Wireless Communication and Energy Harvesting in Automobiles

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***Abstract*—Using wireless communication and energy harvesting in automobiles might have significant advantages considering dependability (no wires and contacts) and weight (no cable tree). In this paper, we give a brief overview of the related technologies, surrounding conditions, and methods for design and optimization. As examples, we focus on methods for harvesting kinetic energy and wireless transmission in a tire pressure metering system (TPMS).**

I. Introduction

Conversion of the energy available in the environment into electricity to drive small, autonomous electronic systems has been steadily gaining momentum in recent years. The progress in energy harvesting technologies has been coupled with significant advances in the functionality and applications of low power systems. Thus, as harvesting is becoming more efficient and electronics is demanding less power, energy harvesting enabled solutions and wireless sensor networks present an ideal combination from the point of view of application needs. Wireless sensors are increasingly deployed in applications where hard wiring or battery maintenance are impractical. This paper addresses automotive applications of energy harvester powered wireless sensor nodes. This is now a rapidly growing market. Typical examples are: GenSchock, the energy harvesting shock absorber from Levant Power Corporation, the roadway power system based on harvesting thermal energy stored in the road surface from Novotech, Inc. and the tyre pressure monitor from Infineon Technologies. Wireless sensor networks are becoming increasingly popular inside a modern car [1], where hundreds of sensors and actuators are networked to enable drive-by-wire functionality, increased safety, reduction of energy consumption or comfort and entertainment. Energy harvesting helps to combat problems that arise from the growing sizes of communication networks. Traditional, wired solutions lead to increasingly complex cable trees required for energy supply and data transfer between computing nodes and sensors and actuators. The cable tree creates major problems related with reliability, cost, weight and difficulties in modularity and standardization. Efficient wireless communication of different kinds could overcome these problems and provide additional benefits beyond reliability, safety and cost considerations, for example comfort functions, such as window lifters, seat detection, heating and infotainment. Both wired Ethernet and wireless networking in automotive context has already been investigated [2]. Wired Ethernet has been used for first-by-wire control and wireless car-to-car networking, as well as for energy harvester based, battery free systems such as Tyre Pressure Monitoring Systems (TPMS). Applications of wireless systems, especially those based on autonomous nodes, either harvester or battery powered is still in their infancy but are very intensively investigated by the automotive industry. Emerging families of wireless sensors, which are being used in a wide range of applications in many industries, especially those related to automotive applications, provide an important stimulus to the electronic design automation community. While automotive thermogenerators using the engine heat are being developed and are nearing market readiness, most current solutions are based on harvesting kinetic energy carried by movement. Section 2 of this paper addresses energy harvesting with a particular focus on kinetic energy harvesting. Section 3 gives an overview of the overall architecture of a recent TPMS which uses wireless communication.

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II. Energy Harvesting

Energy harvesting is the process by which ambient energy from the environment is captured and stored [3]. Most wireless sensor nodes are now powered by batteries, which need charging or replacement after a period of time. If these devices could be self-powered by energy harvesters, great amount of cost in maintenance will be saved. Various devices have been reported to scavenge energy from different sources, such as

- light [4],
- heat [5],
- RF [6] and
- mechanical vibrations [7].

The appropriate source for a particular use case must selected carefully, depending on its location. Kinetic based energy harvester seems to be suitable for many automotive applications since mechanical vibrations are widely present in a moving vehicle. There are three main transduction mechanisms in vibration-based energy harvesting: electromagnetic, piezoelectric and electrostatic, each of which has various examples reported in literature and a good review article has been published [8]. Most of the reported microgenerator designs are based on a spring-mass system with a characteristic resonant frequency [8]. These devices generate maximum power when their resonant frequency matches the frequency of the input ambient vibration and normally have a high Q-factor. Therefore, the output power generated by a microgenerator drops dramatically when there is a difference between the ambient frequency and the resonant frequency. Tunable microgenerators, which can adjust their own resonant frequency through mechanical or electrical methods to match the input frequency, and microgenerators with wide operation bandwidth are more desirable and have attracted significant research interest [9].

