Wiegand-Effect-Powered Wireless IoT Sensor Node

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Abstract

In this article we describe an Internet-of-Things sensing device with a wireless interface which is powered by the often-overlooked harvesting method of the Wiegand effect. The sensor can determine position, temperature or other resistively measurable quantities and can transmit the data via an ultra-low power ultra-wideband (UWB) data transmitter. With this approach we can energy-self-sufficiently acquire, process, and wirelessly transmit data in a pulsed operation. A proof-of-concept system was built up to prove the feasibility of the approach. The energy consumption of the system is analyzed and traced back in detail to the individual components, compared to the generated energy and processed to identify further optimization options. Based on the proof-of-concept, an application demonstrator was developed. Finally, we point out possible use cases.

1 Motivation

The continuing growth of the Internet of Things (IoT) market not only increases productivity and opens up new business models, but also places new requirements on the devices involved. These requirements address reliability, precision, autonomy, and freedom from maintenance.

Prominent participants in the IoT are ubiquitous sensing devices that do not rely on cable connections and can therefore be placed at any spot. Hence, the usage of energy available in the environment ("energy harvesting") to power sensor technology and wireless information transmission are of paramount importance.

2 Energy harvesting

Some prominent approaches for energy harvesting include photovoltaic, thermoelectric and RF harvesting [1], but each of them relies on the availability of the respective energy form. Especially when moving parts are involved, induction-based energy harvesters are another well-established approach to harness parts of the motion energy. The drawback of induction-based energy harvesters, according to Faraday's law, is the minimum speed of the moving parts that is needed to generate sufficiently high voltage pulses in a given pickup coil and hence provide sufficient energy output in a given resistive load. **Figure 1** shows the generated energy output of a coil filled with ferromagnetic material (orange curve). In the zero-speed limit, the energy output approaches zero, even when referred to a single rotation instead of constant time span.

To overcome the low-speed problem for inductive harvesters, spring-based solutions can be used to guarantee a sufficiently high speed of the moving part generating the desired energy output. This solution comes to the price of mechanical wear and hence decreased maintainability.

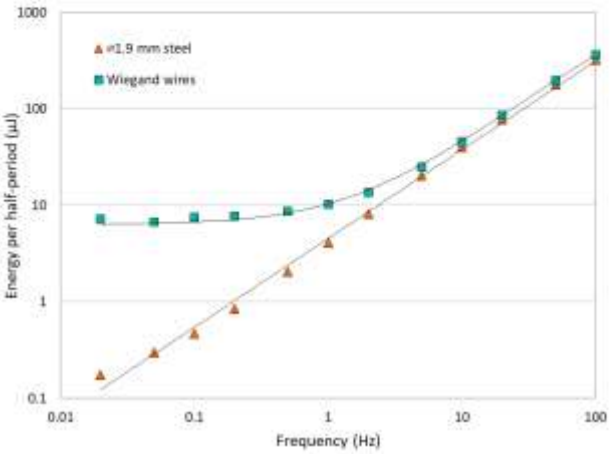

Figure 1 Frequency-dependency of energy output of Wiegand effect compared to regular induction. A coil (8000 windings) is placed in an oscillating external magnetic field of 16 mT amplitude while the Joule heating power in a 3 kΩ resistor is measured. The coil is filled with a standard ferromagnetic material (orange) or Wiegand wires (green), respectively.

By contrast, the Wiegand effect [2] provides a contactless solution of the problem without mechanical support by springs:

2.1 Wiegand effect

Wiegand sensors, well established in low-power applications such as revolution counters in rotary encoders [3] or flow meters, make use of the anisotropic magnetic properties of a specially treated, thin wire of specific ferromagnetic alloys (such as Vicalloy) causing it to be preferable magnetized in one of the two directions along the wire axis [4]. No matter how slow the external magnetic field changes, the transition between these two bistable states, often referred to as macroscopic Barkhausen effect, takes place almost instantaneously [5,6] and is associated with a

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release of magnetic energy that can be picked up as induction voltage in a surrounding coil.
Current commercial Wiegand sensors for position detection applications provide an energy output which does not exceed 200 nJ. By upscaling the sensor and adopting further optimizations to the Wiegand wire, the pickup coil, and ferrite beads at its ends, this output can be increased drastically to about 6-8 µJ for a coil of 21 mm length and 7.5 mm diameter under otherwise optimal conditions even in the low-speed limit, as shown by the green curve in **Figure 1**.

