RF-Embedding of Energy-Autonomous Sensors and Actuators into Wireless Sensor Networks

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ABSTRACT

The principle of energy harvesting, i. e. gleaning of extremely small amounts of energy from the environment, has been around for a long time. For technical reasons, the idea of operating a wireless link, commercially, with energy from the environment was to date only possible with solar cells, and outdoors where there is sufficient light. EnOcean is the first company to offer commercial solutions for operating wireless links in low-light indoor surroundings, or by energy sources that are an alternate to light. In this paper we will discuss two application scenarios for energy-autonomous sensor/actor networks with partly contrary requirements. The first application scenario is typical for e.g. building automation or environmental monitoring, where the wirelessly operated sensors are distributed over a widespread area and only a few measurement values are generated in a moderate time interval. Modern fabrication facilities with highly flexible manufacturing cells or highly dynamic processes in the military environment, where clusters of sensors and actuators have to be read-out and controlled in a limited space under stringent real-time limitations stand for the second application scenario. We will describe the current status of technology, show measurement results, tell about experiences already made in the field and give a prospective view of possible future developments. Although primarily developed for new application scenarios in building systems engineering, household, logistics, environmental protection and production automation wireless sensor/actor networks based on EnOcean technology can also be tailored to military needs for future air, ground and naval vehicle capabilities.

1.0 INTRODUCTION

Wireless networking is a field of intense scientific research and a multitude of potential applications including e.g. habitat monitoring, surveillance in inhospitable environments, maintenance in large industrial plants, seismic activity detection or military surveillance [1, 2]. The basic idea is that the network nodes equipped with low-power radio transceivers, a small microcontroller and multiple onboard sensors are deployed in large numbers and form a dynamic self-organizing and self-healing meshed network. To meet the requirements of a particular application, a successful wireless sensor network design must have several unique features. The need for these features leads to the combination of technical issues, e.g. power consumption and lifetime, data throughput, robustness and network security, coverage, connectivity and costs, not found in other wireless networks. For environmental monitoring or building automation applications, where a large number of sensors are deployed, a frequent battery replacement is impractical. In certain applications batteries cannot be used at all. When compared with WLAN and WPAN technologies like IEEE 802.11 or IEEE 802.15 data throughput for many sensor/actor networks is much lower. A few bits for transmitting status information or an alive signal is often sufficient. Nevertheless, in section 3 we will show that a high data rate can improve system performance even if only

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a very limited number of bits have to be processed. In the preceding section 2 techniques for ambient energy sourcing are discussed. Of course, also the configuration of the hardware components and how data is transmitted through that configuration is driven by the application. Mesh networks offer intriguing features with respect to robustness and scalability. In section 4 we will show that there can be good reasons why it can be worthwhile to employ other topologies even when highly stable and reliable routing is required. In section 5 an energy-autonomous sensor/actor-network tailored for the needs of highly dynamic control systems will be presentend. In the final section 6 the results will be summarized and an outlook will be given.

2.0 AMBIENT ENERGY

Devices operated with environmental energy are not new. Apart from the commonly known procedures in which wind and water are used to obtain energy, a less well known, but technically highly interesting product bears a mention: the Atmos produced by the Swiss company Jaeger-LeCoultre since 1936 [3]. This clock has an expansion chamber filled with ethyl chloride, which expands or contracts during temperature fluctuations, thus winding up a mainspring. Even a temperature change of only one degree Celsius will provide the spring with sufficient energy for two days of operation. To be able to efficiently utilise the low volumes of energy, the clock's engineers took totally new approaches. Unfortunately the innovative concept for the supply of the clock's energy from the fluctuation of ambient temperature could not be directly adopted so that new innovative technologies have to be established for wireless energy-autonomous sensor networks.

Such fascinating, technically sophisticated products do not, however, automatically prove the mass marketability of the technology used, despite their innovative nature. Taking into consideration construction size, cost and reliability, a systematic evaluation of the potential of different ambient energy converters is therefore a significant first step in the assessment of technical feasibility in view of the market. The results of our evaluation in terms of absolute energy level, energy efficiency and construction size for different ambient energy sources with a high level of practical relevance will be given below.

2.1 Photovoltaic Energy

In fig. 1 the electric output of solar cells mass-produced by means of the reasonably priced thin layer technology is shown in dependence of their size and luminous intensity. The efficiency of this technology is not extremely high, at about 5%, however, at low levels of illuminance of approximately 100 to 500 Lux, which frequently occur in buildings, these are considerably better than highly optimised and expensive monocrystalline cells.