At present there are considerable and continuing research efforts world-wide to support the energy harvesting paradigm and self-powered electronics. The amount of power that can be harvested in a particular application is highly dependent upon the energy source being harvested. Typically, power densities of around $800\mu W/cm^3$ for machine vibration applications can be expected [10], however, the power output of vibration-harvesting inertial generators is highly sensitive to the frequency and amplitude of the vibration source [11]. Practical generators have been reported with power densities of $17\mu W/cm^3$ for a non-resonant device [12], [13], to a resonant device capable of generating $30\mu W/cm^3$. Typically the generated voltage from a micro-generator is insufficient to power a sensor node directly, and therefore external circuits are often employed to rectify and boost the voltage and store the energy in a battery or a super-capacitor. A tunable energy harvesting system normally has five major components (Fig. 1): a microgenerator which converts ambient environment energy into electrical energy, a power processing circuit which regulates the generated voltage, a storage element, an actuator used for the tuning mechanism and a microcontroller that monitors and controls the tunable energy harvesting system.

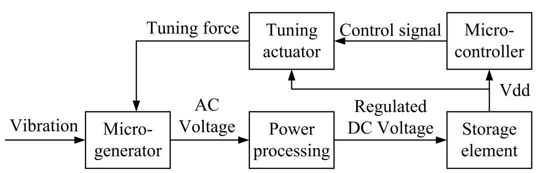

Fig. 1. Block diagram of a tunable energy harvesting system

There are two types of mechanical vibrations that are commonly seen in an automobile: rotational vibrations that are related to the driving mechanism, such as driving shaft and wheels; vertical vibrations that are related to the suspension system. Toh et al. have presented the design of a wireless sensor node using rotational energy harvester [14]. Fig. 2 shows the schematic diagram of their rotational harvester. The rotor is attached to a rotation source which has an angular velocity of ω and the offset mass is attached to the stator. The maximum electrical energy that can be generated is given by [14]:

$$P_{elec(\max)} = \frac{(K_E\omega)^2}{4R_L} \tag{1}$$

where K_E is the motor constant and R_L is the optimal load resistance. After regulation, the generated electrical energy can be used to power a wireless sensor node and such a system is suitable for automotive applications.

Zhu et al. have developed a electromagnetic microgenerator which is tuned by magnetic force [15]. Fig. 3 shows a diagram of the electromagnetic microgenerator together with its tuning mechanism. The microgenerator is based on a cantilever structure. The coil is fixed to the base, and four magnets (which are located on both sides of the coil) form the proof mass. The tuning mechanism uses magnetic force to change the effective stiffness of the cantilever which leads to a change of resonant frequency. One tuning magnet is attached to the end of the cantilever beam and the other tuning magnet is connected to a linear actuator. The linear actuator is controlled by a microcontroller and moves the magnet to desired position so that the resonant frequency of the microgenerator always matches the frequency of the ambient vibration.

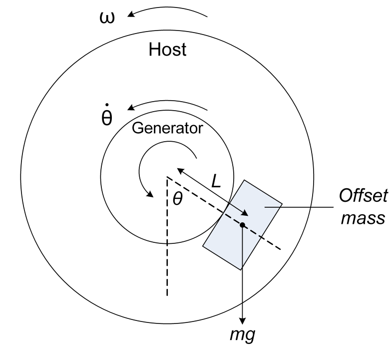

Fig. 2. Diagram of a rotational energy harvester [14] (reproduced with permission)

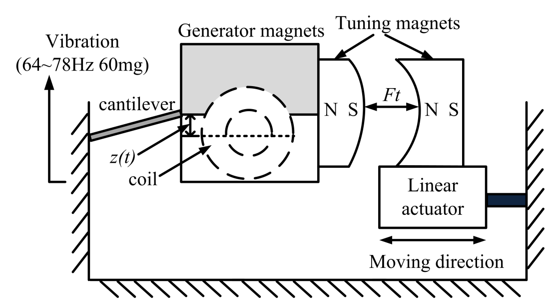

Fig. 3. Tunable electromagnetic microgenerator [16]

