behaves like a normal wireless device in terms of physical installation, accuracy and integration into control systems.

It can be seen that despite the fact that industrial requirements were taken into account, the power supplied by the TEG suffices to power a temperature sensor just from the temperature difference between the process and the ambient air.

## 5. CONCLUSION AND OUTLOOK

In this paper we have shown that the key power requirements, which have to be satisfied by wireless sensors additionally to those which have to be fulfilled by wired sensors, can be satisfied from a power perspective with an energy harvesting based system. In our proof of concept we have chosen the *natural partners* harvesting from a temperature gradient and using the electrical energy to power a temperature sensor due to the fact that the most likely use case for temperature sensors is in places where a temperature difference to the ambient air can be expected.

However, we believe that energy harvesting can also be used for sensor–harvester pairs which are not *natural partners* and sensors which have a higher power consumption. Ensuring that they can at the same time fulfill other industrial requirements nevertheless remains a challenge.

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