Miniaturized Wireless Sensors for Automotive Applications

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Abstract

Innovative packaging technologies and power aware design enable system shrinking considering automotive requirements. During the design process the coupling of very narrow positioned components and the interdependence of hardware, software, and packaging have to be considered. The relevant miniaturisation aspects are discussed on the exemplary application of a tire pressure monitoring system.

1 Introduction

Miniaturized wireless sensors become more and more important. They are increasingly applied to everyday objects, e.g. for tire pressure monitoring to enhance transport safety. Over 440 thousands people were injured or killed by traffic accidents on Germany’s roads in 2004 [1]. Thereby maladjusted or improper filled tire equipments cause 30 percent of technical problems resulting in traffic accidents with personal injury [2]. Next to safety awareness satisfaction, correct pressure improves fuel economy and pollution control. Random inspection by NHTSA mentioned that pressure is erratically checked by drivers and over a quarter of tested vehicles have at least one improper filled tire [3]. As a result of this study the US American legislator passed a law [4], which claims to equip all new vehicles with tire pressure monitoring systems after September 1st 2007. This measure affects about 8 million passenger cars per year [6] and implies a huge market for self-sufficient micro systems, while Germany exports about a half million cars per year into the United States [7].

Today’s rapid development in packaging technologies enables direct tire pressure monitoring systems (TPMS) by additional downscaling of self-sufficient wireless sensors from some cubic centimetre to less than 1cm³. They allow efficient solutions for TPMS, which requires low weighted self-sufficient sensors to reduce out-of-balance forces. Furthermore the lowering of substrate area reduces mechanical stress applied to the electronic device. But not only tire pressure monitoring systems can benefit from miniaturized wireless sensors. Tiny wireless ultrasonic sensors and cameras mounted on wing mirrors are imaginable to monitor blind angles and to be integrated into parking distance control systems. Ongoing system miniaturization at the Fraunhofer Institute for Reliability and Microintegration (IZM) targets self-sufficient wireless sensors with an edge length of 6 mm.

During the design process, the coupling of very narrow positioned components have to be considered in ultra dense 3D packaging more then in conventional 2D printed circuit board design. And also the low-power design benefits the overall system volume and dimensions due to usage of smaller batteries. So the development of tiny, low weighted and mechanical robust wireless sensor systems needs the reflection of multiple disciplines: hardware, software and packaging. Thereby exploitation of battery effects allows a reduction of battery volume. The relevant miniaturisation aspects are discussed on the exemplary application of a wireless tire pressure sensor unit.

In the next three sections, we will discuss the degrees of freedom in selecting components and packaging of miniaturized self-sufficient sensors like wireless tire pressure sensors. Beginning with the exemplary requirements on TPMS, we will introduce selection of components and interconnection technology as part of design flow to achieve miniaturized wireless sensors. Different design options are traded off to meet demands. Finally we present prototypes of network capable wireless sensors as well as sensor modules for a direct TPMS developed for Global Dynamix AG.

2 Requirements

Requirements on wireless sensors are defined by its application and lead the designer through the design space. Because we use it as an example, we want to introduce general requirements on tire pressure monitoring system:

Reliability: If a tire pressure system or another assistant system is at driver's disposal, it is trusted. Hence, reliability is intended by packaging. Wireless sensors mounted in rotating wheels are caught in crossfire of harsh environmental influences. Vibrations and acceleration forces necessitate *mechanical robustness*. A *wide temperature range* and *thermal shock resistance* are required by meteorological condition as well as heating by full breaking. Sensor units must be *shielded against electro magnetic irradiation* and have to be *resistant against chemical substances,* i.e. salt-water, lubricating oil, sulphurous lotions, or cleaning supplies. In all cases, the integrity of sampled pressure values is a necessity and the driver has to be informed when a malfunction is detected. Reliability also addresses fault-tolerant system behaviour (implemented in hard- or software), which is not considered in this paper due to limited space.