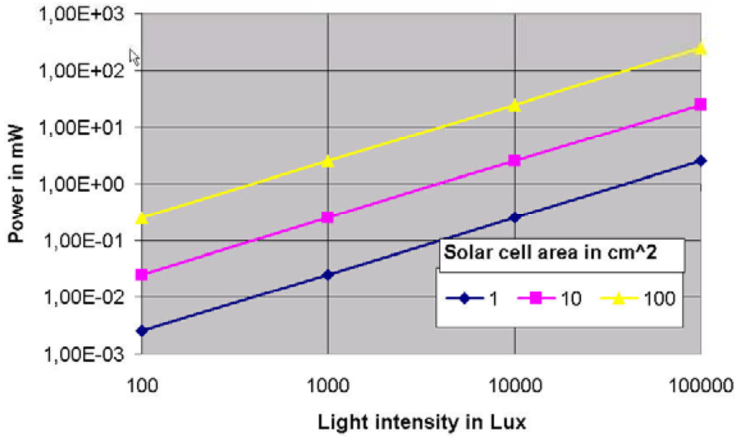


Figure 1: Solar cell output in dependence of construction size

2.2 Vibration Energy

Using vibration converters, relatively large outputs can be generated, even with small masses, if acceleration is high enough. Acceleration of up to approximately 2 g and frequencies between 20 Hz and 200 Hz are typical values that can be measured with operating machines [2]. The quantitative evaluation in fig. 2 was derived from a vibration model under the assumption that converters with a 5% efficiency were used and was verified with electro-magnetic converters, which provide good compliance with the model. At this point, the problem of broadband operation, in particular, need still be solved. Fig. 2 shows the expected output power for three different oscillating masses. The oscillation frequency is given in Hz.

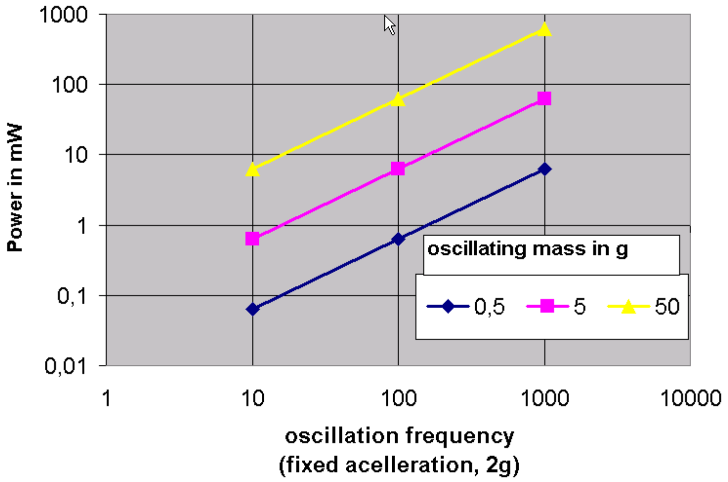


Figure 2: Vibration generator output in dependence of construction size and vibration frequency

2.3 Thermal Energy

Sufficient amounts of utilisable energy can also be found in thermal gradients. The curves shown in fig. 3 were recorded using standard Peltier modules (for CPU coolers, etc.). The problem of low voltage output at minimal differences in temperature was solved through the development of boost converters, which can operate at extremely low voltages (starting at approx. 10 mV) and efficiently transform these to about 3 V.

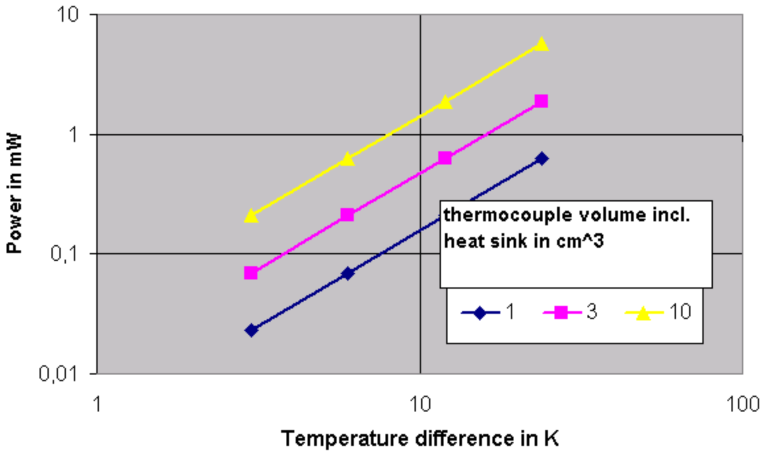


Figure 3: Themal generator output in dependence of construction volume and temperature difference

2.4 Tactile Energy

Laboratory demonstration modules and proof of the feasibility of energy autarkic modules can be realised relatively easily on the basis of rough estimates and often using standard components. Tailoring modules for mass-production, however, poses high demands towards development, especially if stringent customer requirements have to be met. An example is shown in fig. 4 showing a switch module for energy autonomous radio operation.