Figure 2 Wiegand sensor for energy-self-sufficient motion sensing (top) and Wiegand generator (right)

This "Wiegand generator" shown alongside a conventional Wiegand sensor in **Figure 2** can be excited by the movement of two or more bar-shaped permanent magnets magnetized in alternating orientation along their cylindrical axis. As opposed to the often very strict mounting tolerances (~0.1 mm) of standard Wiegand sensors in motion-sensing applications [7], it turns out that the chosen configuration easily tolerates misalignments of the order of 1 mm (see **Figure 3**). Of course, other magnetic systems, for example rotating magnets, can be used for excitation of the Wiegand wire as well.

2.2 Operating mode

Continuous harvesting systems (e.g. photovoltaic or thermoelectric) are designed to continuously provide an amount of power, that is, albeit low, sufficient to exceed the consumption due to memory preservation in some sort of sleep modes and leak-current losses, allowing to perform more energy-intensive operations (like reading out sensors and data processing, storage, or transmission) at least from time to time.
By contrast, event-based harvesters like the Wiegand generators can provide a specific amount of energy at one stroke. Of course they can also be operated in a mode of periodic excitation[8], but if the system is designed accordingly, this single amount of energy will be sufficient to perform an operation (such as reading a Hall sensor [9]), even if no power is provided in between the events, i.e. at the beginning of the operation all capacitors are discharged and all information is available from non-volatile memories only.

In the following, a proof-of-concept system powered from Wiegand generators and using off-the-shelf components is designed to be operated in such a pulsed, or "one-shot", mode and to not only acquire, but also transmit the data wirelessly. As one of many possible applications, the system is then integrated in a physical demonstrator comprising a window opening sensor.

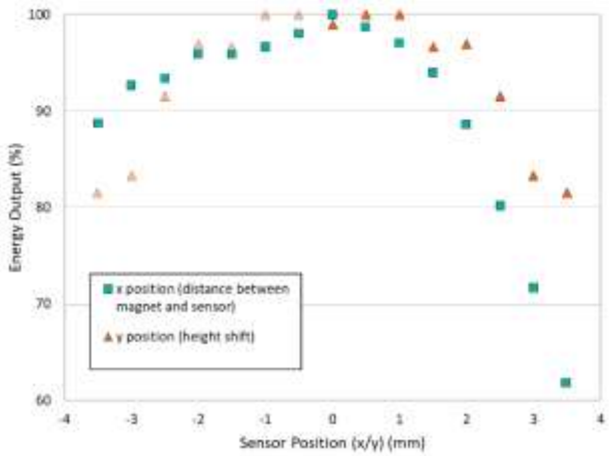

Figure 3 Mounting tolerances of the magnets with respect to the Wiegand generator.

3 UWB wireless technology

The impulse-response ultra-wideband (IR-UWB) wireless technology transmits ultra-short electromagnetic pulses within a frequency range of 3-11 GHz. The shortness in the time domain translates to a widespread spectrum in the frequency domain. This results in miniature spectral energy density, as the energy is spread over a wide spectrum. Therefore, the UWB signals just increase the general radio frequency (RF) noise-floor by a negligible amount, such that the technology can coexist with narrowband (NWB) technologies in the same frequency range [10].
Besides the newly gained resource for data transmission, the UWB technologies features additional benefits. A well-known example is the suitability for high precision ranging via time-of-flight (ToF) measurements, making use of the precisely determinable timing of the pulses [11]. The principle-related low power consumption is another advantage, as the transmitting power is only consumed by short pulses instead of a constantly powered frequency generator for NWB [12].
This results in UWB being a promising candidate for the wireless transmission technology employed in a wireless sensor node supplied by energy harvesting from a Wiegand generator.

4 Digital circuit

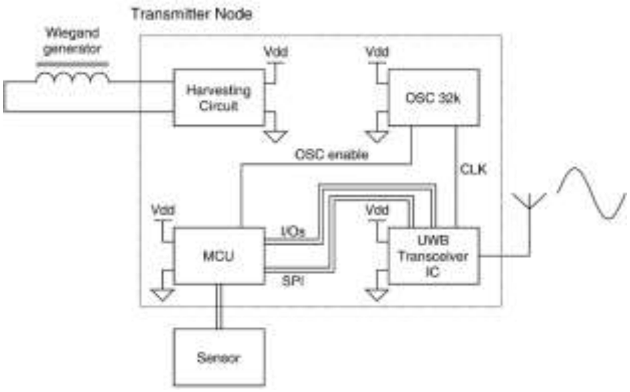

Figure 4 Digital circuit containing the UWB transceiver, MCU, oscillator and an external sensor

The proof-of-concept system setup consists of the wireless sensor node (transmitter) powered by energy harvesting and a UWB base station or IoT-gateway (receiver) powered by an external source. The node shall be operated in a pulsed mode, where the Wiegand generator provides a specific energy pulse upon an external event, which shall be sufficient to start up the logical components, sample a sensor value, and transmit this value via UWB.

