Energy Harvesting for Self Powered Sensor Systems

Case Study: Vibration Energy Harvesting for 'Intelligent Tire' Application

Rob van Schaijk, Rene Elfrink, Valer Pop and Ruud Vullers

Imec/Holst Centre
Eindhoven, the Netherlands
Tel : +31(0)404020553
e-mail : rob.vanschaijk@imec-nl.nl

Abstract - Wireless autonomous sensor systems become steadily standard components in our environment and they become smaller, cheaper and more sophisticated. Energy harvesters fabricated by micro-system technology can realize the autonomy of those systems. An overview of latest results and remaining challenges will be given with the focus on vibration energy harvesters. These harvesters are of specific interest where vibrations or repetitive shocks are present. In this paper the application focus will be on tire pressure monitoring systems (TPMS) and 'intelligent tire' application. The design and characterization of piezo-electric energy harvesters for this application will be presented together with system optimization of wireless sensor systems mounted in the tire.

I. Introduction

The continuously decreasing power consumption of silicon-based electronics has enabled a broad range of battery-powered handheld, wearable and even implantable devices. All these devices need a compact, low-cost and lightweight energy source, which allows the desired portability and energy autonomy. Today, batteries represent the dominant energy source for those devices and in many cases has a large impact on, or even dominate, the overall size and operational cost of devices. For this reason, alternative solutions to batteries are the subject of worldwide extensive research and development. One possibility is to replace them with energy storage systems featuring higher energy density, e.g., miniaturized fuel cells [1]. A second possibility consists of providing the required energy to the device in a wireless mode. This solution, already used for RFID tag, can be extended to more power hungry devices, but it requires dedicated transmission infrastructures. A third possibility is harvesting energy from the ambient by using, for example, vibration/motion energy, thermal energy, light or RF radiation.

The power consumption of a wireless sensor node (WSN) has been estimated by various authors with quoted values between 1 and 20 µW in recent works [2][3]. As schematically illustrated in Figure 1, the components of a typical WSN include micropower module, sensor/actuator, front-end processing unit, digital signal processor and radio. The power consumption strongly depends on the complexity of the sensed physical effect and the number of times it has to be transmitted per second. Practical implementation of a sensor node shows that 90 µW is enough to drive a pulse oxymeter sensor, to process data and to transmit them at an interval of 15 seconds [4]. Whereas 10 µW turns out to be sufficient to measure and transmit temperature readings every 5 seconds [5].

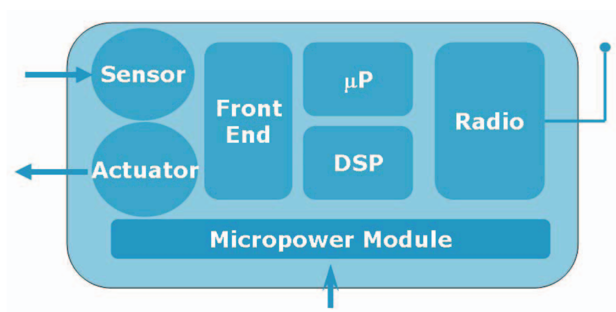


Figure 1. Schematic representation of the components of a typical WSN.

Wireless sensor networks are made up of a large number of small, low-cost sensor nodes working in collaboration to collect data and transmit them to a base station via a wireless link. They are finding increasingly extensive applications in body area networks and health monitoring of machinery, industrial and civil structures.

These networks are intended in many cases to operate for a period of years. Because of the large number of devices and their small size, replacing depleted batteries is unpractical or simply not feasible. Enlarging the size of the battery to ensure energy autonomy throughout the lifetime of the system would increase system size and cost beyond what is tolerable. The combination of an energy harvester with a small-sized rechargeable battery (or with another energy storage system like a thin-film rechargeable battery or a supercapacitor) is the best approach to realize energy autonomy of the network throughout the entire lifetime. For instance, if the power consumption of a sensor node is approximately 100 µW, the lifetime of a primary battery is expected to be only a few months [5]. In comparison, the combination of a rechargeable battery and an energy harvester with a power output of 100 µW is able to ensure energy autonomy for the whole lifetime.