Low unit cost: Designed for mass marked, unit price has to be low. Reducing the number of electronic devices decreases component costs, and decreases the overall system weight and volume. Integrating analogue acquisition components, digital circuitry for computation and RF front-end for wireless communication into a single package allows a very compact single chip solution. Yield is primarily a function of die size. Therefore multi-chip solutions are sometimes preferred because of cost-effectiveness. However, the system requires the inexpensive integration of heterogeneous components, i.e. ICs, sensors, crystals, antenna, and passives.

Low installation and maintenance effort: Installation of tire pressure monitoring system should not influence established factoring processes. Amount of cabling should be as low as possible. Therefore systems with a single receiver are favoured over antennas in each wheel house. Reutilisation of keyless-entry board unit for tire pressure monitoring reduces installation effort and system costs. Exchanging batteries of tire pressure sensor units mounted in air chamber is time consuming and expensive. Therefore long operation time must be granted and a tire pressure sensor should work over a tire’s life time by utilizing an ultra *low power design*.

In this paper we concentrate on techniques to achieve low system dimension and weight.

3 Selecting Components

Figure 1 shows a block diagram of a wireless tire pressure sensor. It can be easily adapted to other wireless sensors applications: Temperature and pressure are acquired by sensors. After conditioning digitized signals are preprocessed and assembled into information packets, which are transmitted to the board unit using a radio link. The radio link can be used in opposite direction to receive calibration and configuration data. All components are powered by a power supply unit.

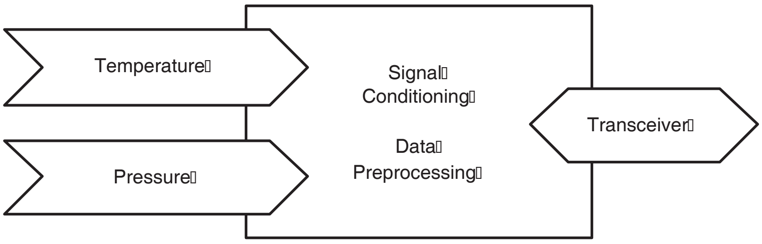

Fig. 1. Block diagram of an active bi-directional tire pressure monitoring unit.

In the field of system miniaturization, the main question is which components mainly determine the final dimensions of the whole system. The optimization focus during the hardware development is to be put accordingly. Components like batteries, capacitances, high quality filters, crystals, and antennas normally dominate the volume of a wireless sensor node below a cubic centimetre. Several trade-offs often allow to adjust the requirements of a single component and to change volume share for a minimal size of the whole sensor node. For instance, a larger battery allows a smaller antenna with a reduced efficiency and vice versa. Our first design stage is to consider the manner, in which functionality will be realized. The subsections below discuss design options according to the requirements mentioned above, and keeping power consumption as well as system size in mind to achieve a long operation time and high mechanical robustness.

3.1 Sensors

Temperature, acceleration forces and supply voltage are reasonable measurements for TPMS next to obvious pressure. Temperature monitoring is necessary for temperature compensation and allows warning on overheated tire. Vibrations are indicators for a moving vehicle and can be used to wake up the TPMS from very deep sleep mode, while detection of low supply voltage is necessary to warn the driver about imminent sensor malfunction. The size and power consumption differs very much according to the type of sensor technology. With declining smaller sensor dimensions, the physical connection to the measuring medium also declines, so that miniaturization can considerably influence the precision. In this section we focus upon pressure and temperature measurement to avoid going beyond the scope of this paper. The selection of any transduction techniques affects the complexity and size of read-out circuitry.

