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Energy consumption analysis of modules for CPS retrofitting

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Abstract

Modern production environments require transparency regarding production status to detect the optimization potential. One of the indicators to identify this potential is the Overall Equipment Effectiveness (OEE). It is usually calculated by hand. In cyber physical production systems and an implemented Total Productive Maintenance (TPM), a permanent analysis of the optimization potential is required. This approach faces the challenges of manual efforts to gather machine data. To get a flexible sensor set, methods of energy supply and wireless radio modules are analysed. The article shows the possibilities of energy consumption to fulfil the requirements of energy harvesting.

Keywords: process planning; indicator calculation; equipment effectiveness; wireless sensor sets; energy harvesting

1. Introduction

According to the hightech-strategy of the German government, data acts as the solution to future challenges in the producing industry. The control of increasing complexity of production and product leads to new challenges in transparency and flexibility during the manufacturing process. Complexity in manufacturing processes is raised by increasing individualisation of the products to batch-size one. In part this development requires new machines and plants. However most companies of the producing industry already have a significant number of machines. These machines have to be retrofitted to collect recent data, exchange it with others and react on deviations in the production process [1].

2. Cyber-physical systems in a cyber-physical production system

Prerequisite for a transparent and self-optimizing production is the application of cyber-physical systems (CPS) to connect the virtual and the physical world [2]. Main parts of CPS are sensors, actuators, embedded computing unit and communication technology [3]. These parts can be applied to e.g. a product, container or a machine within the production system [4]. The connection between virtual and physical world is realiz7ed by sensor- and actuator-technology [5]. Sensors are used to monitor the operating status of a machine by analysing machine data like vibration, temperature or energy consumption [1]. In addition, the sensors can also collect data about the product itself [6]. Advantages of sensor-based data acquisition are higher accuracy, efficiency and higher real-time capability. Therefore, sensors capture the actual status of production processes and translate them into electric or digital signals [7]. Actuators are transforming the digital signals into physical action. They enable process control.

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Embedded computing units process incoming data and use it for controlling, regulating and monitoring production processes in real-time [1].

A central characteristic of a CPS is network-communication, which enables data exchange between different CPS. This communication results in a data-driven, self-optimizing production system [8]. Because of the comprehensive need for interconnectivity, the communication between CPS should be wireless, especially for retrofitting machines. The internet of things is realized through the possibility to exchange data between CPS in an economic and flexible way [4].

The different CPS connected to an industrial production environment, create a cyber-physical production system (CPPS). In a CPPS intelligent machines, plants and products are connected to each other and there is a digital image of every process running through the different CPS in a CPPS [6]. A major challenge in designing CPPS is the heterogeneity and incompatibility of the CPS with each other [9]. In CPPS, a universal standard for data exchange across the manufacturers of machinery is required [8]. Inefficiencies in production processes become visible by historic comparison of performance indicators and CPPS are able to react to deviations [10].

2.1. CPS and productivity ratios

Performance indicators, also known as key-performance-indicators (KPIs), are used to achieve corporate objectives [11]. Problem identification and support for decision-making is possible by quantifying the properties of process flows [12]. Two main assets in developing appropriate KPIs are:

- Fewer and simpler indicators for process description work better.
- Reasons for changes in indicator value must be transparent, so improvements derive directly.

KPIs for the producing industry are separated in three layers. The first layer contains performance indicators for a whole company, quantifying the success of a company. The second layer describes the calculation of indicators for single production lines. Problems with single production lines are analysed by comparison of historic data. The third layer covers KPIs for single stations and machines. Precise detection and localization of problems are only accessible through this third KPI-layer [13]. Detailed data about machine status is required to calculate the third-layer KPIs [14]. This data can be generated by comprehensive application of sensors [2].

2.2. Calculation of Overall Equipment Effectiveness

The Overall Equipment Effectiveness (OEE) is an indicator developed by Nakajima as part of the Total Productive Maintenance for monitoring and increasing efficiency in production systems. The OEE consists of three parts (quality, performance, availability) as displayed in Figure 1. In addition, six losses and their effect on the OEE are shown in the grey boxes [14].