As UWB transceiver, the SR1000 IC family manufactured by SPARK Microsystems is used. One key aspect of the SR1000 IC family is the focus on the power-efficient data transmission, resulting in an outstanding low power performance compared to other manufacturers and technologies [11].

The node's architecture **(Figure 4)** contains, besides the SR1000 UWB transceiver IC, a microcontroller unit (MCU), a 32 kHz oscillator needed for the SR1000 and the energy harvesting circuit discussed in **Section 5**. Additionally, there is the possibility to connect an external sensor, either analogue and sampled by the MCU's analogue-to-digital converter (ADC), or a smart sensor connected via a digital interface to the MCU.

The SR1000 has an SPI interface for communication and three mandatory IO pins connected to the MCU. Shortly after voltage ramp-up, it can be configured via several registers and supplied with the data payload, in a way that it afterwards starts up and transmits autonomously without the need of further external communication. In the used configuration, the SR1000 needs around 5 ms in between configuration via SPI and the successfully completed UWB transmission. One key adjustment to achieve this fast start-up is the use of an external 32 kHz oscillator with a fast-starting internal driver instead of the SR1000's internal crystal driver. Another important adjustment was to perform and store some necessary calibrations once and load them from the MCUs static memory at every start-up.

The MCU chosen for the design is from ST's ultra-low-power MCU series (STM32L0). It is optimized for low-power applications and comes with some beneficial features for the design, as for example different sleep modes, low power clock generators or a fast and efficient start-up.

5 Harvesting circuit

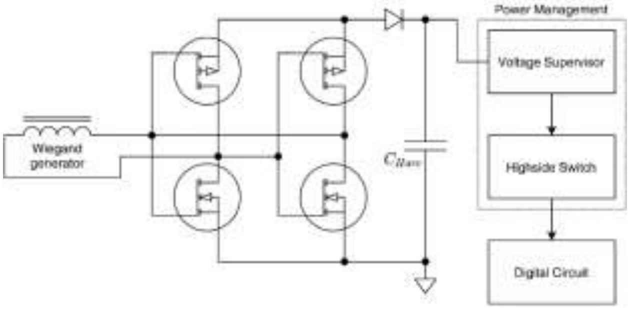

Figure 5 Harvesting circuit supplying the digital circuit with energy from the Wiegand generator

Figure 5 shows the structure of the harvesting circuit. The output current of the Wiegand generator is rectified and charged into a capacitor, from which the components of the digital circuit draw their power after sufficient energy has been harvested.

5.1 Rectifier

As the energy supplied by one Wiegand generator is not sufficient, two identical generators are used. While there are other possible configurations, the use of one rectifier per harvester turned out to reach the highest efficiency.

Moreover, different rectifiers were theoretically and practically tested for suitability. The first important characteristic of the rectifier is the forward or conduction loss, which is determined by the voltage drop over the rectifier while a pulse occurs, and a current is flowing through the rectifier to charge the capacitor. The second characteristic is the reverse or blocking current from the charged capacitor via the rectifier back into the Wiegand harvester coil, while the rectifier is supposed to be blocking.

Table 1 Comparison of rectifier performance for various build-up configurations and diode types.

Rectifier	Type	E_{max} (µJ)	$E_{loss,1s}$
NSR1030	Schottky bridge	4.15	43.3 %
PMEG2020	Schottky bridge	0.30	100.0 %
SMS3922	Schottky bridge	4.25	1.8 %
RB751S	Schottky bridge	4.18	0.9 %
ES1D	Std. diode bridge	3.50	22.2 %
FET-PMEG2020	Schottky FET	2.45	94.4 %
FET-SMS3922	Schottky FET	4.94	1.0 %
FET-RB751S	Schottky FET	4.90	0.6 %

The results of the practical comparison of selected rectifiers (**Table 1**) lead to important findings. To get a realistic

impression, the rectifiers are supplied by a Wiegand harvester, charging a 1.02 µF capacitor, where the maximum energy $E_{\max}$ is calculated from the maximum voltage at the capacitor. $E_{\mathrm{loss,1s}}$ designates the energy loss by the reverse current within 1 second after the maximum voltage occurred.
Firstly, the use of a FET configuration (**Figure 5**) instead of a diode bridge rectifier leads to reduced forward losses due to the reduced voltage drop of only one diode and a better blocking current. Secondly, the SMS3922 and RB751S Schottky diodes, which were chosen due to their state-of-the-art performance concerning the forward voltage drop and reverse current, outperformed the other diodes as theoretically expected. For the demonstrator the FET-RB751S rectifier is used.