Tab. 1. Comparison between piezo-resistive and capacitive pressure transducers [5]

	Piezo-resistive	*Capacitive*
Nominal pressure [kPa]	10-1000	10-1000
Temperature range [°C]	-40 – 125	-40 – 125
Signal proportionality	Displacement	1 / displacement
Electrical impedance	Low	High
Signal drift	High	Low
Signal noise	Low	Moderate
Offset signal	Moderate	Small
Relative signal change	Small (~2%)	Large (~50%)
Power consumption	High	Low
Influence of parasitics	Low	High
Read-out circuitry	Simple	Complicated
Overload-ability [nominal pressure]	5x	100x
Temperature sensitivity [%/K]	-0,15	-0,01

Pressure: Miscellaneous pressure transducers are available on market: resistive wire strains, piezo-resistive and capacitive pressure transducers. Transducers used for TPMS operate in range between 100 and 500 kPa and must be insensible to acceleration forces. The first one is unsuitable, because resistive wire strains are less appropriate to pressures below 500 kPa appearing in tires and their miniaturization potential is limited [5]. Piezo-resistive pressure transducers change their resistance when deformed by applied pressure, while capacitive pressure transducers alter their capacity with distance of electrodes. Table 1 compares both pressure transducer types. Capacitive transducers are less sensitive to temperature but have high requirements on read-out circuitry. Influence of parasitic capacities is high due to measuring capacities in the range of 10 pF. Their low power consumption is less weighted, because sensors are low frequently used and activated for a very short duration. Specific package have to be attended to reduce disturbances by thermal mismatch between chip and package, whereas mechanical restraint due to fixed assembly of chip and package can be seen as reason.

Temperature: A sensor module for TPMS must operate in temperatures between -40°C and 125°C. Suitable transduction techniques are realizable in compact form. Metal resistors, negative and positive temperature coefficient thermistors, silicon-spreading-resistance, and integrated sensors allow simple read-out circuits, while crystal sensors offer higher accuracy [5]. Tire pressure monitoring systems do not require high temperature accuracy.

3.2 Data Processing and Device Control

Signal conditioning and communication management is done by digital backend. Pre-processing allows the reduction of transmitted data in order to save energy. The corresponding algorithms can partly be implemented energy efficiently as hardware or more flexible as software (Fig. 4). Hybrid approaches will often represent the most suitable solutions. Low level functions like the signal acquisition and base band processing are often realized via application specific, integrated circuits. This represents a benefit for computation-devices regarding computation speed and size. Depending on production volume and required flexibility, high level functions are implemented either in hardware or in software. In the case of our TPMS standard, microcontrollers with hardware support for data acquisition are used to achieve a short time to market. However, power consumption and battery size benefiting application specific integrated circuits are predicted due to high TPMS quantities.

Next to signal conditioning and communication management the digital backend implements the power saving policy. An efficient power adaptation for single components allows a considerable reduction of size determined by energy supply. The standard measure is to switch off all components which are not in operation. In case of TPMS the impact of power down current increases due to very low duty cycles (below 0.1%). The microcontroller requires an operation mode with a very low leakage current and a possibility for periodic wake-up. U.S. Federal Motor Vehicle Safety Standards No. 138 [4] allows relaxed duty cycles for TPMS by an acceptance of reaction time up to 20 minutes.

3.3 Radio Interface

The design of radio interface and communication protocol is driven by following intentions: a) reliability of communication channel, b) size and weight of required components, c) power consumption. The selection of carrier frequency plays a key role. Higher carrier frequencies allow smaller antennas and higher data rates, whereas longer ranges and less reflection on surfaces are possible with lower transmission frequencies. Frequencies selection is limited by national frequency assignment plans. We choose 868/915 MHz for TPMS due to antenna size and transmit power consumption balance.

Antenna design is not only influenced by the limited space but also by shielding effects of the electrical circuitry and the power supply. Apart from the development of an efficient antenna, the optimum for the whole system can be a smaller antenna of reduced efficiency, where the saved volume allows a higher energy buffer capacity. In the case of the proposed TPMS lower battery weight has a higher priority then antenna size. The system has to work with a single antenna attached to the board unit. It is not satisfying to mount antenna in each wheel house due to wiring effort, which provides optimization criterion for antenna design in case of TPMS.

A further task of the radio interface is the reception of configuration data. Reconfigure ability of alert thresholds, duty-cycles and carrier frequency allows a very flexible system which can be used in different vehicles and countries. This makes integration of a receiver necessary, which also enables whole-system calibration after module assembly. The communication protocol has to reduce idle-listening, i.e. power-waste of an active receiver without incoming messages.