Taking account of all losses during the manufacturing process, the OEE is able to detect interactions between different types of losses [15]. Thereby the calculation of an OEE on level one or two is not sufficient. Only a calculation on level three reveals problems on station-level. It is obvious that capturing machine status for new machines only is not goal-oriented. New, modular sensor-systems have to be developed to enable the subsequent upgrade of existing machines to CPS.

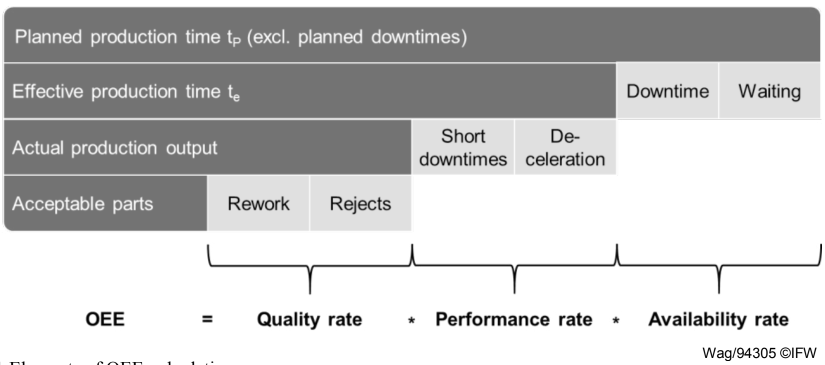

Fig. 1 Elements of OEE-calculation

2.3. Energy Harvesting for sensor-systems

As described before, a retrofit of existing machines with wireless sensors is required to realize a transparent, data-driven CPPS. Increasing sensor deployment claims for decentralized availability of electric energy. A connection of many different sensor-systems to a local energy grid is often not possible. Many machines do not have an interface to power additional sensors or computing units [16]. Furthermore connecting a cable for power supply to a wirelessly transmitting sensor restricts the fields of application concerning positioning and flexibility [17]. Mostly this problem is bypassed by adding a battery to the wireless sensor [7]. The main drawback in using batteries is their limited lifespan. This leads to time- and cost-intensive battery changes [17].

One solution to remedy this drawback is using the present form of energy at the deployment site of the sensor. This energy usually needs to be transformed into usable energy for autonomous operation of the sensor. Because energy harvesting uses the existing process- or environment-energy, a maintenance-free power supply is ensured during lifetime [18].

In most settings, energy harvesting with piezoelectric elements generates only small amounts of energy. These amounts are insufficient for continuous operation of a sensor system. The small amounts of energy with fast switching charge- and discharge-cycles are usually stored in a capacitor that has enough capacity to power the sensor-system for a limited period of time [17]. The energy generated by methods of energy harvesting is lower than a constant energy supply by a battery or power grid. This requires all components of a wireless and batteryless sensor-set powered by harvested energy to be an energy efficient system.

3. Wireless data transmission

A main part of a CPPS is the communication capability of CPS among each other. Wireless communication is required for flexible and versatile sensor-sets, [2]. To guarantee efficient and interference-free wireless communication, not every transmission frequency is free for use with sensor-sets. For short-distance transmission, there are frequencies of the Industrial-Science-Medical-Band (ISM) free for utilization by general assignment [15]. Widely spread frequencies between 2.4 and 2.5 GHz and between 5.725 and 5.875 GHz are used for WIFI, matching the IEEE 802.11-standard. ISM-frequencies 433 MHz and 867-869 MHz are increasingly used for CPPS, because they offer relatively high data rates over large distances while consuming less power than WIFI.

There are different modules available to transmit signals on one of these frequencies. After a comparison of manufacturer information regarding energy consumption two modules out of 23 compared datasheets are chosen for further testing. Main characteristics of the modules are low overall energy requirements, short wake-up times for periodical use, high ranges, and radio frequencies with the ability to pass through objects and walls for indoor use.

Table 1. Radio modules for energy testing

Module	Frequency [MHz]	Range [km]	Operating voltage [V]	Supply current				
				Idle [µA]	TX [mA]	@dBm	TX [mA]	@dBm
CC1101	868	1	1.8-3.6	0.2	16.4	-6	34.2	12
nRF24L01+	2400	0,1	1.9-3.6	0.9	7	-18	11.3	0

The CC1101 by Texas Instruments and the nRF24L01+ by Nordic Semiconductors are chosen for testing them regarding their suitability in wireless and batteryless sensor-networks. The CC1101 is particularly suitable because of its high range up to one kilometre matching with simultaneously low energy requirements. A smooth operation is possible within a wide range of supply voltage between 1.8 V and 3.6 V. In addition, the module allows adjusting the power-level. It consumes 16.4 mA with the lowest and 34.2 mA with the highest power-settings. One goal of the research is to investigate the influence of supplied power on the transmitting range.