It is worth noting that abolishing the energy storage system altogether is not an option in most cases. As shown in Figure 2, the peak currents needed by the wireless transceiver during transmit and receive operation go beyond what is achievable by using the harvester alone. Furthermore, buffering is also desired to ensure continuous operation during times with no power generated. Depending on the application, the energy storage system can be a battery or a supercapacitor.

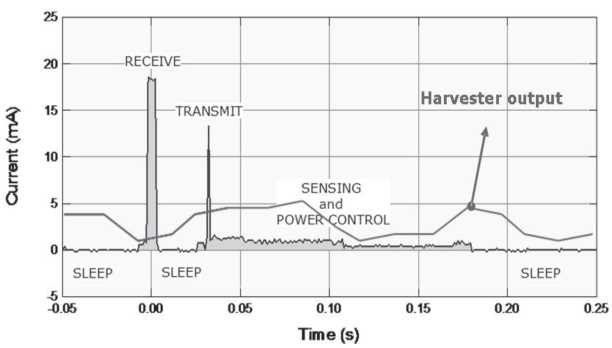


Figure 2: A typical scenario for the power consumption of a sensor node. Since the consumption does not equally match the harvester output, an energy buffer and power management IC in between are necessary.

For most other applications, current harvesting technologies are still far too expensive. A possible route to cheaper harvesting devices is using MEMS technology for manufacturing. The devices can thus be fabricated on a wafer basis in a batch mode, thereby greatly reducing the cost. Nevertheless, reducing the size of a harvesting device not only lowers the cost but also the power output.

As to the power delivered by the different energy harvesting methods, Table I summarizes the data presented in a previous publication [6].
It suggests that energy harvesters can supply approximately 10 µW – 1mW. It is expected that energy harvesters will improve in the coming years, especially those based on vibration and temperature difference. The use of micromachining will result in cheaper devices with higher power output per unit volume. In this paper, we focus on vibration harvesting. We discuss their basic principles and their implementation using micromachining technology. The application focus will be on TPMS and 'intelligent tire' applications. For an 'intelligent tire' the measurement of forces in the tire is an important feature. The electronics are powered by energy harvesting, and results are sent to the car's central controls, which adapt the behavior of the car. The 'intelligent tire' senses the driving conditions and the behavior of the car by force measurement in the tire. This improves the vehicle safety by better driver assistance systems (ABS, ESP..).

Table I. Characteristics of various energy sources [6]

Source	Source power	Harvested power
Ambient light Indoor Outdoor	 0.1 mW/cm^2 100 mW/cm^2	 10 µW/cm^2 10 mW/cm^2
Vibration/motion Human	0.5m@1Hz 1m/s^2@50Hz	 4 µW/cm^2
Vibration/motion Industrial	1 m@5Hz 10 m/s^2@1kHz	100 µW/cm^2
Thermal Energy Human Industrial	 20 mW/cm^2 100 mW/cm^2	 30 µW/cm^2 1-10 mW/cm^2
RF Cell phone	 0.3 µW/cm^2	 0.1 µW /cm^2

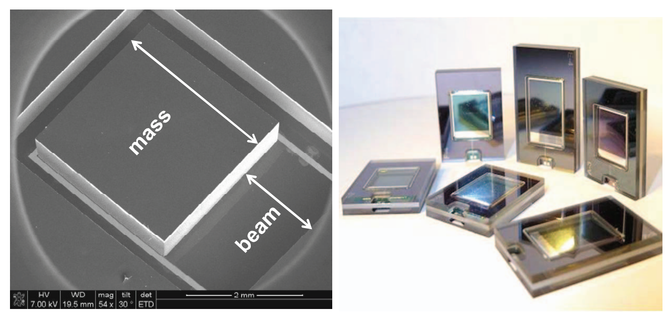


Figure 3: Left, SEM picture of the backside of the harvester showing the DRIE etched seismic mass attached to the cantilever beam.
Right: photograph of various harvesters with different dimensions. The shiny capacitor stack on top of the beam is clearly visible through the glass package.

II Piezoelectric vibration energy harvesting

A. Introduction

For converting motion or vibration into electricity, the established transduction mechanisms include electrostatic, piezoelectric or electromagnetic. In electrostatic transducers, the distance or overlap between the two electrodes of a polarized capacitor varies due to the displacement or vibration of one movable electrode. This motion induces a voltage change across the capacitor, and results in a current flow in an external circuit. In piezoelectric transducers, vibration or movement causes the deformation of a piezoelectric capacitor thereby generating a voltage. In electromagnetic transducers, the displacement of a magnetic mass with respect to a coil produces a change in the magnetic flux. This leads to an AC voltage appearing across the coil.