One area where energy harvesting is commonly considered useful is the tire pressure monitoring systems (TPMS) [17]. Rotational harvesters can be employed to power the pressure sensor and its associated wireless transmission module. The description of a self-sufficient in-tire TPMS demonstrator is presented in Section III. In terms of harvesting vertical vibrations, there have already been reported work on developing wireless sensor node powered by energy harvester for automotive applications. Ventura et al. presented an embedded system to assess the automotive shock absorber condition which is powered by a piezoelectric generator harvesting from the shock absorber itself [18]. The system is capable of monitoring shock absorber conditions and transmitting the data throughout a wireless interface.

Some of the basic requirements for energy harvester for typical in-car applications are:

- Highly reliable;
- Wide working range for different input amplitudes and frequencies;
- Short duty-cycle or ideally continuous monitoring mode.

An energy harvester is a system consisting of several components from different physical domains including mechanical, magnetic and electrical as well as the external circuits which regulate and store the generated energy. To design highly efficient energy harvesters, it is crucial to consider the various parts of an energy harvester in the context of a complete system. Otherwise the gain at one part may come at the price of efficiency loss elsewhere, rending the energy harvester much less efficient than expected. Wang et al. have developed an automated design flow for vibration-based energy harvester systems [19] and various optimisation algorithms can be implemented within the general design flow.

III. Wireless in-Car Communication

A. Ultra-Low Power Wireless Communication

The focus on ultra-low-power wireless communication is especially important where energy is obtained from harvesting sources, or where batteries have to work for several years. In Automotive, replacing batteries at several places every few years is not an option so true wireless sensor nodes have to rely on scavenging sources, where average power availability is in the order of a few μW [20] for typical in-car scenarios instead of mW as usually assumed for low power wireless communication based on standards like ZigBee.

In wireless sensor networks (WSN) energy consumption of wireless communication usually dominates over-all power consumption. Therefore, the node and also its transceiver typically are duty-cycled with very short active periods in order to save power. Because of the limitation in minimum on-time, mainly given by crystal oscillator stabilization requirements, the node reactivity drops at low duty-cycles and hop-by-hop latency can reach seconds when lifetime of a node shall reach several years [21]. To cope with this problem, an additional and highly optimized always-on Wake-up Receiver (WuR) [22] with ultra-low power consumption can be used for RF channel monitoring and notification of packet arrival, if a wake-up condition is detected. Therefore its own-power consumption must be lower by orders of magnitude compared to of state-of-the-art main transceivers [23].

In order to setup requirements for ultra low power wireless in-car communication, the main initial applications where cable free wireless sensor nodes will be applied have to be identified. Fig. 4 shows two sensor applications connected to a central cabled hub node in a car. A Wireless Tire Pressure Monitor System (TPMS) with a star-point communication topology and a seat occupancy detection sensor network are among two applications that are likely to be found in many cars in the years to come. For TPMS, wires are of course no option; for seat occupancy wireless allows saving cables as no cabled infrastructure might be available in these places. For other applications where high powered actors are nearby or sensors placed nearby a cabled infrastructure, ultra low power wireless communication is not mandatory (i.e. receivers can be turned on all the time). Therefore, for Automobiles, wireless ultra-low power communication is only a requirement for specific sensors, where cabling is not feasible or costs can be saved.