The second test is made with the nRF24L01+, which allows transmitting ranges up to 100 m. This module is investigated regarding to its transmitting range in a real production environment. It has the lowest requirements in power consumption of all compared modules. Other modules using LoRA-modulation are excluded from this test, because they do not match the lowest energy requirements, although they are more energy efficient by means of range and power supply.

4. Energy consumption in low-power-environments

Both modules can be set to sleep or idle mode between two sending impulses. The power consumption of the radio modules in both operating modes is analysed to examine the possibilities of energy reduction by idling or sleeping. In this setup, the modules are sleeping for ten seconds followed by ten seconds of idle-mode. The current is measured with a multimeter applied to the circuit of the radio modules.

Table 2. Power consumption of radio modules during idle and sleep-mode

Module	CC1101		nRF24L01+	
Operating voltage [V]	Idle [mW]	Sleep-mode [mW]	Idle [mW]	Sleep-mode [mW]
1.8 / 1.9	2.43	0	0.0861	0.0006
3.6	6.156	0.0004	1.764	0.0104

At operating voltages of 1.8 V and 3.6 V the CC1101 and at voltages of 1.9 V and 3.6 V the nRF24L01+ could run in both modes between two sending impulses. As shown in Table 2 the power consumption of the CC1101 in sleep-mode is almost zero independent of operating voltage. At 1.8 V, the power consumption is not measurable. The multimeter could not measure any current, due to its maximum resolution of 0.1 µA. Also switching the nRF24L01+ to sleep-mode results in a significant drop of power consumption. The CC1101 has an 84 % greater power consumption as the nRF24L01+ in idle-mode, but it uses less energy during sleep-mode. It was expected that switching the modules to sleep-mode results in a time-period where the modules are not ready for sending after the wake-up signal. This was not measureable during the experiments.

Summarising it can be stated that the radio modules should be operated in sleep-mode at their lowest operating voltage in between the sending impulses. This addresses the main asset of using least energy for radio operations. Furthermore the comparison of the radio modules energy consumption to a data-processing unit (ATmega328P-PU microcontroller), which is in power-down-mode, shows a marginal influence of the radio modules on overall power consumption of a CPS. For comparison, an ATmega328P-PU microcontroller V in power-down-mode, with the analog-digital-converter (ADC) turned off, consumes 0.007 mW at 1.8 V operating voltage and 0.016 mW at 3.6.

The microcontroller and the connected radio module exchange operational parameters after turning-on. During this initialization-process, energy consumption reaches its peak. Moreover, this initialization process could lead to a time-delay before the modules transmit their first data. For the following tests to analyse the power-consumption during power-on-routine the system consists out of the ATmega328P-PU as the data processing unit and the radio modules. The power-consumption of the whole system is analysed because the microcontroller controls the initialisation routine. A one Byte message is sent directly after initialization. This signalizes a successfully completed initialization routine. All tests are done at 1.8 V operating voltage as it is the lowest voltage level available for the testing system. Both radio modules are operated at a maximum transmitting power of 0 dBm. The overall power consumption of both microcontroller and radio module is measured with an oscilloscope Tektronix TDS 2024B. The temporal progression of power consumption is smoothened by building an average over 4 ms.