Vibration harvesters are by far the most widely investigated in the literature. Fine-machined versions are the earliest emerging commercial devices while micro electro mechanical system (MEMS, or sometimes also referred to as micro-systems technology, MST) versions are far less mature for the moment [7][8]. At the micrometer scale, electromagnetic is not sufficiently scalable and therefore, most efforts are dedicated to the piezoelectric and electrostatic transduction methods. Interesting applications are condition monitoring in machineries and automobiles, like tire pressure monitoring systems, for which a large market volume is foreseen. The results shown in this section are attained on a MEMS-based vibration energy harvester with aluminum nitride (AlN) as piezoelectric material.

B. Principle

A simple electromechanical model of a piezoelectric vibrator has been proposed by Williams and Yates [9] and adopted by Mitcheson et al. [10]. In this model, the physical behavior of a general piezoelectric generator is modeled as a damped mechanical vibrator consisting of a generic mass-spring system with a driving force. According to that model, the maximum power P_{max}, which is dissipated in the damper and thus converted into electrical or mechanical energy, can be obtained at the resonance frequency (ω_o) as

$$P_{max} = \frac{1}{2} m \frac{Q_{tot}}{\omega_0} \alpha_0^2$$

where Q_{tot} is the total (electrical and mechanical) quality factor and α_0 is the input acceleration. However, Roundy et.al. have elaborated that the maximum power that can be extracted from the piezoelectric vibration harvester is [11][12]:

$$P_{max} = \frac{1}{4} \left(\frac{e_{31}^2}{\varepsilon_0 \varepsilon_{33}^T} \right) \left(\frac{1 - v_b}{Y_b} \right) \left(\frac{m}{\omega_0} \right) Q_{tot}^2 \alpha_0^2$$

where e_{31} is the piezoelectric constant, ε_{33}^T is the relative permittivity of the piezoelectric element under constant stress, ε_o is the permittivity of the free space (equal to 8.85 ×10−12 F/m). For a thin film piezoelectric layer, Young's modulus (Y_b) and Poisson's ratio (ν_b) of the substrate material, instead of those of the piezoelectric film itself, are to be taken into consideration. This simplified model gives a good indication of the maximum power generation obtained with piezoelectric energy harvesters.

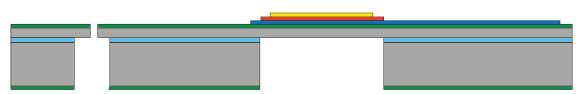
C. Process flow and device dimensions

The piezoelectric energy harvesters consist of a cantilever beam with a seismic mass as shown in Fig. 3, which is a SEM picture of the backside of the harvester. The process flow for the piezoelectric capacitor consists of consecutive depositions, lithography and etching steps of the Pt bottom electrode, the AlN piezoelectric layer and the Al top electrode. The Si mass and cantilever beam are shaped by subsequent front- and backside deep reactive ion etching (DRIE), see Fig. 4. In this paper measurements obtained from devices with different dimensions and two AlN thicknesses (1.2 and 2.0 µm) are used to show examples of our results. The varied dimensions are the beam length L_b, beam width W_b and the mass length L_m. The harvesters are packaged with a 6-inch wafer scale vacuum packaging process. Fig. 3 shows packaged vibration energy harvesters with various dimensions. Electrical connections to the outside are made by standard wire bonding techniques to a small electrode PCB on which wires or large scale connecters are soldered.

D. Sinusoidal excitation

The general operation principle of vibration energy harvesters consists in amplifying a sinusoidal input vibration by its quality factor Q at its resonance frequency F_{res}. A small part of the mechanical energy of the resonating mass is converted into electrical energy by the piezoelectric capacitor. A high quality factor Q of the resonating system is required to generate high output power at low input vibration. Testing under laboratory conditions, where frequency and amplitude of the sinusoidal inputs can be very well controlled, provide a good method for comparing different devices.

4a.