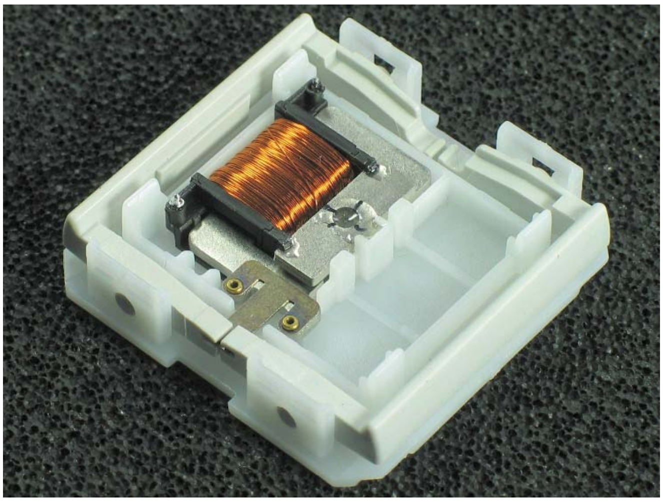


Figure 4: Energy converter of the switch module PTM 200. The magnetic circuit is operatred via a lever-spring system (Product-Status)

Switches used in installation technology must fit into common casings throughout Europe. This restricts the external dimensions of the module to approx. 40 x 40 x 10 mm. Despite its small size and its assembly on metal, timber, concrete, etc. no curtailment of radio range can be observed. With less than 7 N the actuating forces on the rocker are comparable with common switches. The switch module operates reliable over a temperature range between -20°C and +65°C and a minimum of 40,000 switching cycles can be guaranteed even under harsh environmental conditions.

Due to the strict size requirements (8 mm height, 15 mm x 25 mm side lengths) in combination with ambitious cost goals, especially the magnetic circuit, which is shown in fig. 5 had to undergo intensive optimisation. Of particular interest are the parasitic bypasses that need to be minimised. The choice of materials used for the magnet and iron parts, as well as its construction (air gap, cross sections) are significantly influencing factors.

The curvature of the magnetic field strength in the material of the ferrous core (fig. 6 and fig. 7) provides important information on the usefulness of the construction, which had to be optimised in the course of many cycles. The result is an efficiency of the energy converter (incl. voltage regulation) of approx. 5%, which represents a good result under the given restrictions, especially when compared with piezoelectric converters (approx. an efficiency of 2% is currently achieved).

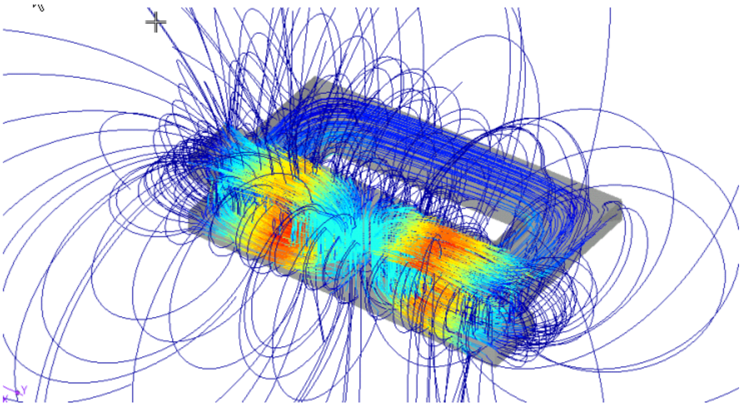


Figure 5: Simulation of the magnetic field lines surrounding the magnetic circuit

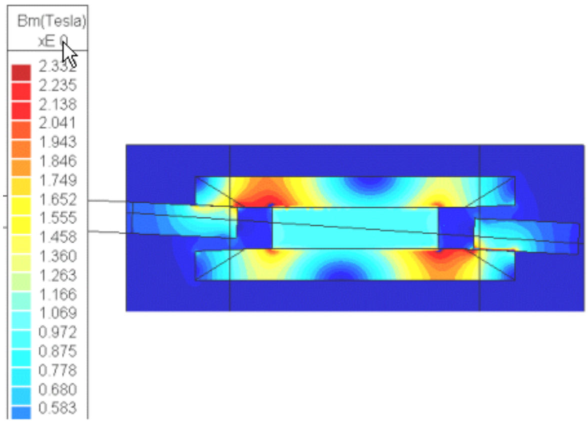


Figure 6: Simulation of the magnetic flux density in the soft iron anchor of the energy converter

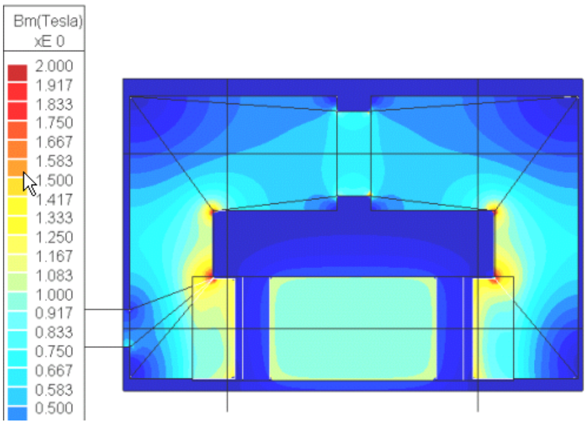


Figure 7: Simulation of the magnetic flux density in the soft iron U core of the energy converter

3.0 RADIO PLATFORM

Energy consumption of common low-power communication modules developed especially for wireless network operation [5-8] are summarized in table 1. Typically, the modules are made up of a low-power radio frontend a microcontroller unit (MCU) for sensor/actor communication. The EnOcean TCM 120 radio transceiver also included in table 1 is controlled by a Microchip PIC18F452 MCU, which offers all the common features like UART, ADC, Timer, SPI, I^2C, etc. The MCU is driven by a 10 MHz crystal. This enables the clocking of the transmit data into the radio part in such a speed that a data rate 120 kbps could be achieved. The radio part, which is split into a discrete very low-power transmitter and an Infineon TDA 5200 receiver, operates at center frequency of 868.3 MHz. The modulation type is ASK, the maximum transmission power is 10 dBm. The received radio signal strength (RSSI) is made available at a MCU pin. Additionally, the TCM 120 has one 16-pin selector and an extension board containing 20 pads which both expose various MCU features.