3.4 Clock Generating Components

Because clock generating components can take a high volume share, they are discussed separately. For the clock generating components a decision had to be made which frequency tolerances could be admitted. On-chip RC oscillators of a very low volume show a drift of 3 … 25% due to aging and temperature dependency. Frequency of larger crystals vary below of 0.1%. The clock source for radio frequency synthesis is most critical to keep radio frequency drift low. This clock source must be quite temperature and long term stable, because the tire pressure sensor is exposed to wide temperature range over several years. It is only possible to apply a frequency trimming factor in dependence of temperature if aging effects are negligible. In that case the avoidance of expensive temperature stable crystals with relative high volume share is possible.

3.5 Power Supply

An essential component of the self-sufficient wireless sensors is their own energy supply, which strongly determines size. The energy supply of tire pressure sensors is often based on electrochemical batteries due their relative high energy density and relative low costs. The selection of appropriate micro batteries can raise issues. Not only high energy densities for small volumes, but also the nominal voltage, the self discharge current, and the maximal load have to be considered for the choice of material. For instance, zinc air cells with a very high energy density (Fig. 2) can be used only for a few weeks due to their high self-discharge current. On the other hand, lithium button cells can only drive relatively low currents, which can cause non-tolerable voltage drops in transmission phases. Here, electrode area is a major factor.

Furthermore, the estimation of the necessary battery volume for a given operation time is quite complex. The capacity of a small battery decreases rapidly at higher loads, whereas the capacity increases during intervals of reduced currents. This is known as the rated-capacity effect and the recovery effect. Additionally temperature dependency of chemical reactions, aging of battery caused by side reactions have to be considered – especially in case of long operating TPMS. Hence, determination of required battery size depends massively on the load profile and climatic environment.

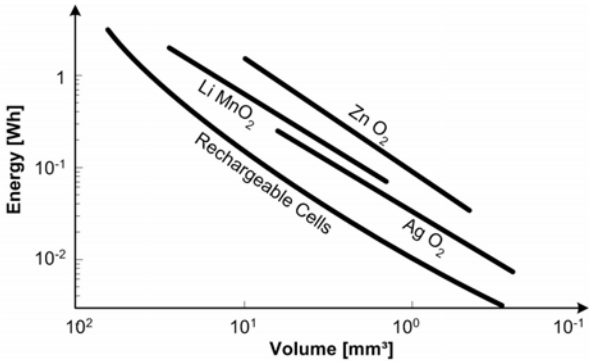

Fig. 2. Energy capacity of some batteries [9].

Indeed batteries have the lowest primer costs, but we have to think about the huge amount of batteries, which have to be disposed as hazardous waste after TPMS operation time ends. Some applications allow a replacement of large energy buffers by energy harvesting using movement, heat, radiation or biochemistry. The size of energy converters depends on energy demand and available intensity. Energy buffers will be necessary for most cases, because the harvested energy will rarely satisfy the total power consumption at anytime. Piezoelectric devices are imaginable in TPMS to benefit from vibration, but they require huge vibration pick-ups and oscillating weight, which increases wheel unbalance. An additional option is the usage of wireless charging techniques to enhance the system life time. Besides electrical charging via radio antenna or inductive coupling, the same principles of energy harvesting can be taken into account depending on coupling factor, shielding, and directivity. Charging by inductive coupling adds unwanted wiring effort in case of TPMS, because coils have to be mounted in each wheel house.

4 Integration Technology Selection

As have been shown above, a system like TPMS consist of several heterogeneous components. Design methodologies and reliable packaging technologies of heterogeneous components are research objects of Fraunhofer Institute Reliability and Microintegration and Technical University of Berlin.