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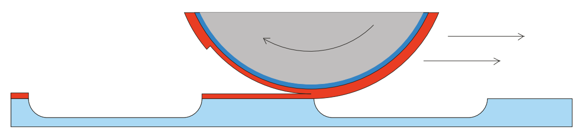

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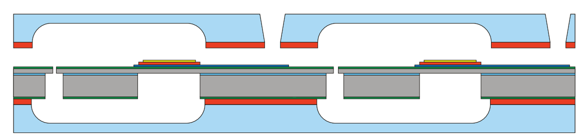

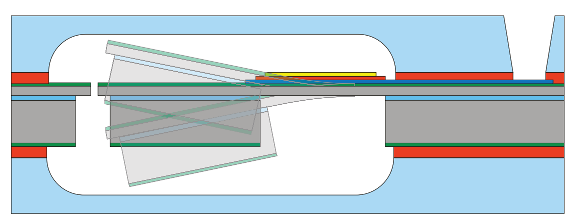

4d.

Figures 4a-d: Process flow.
4a. The piezoelectric capacitor is formed by consecutive deposition, lithography and etching steps of the Pt bottom electrode, the AlN piezoelectric layer and the Al top electrode. The Si mass and beam are shaped by subsequent front- and backside DRIE.
4b. The cavities in the glass wafers are etched with HF and the contact holes are made with powder blasting. The SU-8 bonding layer is applied with a wafer scale roller-coating process.
4c. The glass substrates are bonded to the Si device wafer in two consecutive wafer scale vacuum bonding steps.
4d. Single devices with the movable mass and beam in the vacuum cavity are obtained after dicing.

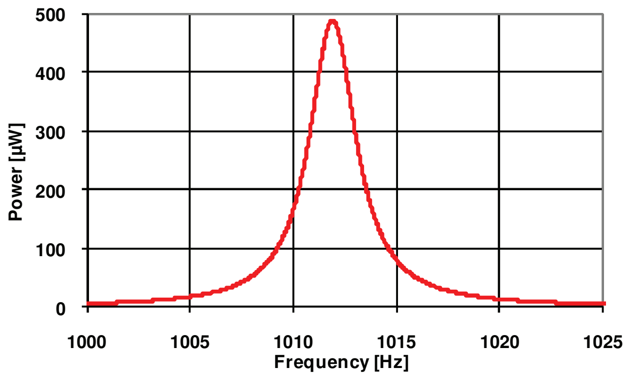

Figure 5: The resonance curve at sinusoidal input. A record power of 489 µW for a MEMS type energy harvester is shown. The quality factor is 370 and the bandwidth is 2.7 Hz or 0.27%. (Device 1.7x3.0x3.0, 1012 Hz)

From the resonance curve as shown is Fig. 5 the resonance frequency F_{res}, output power P and 3 dB bandwidth BW can easily be determined. The quality factor Q is defined as F_{res} divided by BW. The input acceleration can be increased until the mass displacement is limited by the 600 µm cavity depth of the package. For the example presented in Fig. 5 and Fig. 6 the maximum input acceleration a_{max} is 4.5 g at which the record power for MEMS based vibration harvesters P_{max} of 489 µW is measured.

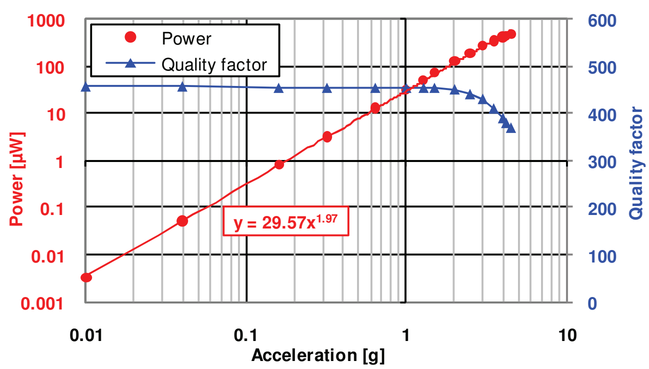

Figure 6: The power output is quadratic with the input acceleration and with Q. Since Q is almost constant one can determine the sensitivity for sinusoidal input as 30 µW/g^2 over a broad range. At higher acceleration Q decreases due to non-linear effects. (device 1.7x7.0x6.4mm3, 1012 Hz)

A drawback of using resonant systems with a high quality factor Q is the resulting small bandwidth. This limits the systems applicability to input frequencies matching with the harvesters' resonance frequency. The measured bandwidth of the harvesters is less than 0.25%, but the frequency variation across 6-inch wafers is about 1.5%. Therefore the production of devices to the desired frequency within its small bandwidth is challenging.