Parameter	EnOcean TCM	Crossbow Mica 2	Telos	EyesIFX
MCU	PIC 18F452	ATMEL 128 L	TI MSP 430	TI MSP 430
Current Active Mode (mA)	13.40	8.90	1.70	1.40
Current Sleep Mode (µA)	8.00	27.70	3.30	2.90
Tx Current (mA)	9.90	15.50	19.40	11.90
Rx Current (mA)	15.80	10.70	21.10	14.80
Supply Voltage (V)	4.75	2.70	1.80	2.10
Data rate (kbps)	120.00	38.40	250.00	64.00
Energy per bit - Tx (µJ)	0.92	1.72	0.15	0.44
Energy per bit and mW (µJ/(bit*mW))	0.09	0.52	0.15	0.31
Tx Output Power (dBm)	10.00	5.00	0.00	1.50
Tx Input Power / Tx Output Power	4.70	13.23	34.92	17.67
Energy per bit - Rx (µJ)	1.16	1.38	0.16	0.53
Rx Sensitivity (dBm)	-95.00	-98.00	-94.00	-95.00

Table 1: Comparison of radio platforms

The power consumption in transmission mode is 47 mW for the EnOcean module, 42 mW for Mica 2, 35 mW for Telos and 25 mW for EyesIFX. At first sight it may seem that the EyesIFX platform offers best performance in the transmisson path. But at a second glance, taking data rate and transceiver efficiency into account, the energy required for transmission of a single information bit is lower for the EnOcean and Telos platforms. Relating the energy per bit on the output power (the output power of the EnOcean transceiver is 10 dBm, whereas Telos transmits with of 0 dBm) the EnOcean platform offers highest performance. This is mainly due to the high data rate and the high transceiver efficiency of approximately 21 %. Presuming a good efficiency in the RF part, then the relatively high current consumption required for high data rate transmission can be overcompensated by saving transmission time.

Of course, energy saving rates can also be achieved by increasing the efficiency of the RF module, but only with great efforts and sometimes with only small improvements. For comparison, the power consumption of a standard Bluetooth module varies between approximately 30 mW and 100 mW for the Bluetooth master depending on the number of slave-connections [9]. The power consumption of a Bluetooth slave lies around 200 mW. With 0 dBm transmit power the power consumption of a standard 802.15.4 modules (Zigbee) is approximately 30 mW.

From these considerations it can be concluded that the continuous operation of state-of-the-art radio transmitters/receivers is not feasible with current technology. However, in our experience this is no limitation for many applications, because only a few information bits must be transmitted by the energy autonomous sensor nodes in relatively large time intervals so that there can be long sleep times between active states. Of course things get more complicated if sensor nodes should also serve a communication nodes routing the information through a widespread network. In chapter 4 we will have a closer look on this subject.

While several components of the sensor modules can be switched virtually completely power-free, others must be operated permanently. Among these are timer modules or threshold switches, which e.g. trigger the MCU to read-out external sensors or to receive or transmit data packages. It is not unlikely that these components can dominate the total energy consumption and were therefore aggressively optimized. An example is the timer module of the EnOcean STM 100 and STM 250 sensor platforms, which draw a current of only 20 nA.

For monitoring slowly varying parameters, e.g. temperature changes in process engineering this approach is often feasible. If, however, highly dynamic processes like oscillations of machine components are to be analysed, preprocessing of the measurement values is worthwhile. In the best-case scenario, no measurement values but only status/decision messages or warnings have to be transmitted.

In fig. 8 the circuit board of the solar powered transmitter module STM 100 is shown. The timer, realised in analogue technology, completely deactivates all components during the sleep phase. This enables a “power reserve” of up to one week, even in complete darkness, solely powered through the reservoir capacitor located on the circuit board.