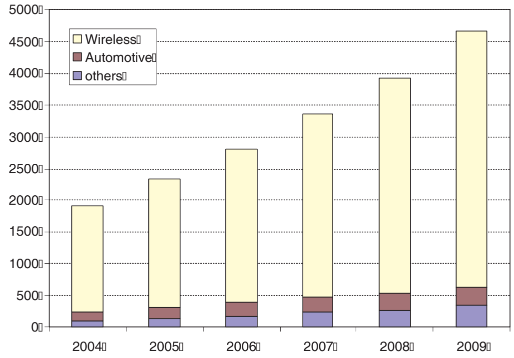

Fig. 3. SiP market projection, millions of units [10]

The common planar On-Board integration techniques like SMT (Surface Mounted Technology) allow low cost realization. But the increasing system complexity and high miniaturization demand for the automotive applications require another integration technologies, which have to be applied to achieve a size constrains. On-Chip integration of heterogeneous elements is challenging from design as well as from technological point of view. A promising solution for achieving highest integration density in smallest volume has been seen in vertical integration of heterogeneous components as a System-in-Package (SiP) (Fig. 5). This integration approach is well established in the area of wireless communication and it is also gaining for automotive market more and more in importance (Fig. 3, [10]).

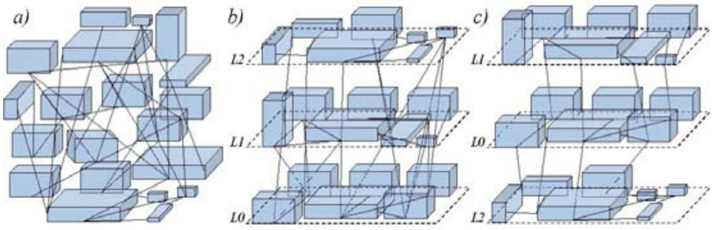

Fig. 4. Global layout for 2.5 D systems - Components and Nets: a) on the beginning, b) after partitioning, c) after placement and routing

The selection of the optimal integration technology as well as geometrical arrangement of components and preparing of the manufacturing data are obvious parts of the physical system design. It begins after the previously described functional units are defined und their electrical schematic is finished. In the beginning of the physical design, the component set (ICs-bare dice, passives in their values etc.) for the realization of TPMS and their electrical interconnection (net list) are defined by the schematic. Within the 2.5D integration, where the functional layers are vertically integrated on each other, the physical design could be subdivided into two stages [8]:

1. Global Layout, which can be abstracted away from any certain technology,
2. Detailed Layout/implementation, which is obviously based on definite technology.

In analogy to PCB/MCM- and IC-Design, both stages consist of three main steps: Partitioning, Placement and Routing. The aim of global partitioning is to group the components and to allocate them on certain vertical layers. Global placement means the arrangement of layers in stack, and global routing is in this case the optimization of the electrical wiring/nets between the layers (Fig. 4). All these steps can be formulated as a mathematical problem with a number of boundary conditions and objectives, such as floor plan and volume minimization for partitioning, minimization of wire length in the placement, the reduction of nodes quantity in the routing, testability of the layers and of the complete system as a general task etc.

Whilst a designer of “traditional” planar applications such as PCB or MCM has several clear technological criteria to make a decision regarding substrate and interconnection technology (e.g., wiring density, via types, the number of layers of laminated, thin film or ceramic substrates, interconnect pitch, cf. Tables 3 and 4), there is no clearly defined criteria for choosing optimal SiP technology for vertical integration. The system designer is faced with many different technological solutions presented by several industrial and research institutions. The currently available and practicable technological 2,5D SiP solutions for realization of highly miniaturized wireless sensor systems such as TMPS can be exemplary subdivided in four main groups [8] (Fig. 5):