E. Shocks in tires

In case of shock induced vibration energy harvesting, the harvester is excited with a mechanical shock. After the shock the mass will 'ring-down' at its natural resonance frequency with a logarithmic decay [13], see Fig. 7. During the ring-down period, whose duration increases with increasing Q, part of the mechanical energy is harvested and is amplified again with the next shock.

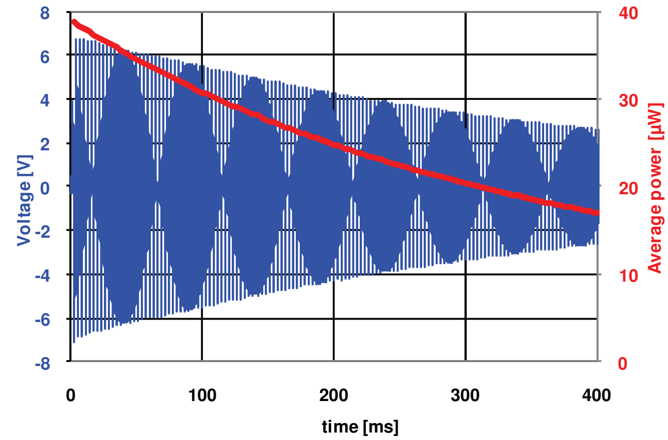

Figure 7: The ring-down signals decays logarithmically and the average power that can be harvested after the shock decreases according to (2). This measurement shows a 349 Hz device after a square shaped shock of 80g amplitude and 1.4 ms duration.

In Fig. 8 the sinusoidal output power is shown under resonance conditions and the initial shock output power (t=0). It shows that the generated power is a quadratic function of the acceleration regardless the input excitation method. The shift between sinusoidal excitation at resonance and with shocks is given by Q/2 for the same device.

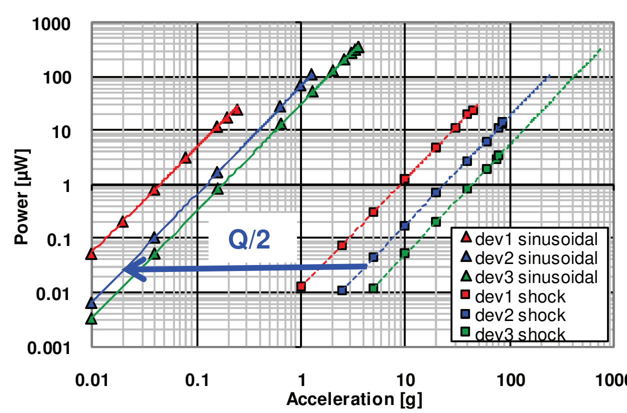

Figure 8: Three devices 1,2,3 (with F_{res}=250, 592 and 1007 Hz resp.) were measured at sinusoidal vibration and square shock excitation with optimum pulse duration. The power (initial power at t=0) is quadratic with acceleration in both situations. The shock amplitude was limited to about 90g due to test-setup limitations, the fitted lines are extrapolated to the displacement limit of the harvester.

The radial acceleration a_{rad} is proportional to the square of the car velocity (see Fig. 9). The amplitude can be a few tens of g (g=10m/s^2) for low speeds, up to hundreds of g for high car speeds. For the area where the tire is in contact with the ground, the contact patch, a_{rad} is small and the shock duration is in the millisecond range. A measured example of a radial shock is shown in Fig. 9 for a car speed of 60km/h. For these shock amplitudes and duration tens of microwatts of power can be generated as shown in Fig. 8.