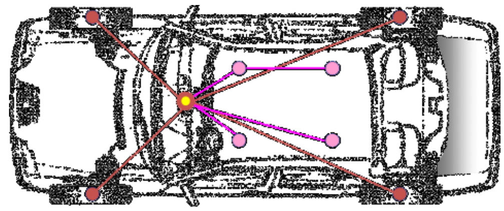

Fig. 4. Two overlapping true Wireless in-Car Sensor Applications

The requirements for energy self-sufficient wireless nodes for typical in-car applications are summarized as follow:

- Turn-On Time: as small as possible $< 100\mu$s
- Average power consumption 1-20μA
- Peak power consumption $<$ 10mA
- Data rates $<$ 10-100 kbps , Modulation FSK
- Use of ISM Band 868/915 MHz or 2.4GHz.
- Node Standby $<$ 100nA

B. A Self-Sufficient In-tire TPMS Demonstrator

State of the art direct tire pressure monitoring systems (TPMS) are wireless sensor nodes mounted on the rim. By the advances of ultra low power communication and energy harvesting as well as energy conversion, harvesting based battery less active systems have been demonstrated to work well. Fig. 5 shows a block diagram of the in-tire TPMS demonstrator, consisting of a MEMS sensor, a power supply module, a microcontroller ASIC, and a transceiver ASIC which directly generates the RF carrier by using a BAW resonator.

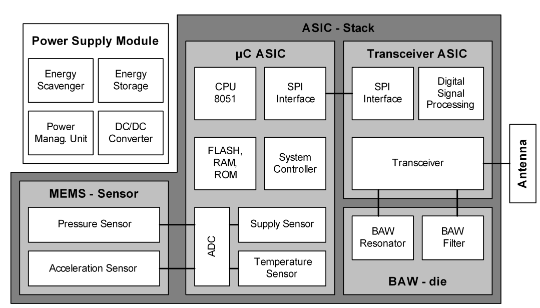

Fig. 5. Block diagram of the in-tire TPMS sensor node demonstrator

The key innovations of the demonstrator are:

- a bulk acoustic wave (BAW)-based Frequency Shift Keying (FSK) transceiver

- pioneered for an energy scavenger based low volume and low weight power supply
- a 3D vertical chip stack for best compactness, lowest volume, and highest robustness for pressure, inertia, and temperature sensing

In the following sections we focus on the innovations in Wireless Communication and Mems Device and its power supply.

1) Wireless Communication Transceiver: For use in the proposed sensor node a BAW based RF transceiver has been developed (Fig. 6), which directly generates a 2.4 GHz carrier by using a BAW resonator with a size of only 0.02mm^2. It avoids the employment of a bulky and shock-sensitive crystal and a phase locked loop (PLL), which makes the system more robust and radically reduces the turn-on time to a few ?s from several ms as in state of the art crystal oscillator systems. This improves the overall power consumption [24], [25].

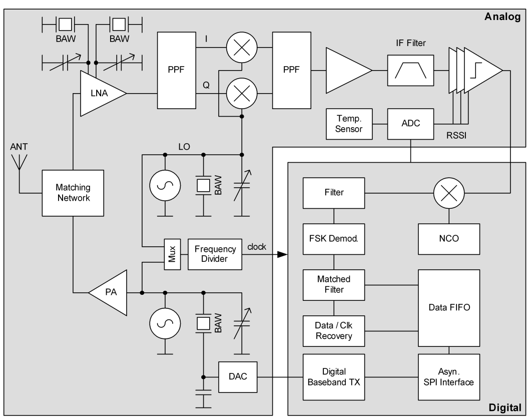

Fig. 6. Block diagram of the BAW transceiver

For the receiving section an image-reject architecture has been chosen with BAW resonators integrated into the LNA for filtering [26]. In contrast to [27], the presented receiver utilizes the narrow bandwidth of a single BAW resonator instead of a filter consisting of several resonators. The LNA is followed by an RC-polyphase network to generate the I- and Q- phases for the image-reject mixer. At the IF the received signal is filtered and fed into a limiting amplifier delivering a binary signal, which is directly mixed into complex baseband in the digital domain. After digital filtering, demodulation, and de-framing the received payload is stored in a FIFO.