5.2 Capacitor

The size of the harvesting capacitor has a major influence on the reached voltage and thus the efficiency of the generating system (Wiegand harvester, rectifier) and consuming system (MCU, UWB IC, etc.).
To further evaluate and optimize the energy efficiency, the consumption of the circuit is precisely simulated as a model. As the output power of the Wiegand generator is also electrically modelled, this allows a precise Model-in-the-Loop (MIL) simulation of the whole demonstrator circuit. This benefits in a better understanding where avoidable losses occur and how to dimension relevant components like the harvesting capacitor. In conclusion, the best dimensioning fit for the harvesting capacitor was found with 3.3 µF, which is therefore used to build the demonstrator in the proceeding.

5.3 Power management

The power management is required to ensure that sufficient energy has been harvested in the capacitor to perform the start-up and transmission cycle. It is realized with a voltage supervisor IC and an optimized discrete high-side switch circuit.

6 Measurement results

6.1 Energy distribution

A precise analysis of the energy distribution introduced by different components and phenomena is shown in **Figure 6**. The Wiegand generator in the used configuration with two coils and two magnetic inversions per triggering event is theoretically capable of generating 29.6 µJ, which corresponds to 100 % of energy yield. As this energy was measured in a homogeneous magnetic field and with an optimal resistive load of 3 kΩ, the energy yield in a more realistic scenario differs. The optimized rectifier used and discussed in **Section 5.1** is accountable for 26.7 % less energy yield on the resistive load, while the use of the 3.3 µF capacitance reduces the energy by further 7.0 % points, compared to the resistor.

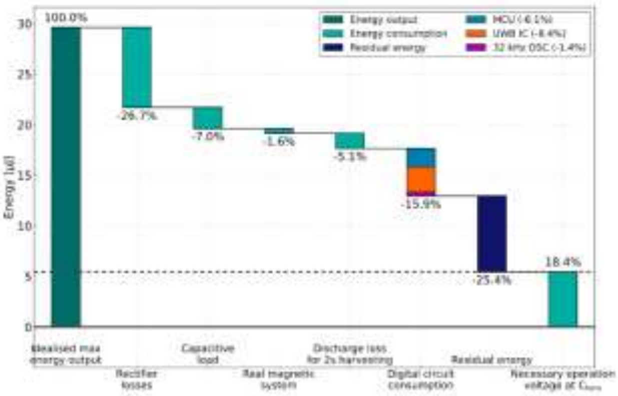

Figure 6 Energy distribution and losses during a pulsed-operation cycle

The use of moving permanent bar magnets to excite the generator accounts for an almost negligible reduction of the useable energy of 1.6 % points, compared to the homogeneous magnetic field.
For the measurement cycle, the harvesting process is stretched over a period of 2 s, simulating a worst-case scenario of very slow movement, during which a constant discharge of the capacitor occurs. This happens due to the reverse current of the rectifier and the supply current to the voltage supervisor and is responsible for additional 5.1 % points of the energy consumption.
The digital circuit consumes in total only 15.9 % points of energy, which can be further divided to 6.1 % points for the MCU, 8.4 % points for the UWB IC and 1.4 % points for the oscillator.
As these components need at least a voltage of 1.8 V to operate, the harvesting capacitor needs to hold the corresponding charge / energy until the cycle is finished. Therefore, another 18.4 % points of the possible energy cannot be used for the application.
On average, a residual energy of 25.4 % (7.5 µJ) remains unused, but usable. This is partly necessary as a safety reserve, but may be also used for additional sensor readouts, further MCU calculation for stability and security or increased UWB payload data transfer.
These findings lead to the conclusion that the supply of a wireless sensor node with a Wiegand generator is generally possible and promising.