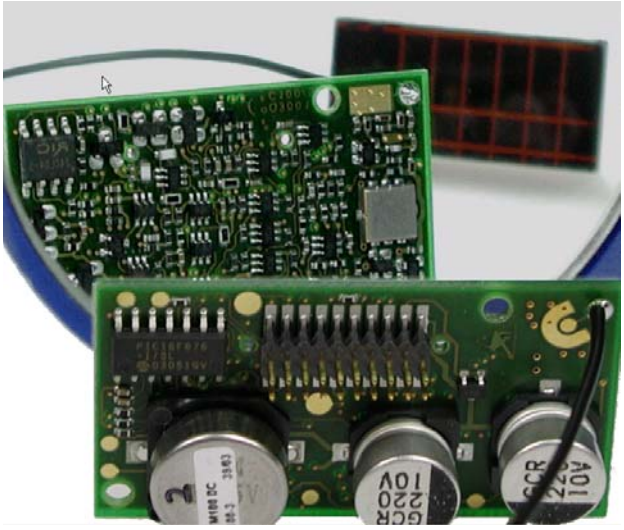


Figure 8: Universal Sensor Module STM 100 with 20 nA timers, processors, energy storage elements and 868 MHz radio module in front of a mirror (Product-Status)

4.0 NETWORK EMBEDDING

Ad-hoc networks can get sensor/actuator information to where it is wanted without any given infrastructure even if there is no direct link between the transmitter and receiver. At the same time the ruggedness and reliability of data transfer increase due to their distributed nature. Thus meshnets perform robust and reliable data communication, presumed that efficient routing algorithms can implemented. In the last years enormous advances in hard- and software technology and networking research has been made [10], but as already shown in section 3 the energy requirements for intelligent communication nodes are still not negligible. Therefore, battery changes or a fixed power supply is still needed to benefit from the advantages of the mesh network. We therefore propose a hybrid approach for embedding wireless energy-autonomous sensors in a robust communication environment, where the batteryless radio sensors are arranged in a star topology, and the battery or line-powered actors or communication nodes are arranged in a mesh network (fig. 9). So the advantages of both topologies can advantageously be combined, i.e. the simple design and lowest energy requirements by the star network and the robustness, reliability and scalability of meshnet configurations.

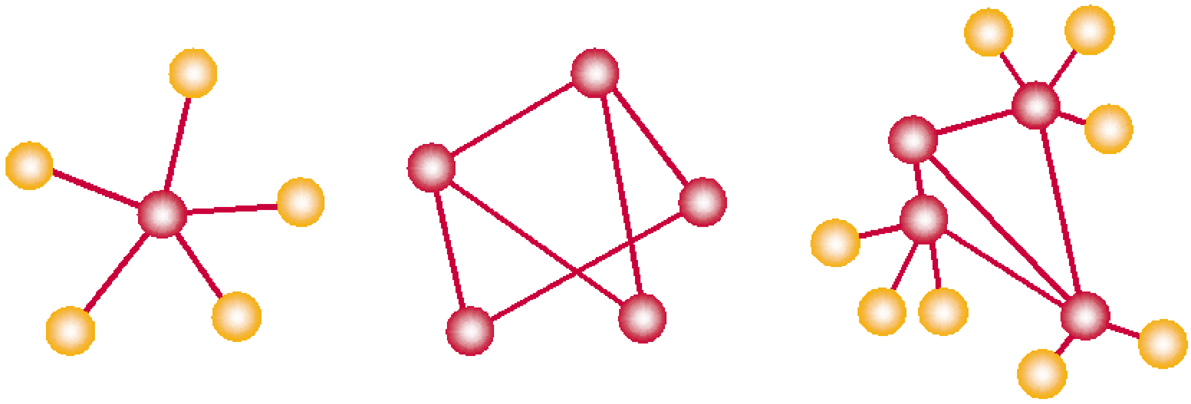


Figure 9: Network topologies typically used in wireless sensor networks. From left to right: start, mesh and hybrid.

For network embedding an efficient network operating system is vital. Different solutions are available. Surely the most prominent industry standards are Bluetooth and Zigbee basing on the IEEE standards 802.15.1 and 802.15.4. An open-source operating system, which also found widespread use and which can be regarded as a quasi-standard is TinyOS, developed at the University of California [11].

To exploit the possibilities for EnOcean’s energy-autonomous sensor/actor systems a gateway to the TinyOS world was created on the basis of EnOcean's TCM 120 transceiver module. In this way the TCM 120 can now receive and transmit both, all EnOcean messages, and messages in TinyOS style. SPI and I^2C buses are lined up for connection of the appropriate sensors to the TCM 120.

We implemented a TinyOS module which handles both the radio transmitting and receiving in such a way that the user gets full freedom of transmitting/receiving the various EnOcean messages as well as standard TinyOS message. The raw data is transferred to the transmitter by switching a pin of the MCU. In the case of receiving an interrupt occurs and the jump into the respective handler function is executed, where the radio message is processed all at once.

The Zigbee protocol stack was especially optimised for low-power wireless near-field applications offering data rates of 20 kbps in the European 869 MHz band and up to 250 kbps in 915 MHz band or the worldwide available 2,45 GHz ISM band. Point-to point, mesh and star networks can be implemented. A standard transmitter sinks 25mA from a 3V resulting in a power requirement of 75mW. Relating the input power to the data rate of 250 kbps and an output power of 0 dBm the energy per bit and mW transmisson power is 0.3 µJ/(bit·mW). For applications where EnOcean RF modules should operate in a standardized environment a gateway between the EnOcean and the Zigbee world was developed allowing the user to combine the advantages of both worlds.