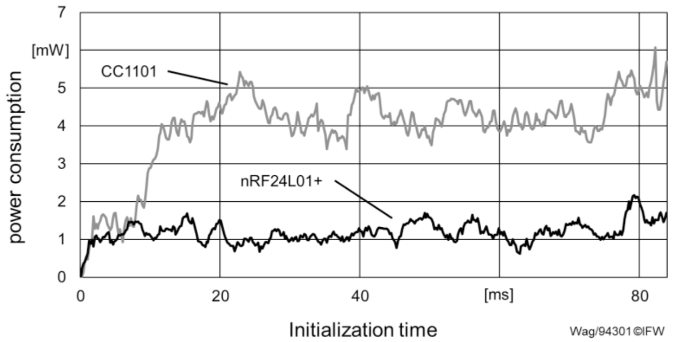

Fig. 2 Power consumption during initialization process

Figure 2 shows the total power consumption of the CC1101 and the nRF24L01+ during initialization. It is apparent that the power consumption is raising during the initialization process and stays constant afterwards for the CC1101 and for the nRF24L01+. The CC1101 used 0.35 mJ during power-on routine, whereas the nRF24L01+ consumed 0.105 mJ. The nRF24L01+ uses about 3 times less energy during the startup-routine, although it is running at 1.9 V instead of 1.8 V of the CC1101. Cross testing at 3.6 V operating voltage showed, that voltage has no effect on the timespan until the first message is transmitted.

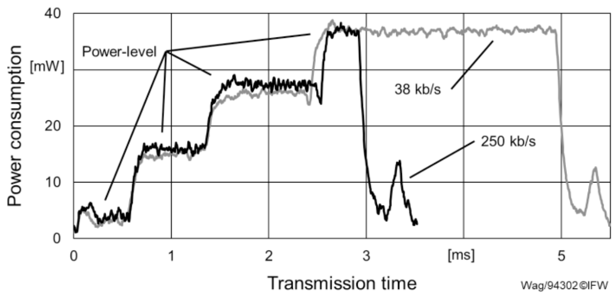

Fig. 3 Power consumption of the CC1101 during message transmit

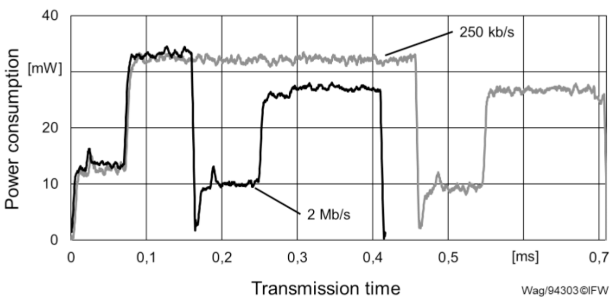

Fig. 4 Power consumption of the nRF24L01+ during message transmit

Figure 3 shows the characteristic power consumption of the CC1101 while transmitting a one Byte message. During transmission the power consumption raises, independent of data rate, in four steps to a maximum of about 38 mW. Before falling back into sleep-mode, the power consumption decreases with a last peak shortly before transmitting ends. Similar to the initialization-process, voltage has no effect on transmitting times, but in this case data rate has. After raising, the data rate from a default of 38 kb/s to 250 kb/s for the CC1101 (Fig. 3) the transmitting time is shortened from 5.5 ms to 2.6 ms while remaining at the same power-level with 38 mW average power consumption. Only the fourth power-level is shortened when operating at 250 kb/s, which clarifies that the data transmission itself is characterized by this level.

The same test is made with the nRF24L01+ module. Figure 4 shows the power consumption of the nRF24L01+ module depending on data rate. Like the CC1101, the nRF24L01+ transmits messages with four different power levels. The nRF24L01+ uses a default data rate of 250 kb/s. This module is able to transmit messages within 0.7 ms, which is about 80 % faster than the CC1101 operating with the same data rate. Raising data rate to the modules maximum at 2 Mb/s shortens the duration of message transmission to 0.42 ms compared to 0.7 ms at 250 kb/s. The module achieves this by shortening the duration of the second power-level whilst the other levels stay the same. The second power-level is responsible for the message transmission of the nRF24L01+.

In summary, higher data rates result in lower energy consumption. Figure 5 shows the effect of lower energy consumption with higher data rates. The 2 ms shorter transmission time due to a higher data rate of the CC1101 results in a drop of -51 % less energy for a one byte message transmit. Transmitting messages using the nRF24L01+ at 2 Mb/s also results in a -50 % energy drop to 0,009 mJ consumed for a one byte message, due to the shorter transmission time.