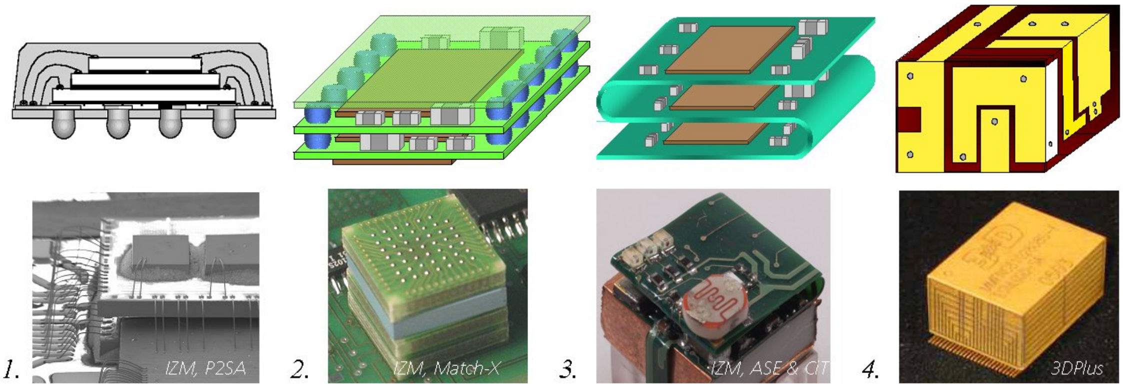

Fig. 5. Four main integration schemata and application examples of 2,5D SiP

1. Systems, where no signal redistribution in vertical wiring (In this case, it can be called vertical interconnect – VIC) and lower signal redistribution level in lateral wiring possible, so the routing can be down only in lateral level (mostly represented by wire bonded die stakes, e.g. Sharp),

2. Systems with no signal redistribution in VICs and high signal redistribution / routing capability in lateral levels (represented by solutions with functional layer on stacked modules e.g. North),

3. Systems, where signal redistribution level in vertical and lateral wiring is high and approximately equal (represented by solutions with components on the folded flexible substrate, e.g. Tessera),

4. Systems with medium and approximately equal redistribution level in vertical und lateral wiring, represented by stacked and molded devices with connecting metallization on the surface/sidewalls (3D Plus, Irvine).

For the compare and choice of optimal technology for the realization of TPMS at the beginning of the detailed layout/implementation stage, the designer needs objective criteria, as they are usual in the two dimensional design flow (Tab. 3 and 4). Table 5 demonstrates partly a parameter set for the four labeled technology groups. The parameter set is currently been explored at Fraunhofer IZM and practically verified by the prototypes, which are discussed in the section 4. The parameter provide not only key data for a qualified comparison and selection of integration technologies, they can also be used for the constrained placement of the components in 2,5D-Room in global layout stage. The available CAD tools for PCB-, MCM- and Packaging-Design include highly automated autoplacer and autorouter for the two-dimensional applications. But for vertical SiP- Integration of heterogeneous systems like TPMS, the designer still places components manually over the number of layers. The Fraunhofer IZM is working currently in cooperation with Fraunhofer ITWM on the novel 2,5D auto placement procedure, which is based on the volume optimization algorithms constrained by investigated technological parameter, targeting higher design effectiveness for TPMS- and further automotive applications. Furthermore, the automotive applications require very smart and robust concepts for the system encapsulation. In the traditional packaging design, the system molding issues are often been seen as an additional post design step. In the case of 2.5D integration for automotive area, the encapsulation concept influents the design flow in early stage for example during layer planning and components placement. Fraunhofer IZM investigates also molding technologies for the application environments with high temperature and mechanical stress, as they are usual in the automotive area.

Tab. 3 Design relevant parameters for laminated (MCM-L), ceramic (MCM-C) and thin film (MCM-D) substrate technologies [8]

	MCM-L		***MCM-C***	***MCM-D***
	HDI	***PCB Standard***	***Ceramics***	***Thin Film***
Line width [µm]	50…75	125	75..100	10
Line space [µm]	50…75	125	250	10
Via land diameter [µm]	100…225	650	200	30
Number of layers	8…10	8...30	15..30	2..5
Dielectric constant [mm^2]	2,3…4.7	4,7	6...10	2,7...3,5
Material	FR4	FR4	Alumina	Si, Metal…
Price appoxim.	medium	Lowest (cents/cm^2)	medium	High (\$/cm^2)

Tab. 4 Design relevant parameters for different interconnect technologies [8]

		Wire Bond	***Flip Chip***	***TAB***
Min. Pad Pitch [µm]	***Die***	50	100 … 120	60
	Substrate	120	100 … 120	200