5.0 WIRELESS SENSOR/ACTOR NETWORK FOR HIGHLY DYNAMIC APPLICATIONS

Frequently wireless sensor networks are deployed for monitoring applications of process variables with large time constants. As wireless sensor/actor or communication systems potentially offer many advantages such as easy installation, simple engineering, significant reduced failures in operation as well as improved flexibility and mobility wireless technology is already paving the way towards applications, where a high degree of security or a very low latency is required, e.g. automated guided vehicles, automated material handling systems, wireless factory automation [12, 13] or in military environments. The focus of our development is the limited space of about about 5 m x 5 m x 3 m, where a few tens of self-sufficient sensors and actuators have to be monitored and controlled. By the restriction to a limited space radio technologies originally developed for short-range wireless networks can be employed. In [xs] a compilation of current short-range wireless network platforms can be found, but none of the existing wireless systems/standards satisfied the necessary requirements for the production environment, i.e. very low latency of a few milliseconds, high reliability and high node density. In order to provide a real benefit to the user the sensor/actor nodes should also operate energy autarkic on small power cells. Therefore a novel system development had to be started. As the number of pieces in the industrial environment is not as high as in consumer applications it is mandatory that standard modules are to be used.

To guarantee the real-time capability of the system the network is organized in a star topology showing much better performance with respect to latency than mesh networks as for each single sensor/actor node a time and/or frequency slot is allocated by the system controller so that collisions between sensor/actor nodes can be avoided. In order to communicate with a maximum of sensor/actor nodes within a limited but strongly defined time interval a combined F/TDMA scheme (fig. 10) is applied as multiple access technique, which is also implemented in the Bluetooth standard or in the Zigbee/802.15.4 world, when configured in star topology and beacon enabled mode.

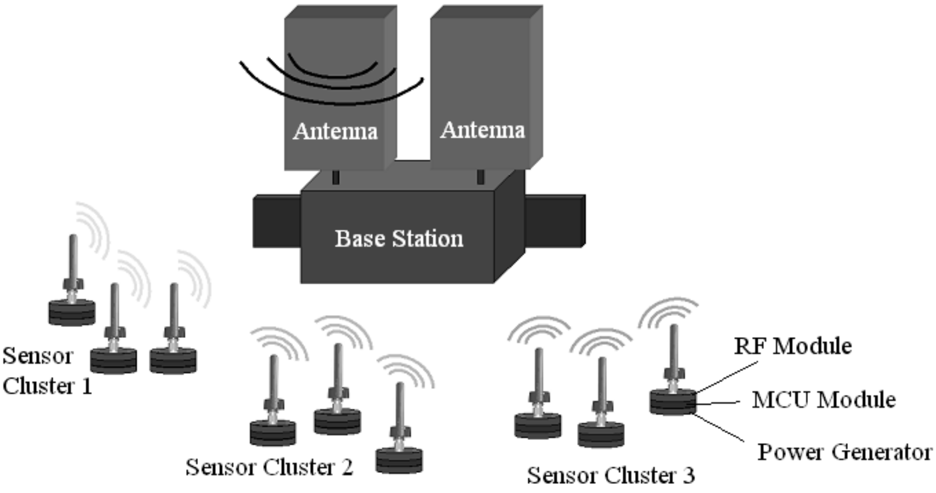
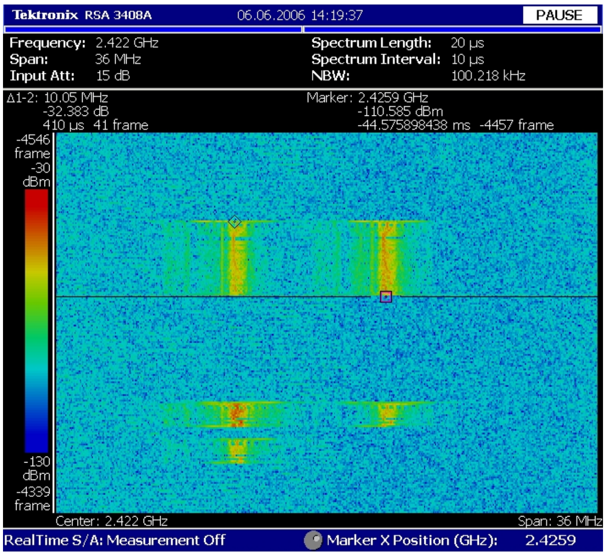


Figure 10: Schematic drawings of a star, mesh and a hybrid network

The architecture was chosen to have a maximum scalabiliy with guaranteed system response times, where the term system response time stands for the time interval between an activation signal of an arbitrary sensor module within the network cell and an the activation of another actuator module in the same network cell. The master unit, i.e. base station is made up of a transceiver unit with the capability of multi-frequency operation at the same time. RF signals are preprocessed by an FPGA. A standard microcontroller handles digital baseband processing and interfacing of the sensor/actor network to a superior process control system.

To demonstrate the system operation, which is totally realized with COTS modules, measurements were taken with a Tektronix spectrum analyser. In the spectrogram shown in fig. 11 the horizontal axis represents the frequency scale and the vertical axis stands for the time scale so that the F/TDMA principle can be visualized. In this case the system was running on two frequencies and three sensor/actor modules (two on the lower frequency and one single network node on the higher frequency) have been used. On each frequency a periodic beacon is transmitted by the base station, which contains all the control and user data delivered by the superior process control system.