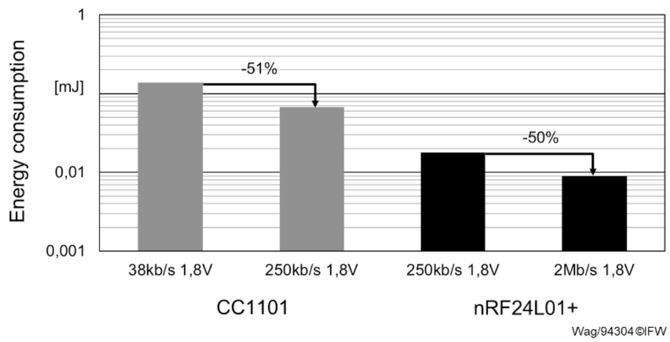

Fig. 5 Relation between data rate and energy consumption for a one byte message

This result shows that the nRF24L01+ consumes less energy. With 100 m visual transmission range, it is able to cover up a typical range in production environments. Therefore, the nRF24L01+ should be chosen for applications where energy availability is the main restricting factor.

4.1. Radio ranges in low-power mode

According to the datasheet, the nRF24L01+ provides a visual range of 100 m. Usually, wireless and battery-less sensors are attached to objects or surfaces where the maximum range is estimated to be under 100 m visual range, because of their damping effects on radio waves. For a practical use of wireless sensors, high indoor ranges are necessary. In the following test, two nRF24L01+ modules are used in an environment with different rooms and machines. To test radio ranges in a realistic surrounding, one module acts as the signal-receiver and one as a transmitter. The transmitting module sends an one byte signal every 10 ms for a duration of 60 seconds. The receiver counts the received messages. For testing purposes, signals are received at eight different positions in the factory with different distances and objects within the transmission path. The failure rates of the nRF24L01+ are shown in Figure 6. The CC1101 has an error-free operation at all power levels and at every position.

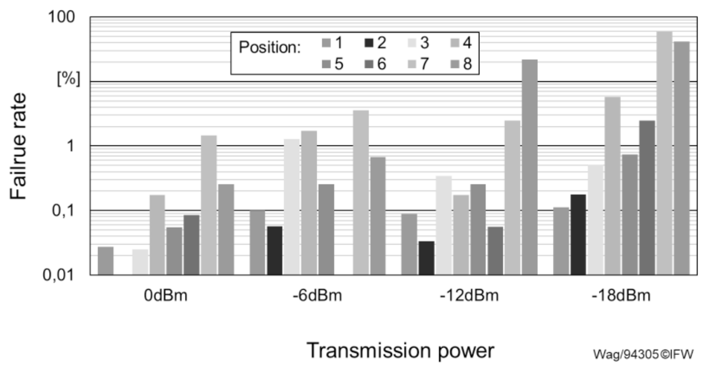

Fig. 6 Failure rates of the nRF24L01+ concerning position and transmission power

The tests with the nRF24L01+ show that not every message is arriving at the receiver. In position 7 a maximum failure rate of 1.2 % with a maximum transmission power of 0 dBm could be observed. This characterizes the ability of the radio signal to penetrate walls. In position 8 at least two walls are positioned between transmitter and receiver. The maximum distance of 8 meters between transmitter and receiver is reached at receiver-position 6.

As conclusion of the range test, the nRF24L01+ should be operated with its highest transmitting power to achieve the best possible penetration of walls and objects along the transmission path. Further energy savings by reducing the transmission power lead to failure rates above the 1 %-level specified in the datasheet. An approach to further reduction of failure rates could be sending the data twice. This would have an impact on the maximum failure-level of 1.2 % in position 7 at 0 dBm. First experiments show that it is possible to reduce failure rate to 0.0144 % by redundantly sending the data.

5. Conclusion and Outlook

A first approach to wireless and batteryless sensor sets for OEE-calculation is made by examining the possibilities of using radio modules that are suitable for use with energy harvesting methods in a production environment. The results show that wireless technology meeting the requirements of low-power networks is already available. It is possible to run the nRF24L01+ in a low-power environment at only 1.8 V. Here the nRF24L01+ in combination with an ATmega328P-PU performed as a low-power CPS. Considering automated OEE-calculation, this CPS could be used for interpreting and transmitting the actual machine status from the sensors data to a higher-level system, such as a manufacturing execution system (MES). In this approach, the CPS was powered by a laboratory power supply, which will be replaced by a piezo-generator in further research. First attempts with a DuraAct P-876.A12 by PiCeramic connected to an energy harvesting circuit LTC3588 by Linear Technology already showed good results regarding power delivery. Furthermore, automatic pattern detection for use with automatic KPI and OEE calculation must be investigated.

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