Mounting		serial	parallel	serial/par.
Electrical Performance	L [nH]	1 … 5	0.06 … 0.2	1 … 3
	C [pF]	0.2 … 0.6	0.02 … 0.03	0.2 … 0.6
Mechanical Protection		glob top	underfill	None

Tab. 5 Parameter set for labelled SiP technology groups

		Stacked Dice	***Stacked Modules***	***Folded Flex***	***Moulded Devices***
Redistribution capability	***Vertical***	-	-	High	Medium
	Lateral	low	high	High	Medium
Passive Integration Capability	***Discrete***	low	high	High	High
	Embedded	low	high	Medium	Medium
Wire Length	***WL***	high	low	High	Medium
No. Functional Layer	***L***	up to 5	7	10	32
Layer Thickness L=G+C	***Layer Gap G [µm]***	negligible	100 … 1200	200 … 1200	50 … 600
	Carrier C [µm]	200 … 600	≈50 … 1200	20 … 100	50 … 200
Vertical Interconnect Density	***[1/mm^{2}mm]***	≈0.5; ~f(G)	0.5 … 12; ~f(G)	5 … 30	10 … 50

5 Prototypes

For evaluation of high integration packaging techniques tiny wireless sensor are implemented on flexible substrates (Fig. 6a). These sensors measures brightness and temperature and interact in multi-hop sensor networks. All components are integrated in volume of 1 cm^3. A self-sufficient tire pressure sensor unit developed for Global Dynamix AG is shown in figure 6b. They allow the reconfiguration of the tire pressure sensor module using radio communication like measure intervals, thresholds and radio frequency. The system uses 868/915 MHz-ISM-band and allows the usage of a single antenna integrated in the board unit.

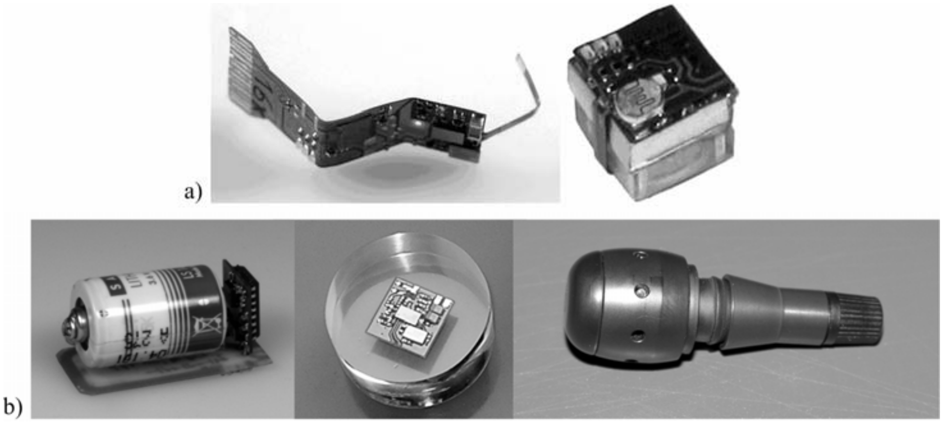

Fig. 6. a) Components of wireless sensor mounted on folded flex b) Electronic of a tire pressure monitoring sensor developed for Global Dynamix AG

6 Conclusion and Future Work

In this paper we discussed the degrees of freedom in designing miniaturized self-sufficient sensors considering a TPMS as an example. Especially tire pressure sensors electronics can be extended to equip a tire with intelligence and to allow vehicle adaptation to weather and road condition. The tire ID in future will prevent the usage of ineligible tires in dependence on vehicle type, road and weather conditions. This addresses a further main source of accidents with damage to persons. Thereby, miniaturization of application specific autarkic sensors requires system knowledge and multidisciplinary overview due to interdependences of different domains. Today's advances in packaging and manufacturing technology allow the enhancement of the miniaturization level, which enables the integration of reliable self-sufficient sensors into objects like valves. Further power efficiency is needed to achieve long operating lightweight systems.

Acknowledgements

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