Frequency: 2.422 GHz
Span: 36 MHz
Input Att: 15 dB
Spectrum Length: 20 µs
Spectrum Interval: 10 µs
NBW: 100.218 kHz
Δ1-2: 10.05 MHz
-32.383 dB
410 µs 41 frame
Marker: 2.4259 GHz
-110.585 dBm
-44.575898438 ms -4457 frame

RealTime S/A: Measurement Off
Marker X Position (GHz): 2.4259

Figure 11: Spectrogram of communication between base station and sensor/actor nodes

In order to save energy it is not necessary that the sensors/actor nodes send a message in each time slot, instead each time slot is exclusively reserved for one each single sensor/actor node. If there is only low dynamic in the system the sensor/actor nodes can be programmed to send an alive signal in a predefined time interval.

In fig. 12 the timing diagram is shown. Each superframe in which n sensor/actor nodes communicate in n consecutive time slots on a single frequency is characterized by the T_{SF}, the superframe time interval. T_{SFP} represents super frame preparation time. T_{ToSL} and T_{SL} stand for “time to slot” , where the first sensor/actor node starts with transmisson and slot time, respectively. At the moment the super frame preparation time is used for protocol conversion, i.e. for communication of the base station with the superior process control system. With the current implementation of our demonstrator system 18 sensor/actor nodes can be accessed by the process control system within 5 ms via Ethernet under laboratory conditions. Further improvements can be achieved by parallel processing of communication with sensor/actor nodes and process control system.

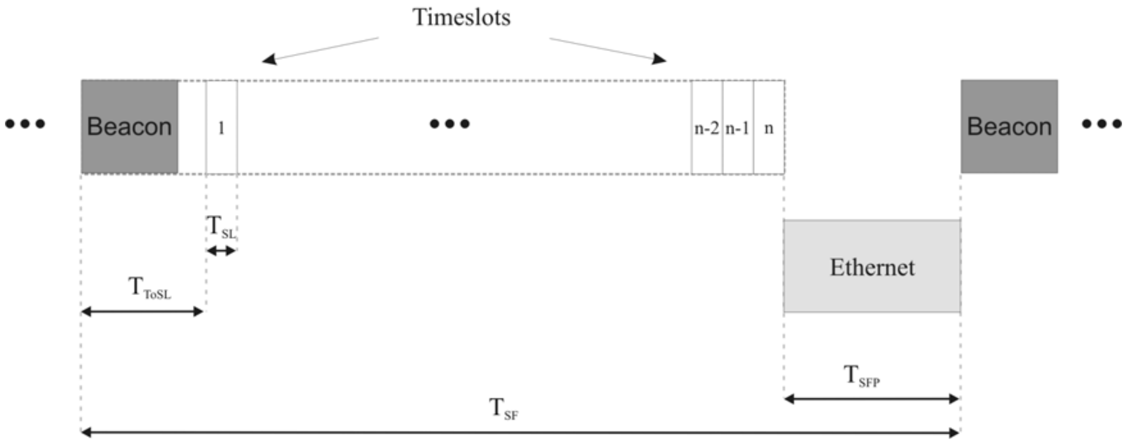


Figure 12: Timing diagram of F/TDMA protocol

Theoretically, there exist two scenarios with respect to the system response time (fig.13). In the best case scenario a sensor element connected to a communication unit triggers an interrupt just before the sensor node transmits data in the predefined time slot. In worst case the time slot reserved for the communication with the base station was just missed so that a complete superframe cycle has to be waited.