6.2 UWB transmission

The SR1000 UWB IC allows precise configurations of the radio signal, all of which affect the signal range or the energy consumption of the transmission (TX) backend differently. A comprehensive analysis of these parameters result in an achievable open-field range of around 60 m for the SR1010 at 4 GHz frequency with a power consumption of 500 nJ for a 100 byte data payload transfer. When optimizing the parameters for energy efficiency, the consumed energy can be reduced to just 75 nJ for 100 byte, while still achieving 30 m of range.
The signal transmission is found to be susceptible to interference with surrounding objects, such that a implementation in a building may, on the one hand, result in reduced

range. On the other hand, the antenna used was an omnidirectional wideband PCB antenna, and directed transmission is expected to enhance the range.
Comparing the total energy consumption of the complete demonstrator from **Section 6.1**, only a minor portion is consumed for the actual transmission compared to the initial start-up energy and other losses. Due to this only minimal share, a further energy reduction of the radio, which would bring disadvantages in terms of range or data payload, seems to be a low priority step. In contrast, a new implementation of the UWB functionalities meeting the requirements of the pulsed-operated transmitting-only IC would result in elimination of redundant IC-internal components and is expected to achieve a much higher efficiency increase.

7 Demonstrator

With the aforementioned results, a physical demonstrator for presentation purposes is built up comprising a window sensor. The sensor node consists of the demonstrator PCB with a UWB PCB antenna (a) and two Wiegand generators (b), mounted to the moving window and the magnet assembly containing three magnets mounted to the frame (c) (**Figure 7**). Via a connector, various sensor devices can be connected, a few examples are stated in **Table 2**.
The design is able to sample and transmit the sensor data each time the window is opened or closed, which are then displayed in the receiving UWB base station.

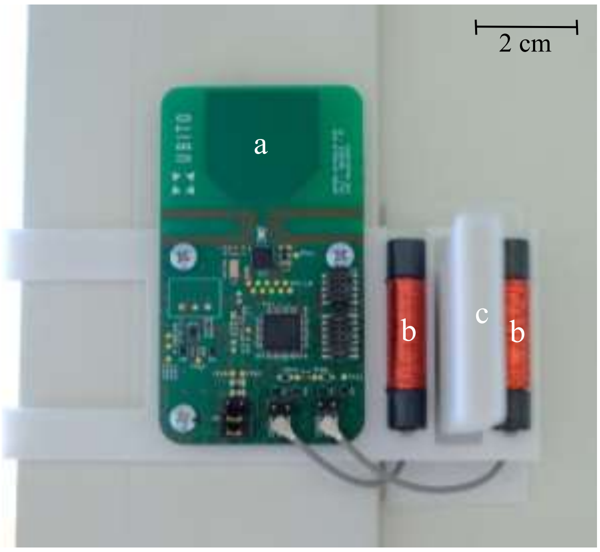

Figure 7 Demonstrator PCB

Table 2 Sensor devices evaluable with the demonstrator and their additional energy consumption

Acquisition	Sensor / IC	Additional Energy (µJ)
Voltage / Resistance sampled by MCU internal ADC	Magnetic field / movement, position (Hall effect)	1,0
	Temperature	
	Photoelectric	
	Proximity	
	Voltage / Current	
Smart IC with I²C / SPI	SHT25: Temperature, Humidity, Pressure	1,0 [13]
	BMA400: Accelerometer	0,022 [14]
	BMG250: Gyroscope	2,54 [15]

8 Conclusion

The demonstrator proves the concept of using energy harvesting based on the Wiegand effect to power a circuit that performs data acquisition, processing, and wireless transmission in a pulsed, "single-shot" operating mode.
Obvious applications of such a system include door or window opening sensors for smart-home applications or industrial logistic automatization. But the ability to sense other physical properties also makes this idea suitable for monitoring applications in the vicinity of moving parts (e.g. pumps, wind mills, turbines, wheels, assembly belts, etc.). This can result in a novel plug-and-play solution for situations, where a power supply via cable, battery or other energy harvesting technologies was so far impossible or uneconomically.
It should be emphasized that the demonstrator has been built up from off-the-shelf low-power electronic components, some of which are more optimized for applications with continuous energy harvesting rather than pulsed operation.
The findings of **Section 6.1** elucidate the potential for further optimization of energy efficiency when dedicated parts would be developed and employed. For large volume applications, it might be worthwhile to develop dedicated ICs that integrate rectifier, power management, sensors, data processing and wireless transmission unit. Enhancing the energy efficiency hereby and thus reducing the energy requirements would allow for size reduction with respect to the Wiegand generator, leading to additional decrease in size beyond that of the circuit integration.
To produce its full energy output, the current design using the two Wiegand generators still requires a finite change ΔH of the external magnetic field, hence a finite range of movement, which therefore needs to take place in a limited time span to avoid exceedingly large losses due to self-discharge. Several approaches are currently being investigated which may help to overcome this limitation.

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