Small sized shock-resistant BAW resonators are utilized as frequency reference for the TRX and channel selection filter in the receive chain [28]. A BAW resonator can be considered as a thin film of piezoelectric material sandwiched between two metal electrodes. When an electric field is applied between the electrodes, the structure is mechanically deformed by way of inverse piezoelectric effect and acoustic waves are launched into the bulk of the device [29]. One major drawback of BAW devices is their temperature dependency, which is typically in the range of -18ppm/°C. To overcome temperature drift effects the temperature is measured and compensated via digitally controlled capacitors (9bit) in parallel to the resonator in the range of -40°C to +125°C. Due to the fast response of the resonator, this effect is used for FSK modulation in the transmitter. Direct carrier modulation and frequency tuning is also possible with the digitally controlled tuning capacitors, but the nonlinear and process dependent relationship between capacitance and resonance frequency is a drawback, which has to be considered when applying this method.

The transceiver ASIC was fabricated by using a 0.13μm standard, automotive qualified CMOS process. Its current consumption is 6mA in transmit mode at a transmit output power of 1dBm and 8mA in receive mode with a sensitivity of -90dBm at a data rate of 50kb/s. The turn on time of the transceiver is only 2μs.

2) Power Supply Subsystem: The power supply subsystem (Fig. 7) consists of

- Miniaturized MEMS transducer device
- High efficient power translation ASIC (0.25 μm automotive qualified CMOS process)
- External coil for the inductive AC/DC converter
- Energy storage device (low leakage capacitor)

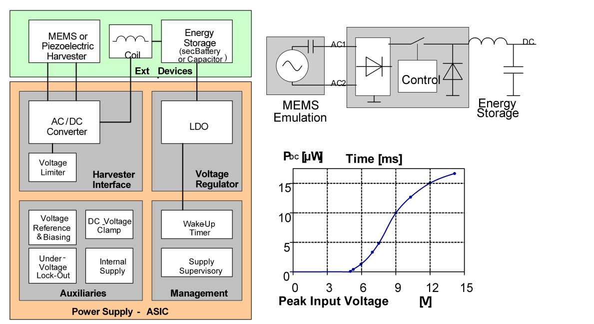

Fig. 7. Block Diagram of the Vibration Scavenger based Power Supply Subsystem

For the MEMS vibration scavenger an electrostatic transducer device has been chosen, manufactured by using high aspect ratio micromachining (Fig. 8) [30].

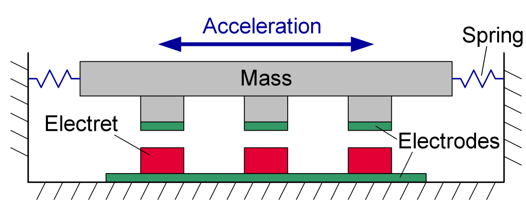

Fig. 8. Functional Principle of Vibration Scavenger

It already integrates an electret for biasing of the transducer, hence there is no additional external voltage source required. Due to the very small mass of the miniaturized vibration scavenger and the resulting very weak mechanical coupling, only a small portion of the available mechanical energy in the tire can be actually translated into electrical energy. In-tire measurements and electromechanical simulations have shown that the scavenging system with a vibrating mass of about

30 mm^2 is able to deliver some μA at 50 km/h driving speed, which is sufficiently high for regular reporting of the tire pressure at appropriate intervals. With increasing driving speed, the available vibration power also increases, allowing for shortening the reporting intervals, which results in higher update rates for pressure reports at higher driving speeds.