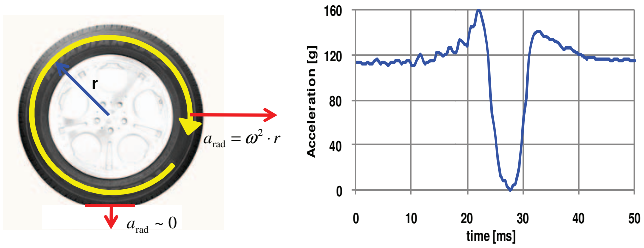

Figure 9: Right: The radial acceleration is constant except when the tire contacts the road. During this contact a high amplitude shock is generated. Left: Measured shock inside a tire with r=325 mm at 60 km/h on an asphalt road

F. Intelligent tire

The radial shocks were measured with small sensor system consisting of a tri-axial accelerometer (Measurement Specialities), microcontroller (MSP430 Texas Instruments), power management + ADC (TPS780 Texas Instruments) and radio (nRF24L01 Nordic Semiconductor). A lithium-ion battery (GMB) was used for powering the system. The system also measures the output voltage power of a piezoelectric energy harvester mounted in the tire (see Fig. 10). The voltage is measured after rectification (diode bridge) on a parallel configuration of a small capacitor and load resistor. The power generated by the energy harvester is sufficient to power TPMS mounted in the tire. It is not yet sufficient for the acceleration measurement with high sample and data rate. The total power consumption of the system with commercial state of the art components is ~7mW. As shown in Fig. 12, the major contribution is by the wireless communication. System optimization should be done with a systematic approach that enables power, area and cost optimization at architectural and application level [14]. A well balanced choice can be made for the technology and components for the selected application. For the ‘intelligent tire’ application a strong decrease in power consumption can be expected. In Fig. 12 a 95% decrease can be expected if ultra low power components will be used. The components are still R&D devices and not yet available on the market, but it shows the potential. Even further power consumption decrease is expected if smart algorithms can be used on the sensor system and only sends relevant data. In this case the power consumption part of the radio can be further decreased.

Figure 10: Left: Energy harvester and wireless sensor system for measurement of accelerations mounted in tire. Right: mounting of tire on rim in tire shop.

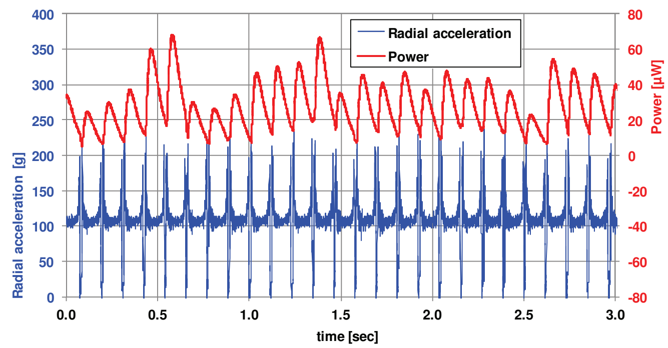

Figure 11: Measurement of radial acceleration inside tire for a speed of ~75km/h. The power output of piezoelectric energy harvester is shown for this speed and results in an average power of 35µW.

III Conclusions

A short introduction on energy harvesting for self powered sensor systems is given in this paper. The main focus was on vibration energy harvesters fabricated by micro-system technology. These devices are suited for TPMS and ‘intelligent tire’ applications. With shock excitation tens of µW up to hundreds of µW can be harvested by shocks in tires. This power output is sufficient for TPMS applications, but not yet if more power hungry features is added. An added feature can be the measurement of forces in the tire. This can be used for improvement of the vehicle safety by better driver assistance systems (ABS, ESP..). The power consumption of such a feature is still too high to match the power generation of the energy harvester. Ultra low power component development together with system architecture optimization is needed to match power generation and consumption.

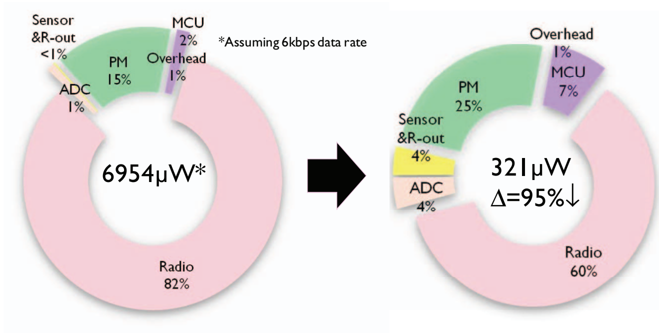

Figure 12: Left: power consumption division for the different components of the wireless acceleration sensor. The main contribution is due to the radio. In this example state of the art commercial components are used. Right: System optimization with newly developed ultra low power components (R&D devices).

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