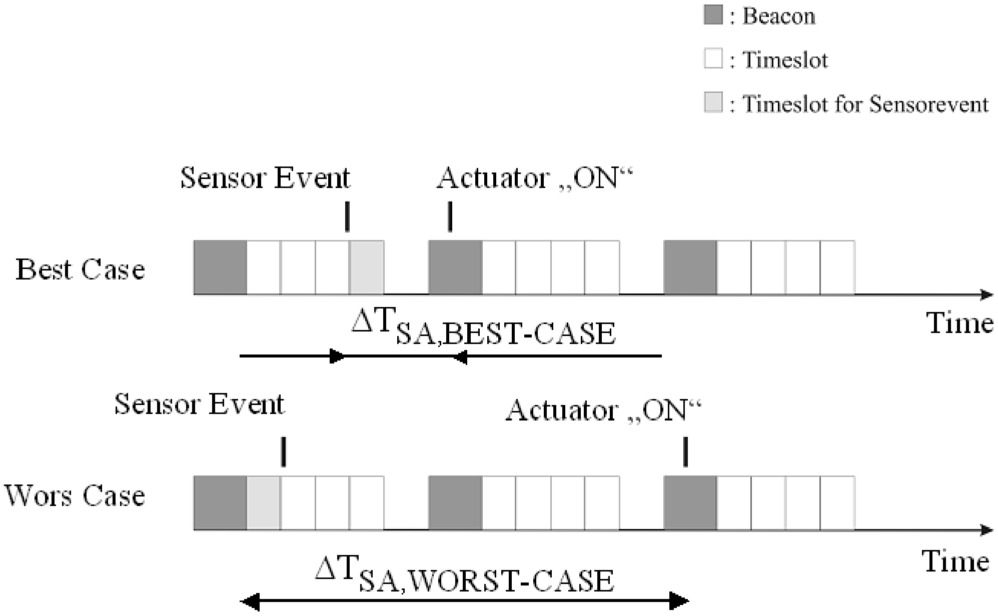


Figure 13: Timing diagram for latency calculations

In fig. 14 the best-case scenario is exemplified. It shows the state change of an actor triggered by a state change of a sensor module. In this context a sensor element connected to a communication unit triggers an interrupt just before the sensor node transmits data in the predefined time slot, i.e. ΔT_{SA} stands for the time interval, which is required to transmit data to the base station, handle the communication with the superior process control system and to access the actor module within the same fabrication cell. In the best case ΔT_{SA} equals 6,1 ms.

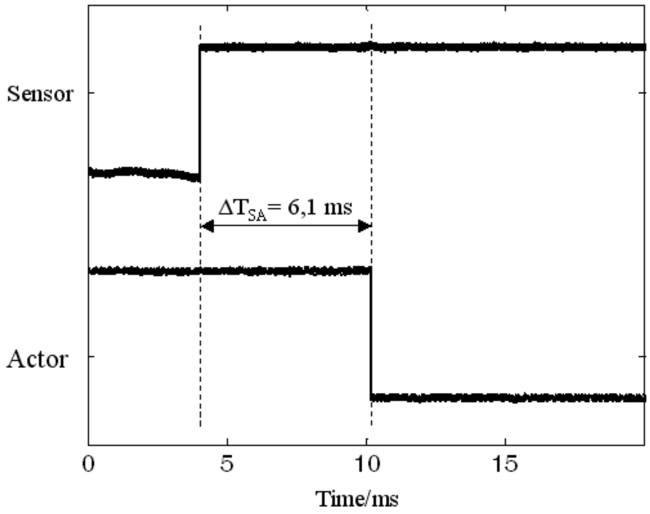


Figure14: Status diagram of best-case scenario

The worst-case scenario is shown in fig. 15. Here the time slot reserved for the communication with the base station was just missed so that a complete superframe cycle has to be waited. In this case a typical latency time is 11,4 ms. Clearly, these values were achieved under benign laboratory conditions and cannot be hold under harsh environmental and electromagnetic interference conditions. But otherwise there should be enough performance reserve in our system, which can easily be scaled in performance with only a moderate cost increase. An additional feature of our system is that, depending on user requirements, the system can easily be configured either for high data throughput or high robustness.

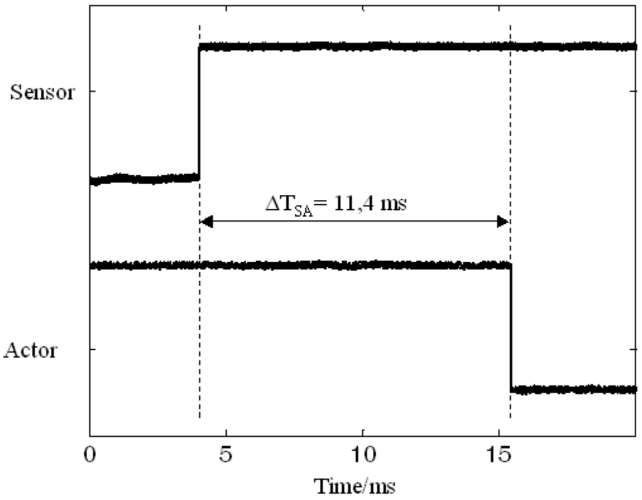


Figure 15: Status-diagram of worst-case scenario

6.0 OUTLOOK

In this paper different methods for ambient energy sources with a high practical relevance were evaluated and a robust batteryless wireless switch module, which is already in product state (approx. 100,000 installed EnOcean components by the end of 2005), was preseted. Also sensor/communication nodes powered by solar or vibrational energy are available. Typically the sensor modules are configured in a star or a hybrid network. Gateways to the TinyOS and Zigbee world exist. Finally a wireless sensor/actor demonstrator system was presented., which was realized with COTS components and is targeting highly dynamic scenarios, where very low and particularly defined latency times are required. Products for industrial applications are only just being established on the market. Industrial, energy autarkic radio sensors will be pushed in the public founded project EnAS [15], in which, in particular, the issues of energy converters, transmission safety and transmission speed under harsh industrial operating conditions are at the forefront of development. Applications for medical technology are also being developed within a joint project [16]. In this case acute cardiac risk patients are monitored via sensor networks. Another area of application, which is undergoing intensive development, is the use of sensors in cars. Here, the focus of development is on the use of sensors to measure the pressure and temperature of car tyres, while significant progress has been made in recent years regarding the performance and reduction of costs. The vision for the real-time sensor/actor demonstrator system is to achieve a high robustness and a 100% availability at low or even medium costs in the field under harsh industrial or military conditions.

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