The successive power conversion ASIC integrates a high efficient inductive AC/DC down-converter for charging a capacitor up to the desired voltage level. It can process AC input voltages up to $\tilde{4}0$V. The input stage of the harvester interface consists of an active full bridge rectifier with peak detector. The peak detector generates the optimum trigger time-instant for voltage conversion, independent of the output voltage. Once the switch has been turned on, down conversion is done within a "single shot" via the external coil. Upon completion of the conversion cycle, the harvester's capacitance is discharged and starts recharging again with opposite polarity due to mechanical oscillation. Therefore the amount of conversion cycles is minimized for high power efficiency at lowest switching losses. An additional Low Drop Output (LDO) voltage regulator is used to remove a potential ripple voltage at the output of the AC/DC converter. Further on the ASIC provides auxiliary and control circuitry that are used for output voltage monitoring and switching off and switching on of the output power supply system. It makes sure that the output voltage is switched on once a certain voltage level is reached. Alternatively the integrated wake-up timer, making use of an ultra low power 2 kHz RC oscillator can be used for interval-based duty-cycling of the power system. For the in-tire TPMS demonstrator the power supply is regularly switched on after exceeding a certain energy level (respectively voltage level) available in the capacitor (low-leakage ceramic capacitor with C=200μF), which has been properly dimensioned to ensure, that sufficient energy can be stored for at least one pressure measurement and reporting cycle. A capacitor was used for energy buffering, as alternative secondary battery technologies suitable for harshest environmental conditions as present in the tire (high temperatures and high mechanical forces at the same time) are not available on the market.

C. Ultra low power Wakeup-Receiver

As depicted in Fig. 4 the seat occupancy detection networks could make use of multi-hop communication to reduce transmitting energy by shorter hop-to-hop communication and data aggregation. I.e. the rear seat detector could send its data to a neighboring node seat detector, which only then triggers the message sent to the central hub. In this case the nodes must be able to listen to incoming packets by means of duty cycling and synchronization or by incorporating an ultra low power always on Wakeup receiver. In a first research attempt our research wakeup receiver chip [22] could prove an always-on power consumption of less than 10μW with the drawback of reduced sensitivity overcoming distances of a few meters. In a second generation design approach finished in 2010, a much higher sensitivity receiver (-70dbm) at even lower power consumption could be demonstrated to work.

To meet the ultra low power consumption numbers, on-off-keying (OOK) modulation together with a simple and old-fashioned RF envelope detector demodulation technique is preferred over more complex schemes. Compared to a common heterodyne architecture of main receivers, this approach eliminates power-hungry generation of the local oscillator frequency which would exceed the small power budget. The block diagram in Fig. 9 gives an overview about the implemented WuR ASIC. Without the application of a low noise preamplifier, signal processing in RF domain is ensured only by passive filters and nonlinear signal detection for low power consumption. The resulting signal-to-noise ratio (SNR) after RF to baseband conversion is comparably low. To enhance SNR and receive sensitivity after signal filtering and amplification, a low-power analog/mixed-signal correlation unit for digital 64 bit patterns exploits coding gain. A full paper on the latest WuR research results is about to be published, therefore only a short overview was given in this section.

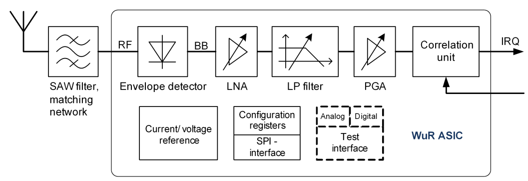

Fig. 9. Block diagram of wake-up receiver ASIC

IV. Discussion and Conclusion

Energy harvesting is a suitable option for more and more sensors within a car and allows a maintainance free and cableless operation reducing cost and increasing the dependability. Since energy harvesting in typical in-car scenarios only provides very little amount of energy in the order of 10-100uW the other wireless node building blocks such as power conversion and voltage regulation, CPU and specially the wireless communication transceiver must all be ultra low power and the operating voltages have to fit together to avoid losing energy due to conversion inefficiency. The conclusion is that only a whole system design approach that optmizes not only the single subsystems but also the dependencies between subsystems allows for market applicable solutions as has been seen in the example of the TPMS wireless sensor system presented in this paper.

The potential impact of the availability of a WUR in combination with energy harvesting allows the exploitation of new applications because the main energy consumer in traditional wireless sensor networks came from the radio transceivers (idle listening, even when duty cycled) and can now be replaced by an ultra low power WUR that fits the power budget of energy harvesting based nodes. More and higher efficient energy harvesting generators will become available in the years to come allowing to expand the amount of applications that potentially can benfit from a true wireless and maintainance free in-car sensor network.

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