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Towards Power Autonomous Wireless Sensors

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Abstract

This paper presents an introduction and overview of wireless sensors in IoT applications. A typical sensor architecture is described from sensor to the cloud. Four distinct methods of achieving power autonomy are developed. These are battery powered short lifetime devices, energy harvester powered devices for indefinite operation, inductively coupled wireless powered devices for short distances and devices based on passive radio back scattering. Four concrete technical examples of whole system solutions, each exploiting one of the mentioned powering strategies are presented.

1 Introduction

Two key challenges in enabling widespread deployment of sensing systems relate to powering them and communicating with them. It is clear that wireless communication is preferred in a wide range of applications. In respect to powering, the optimal solution allows for full power autonomy where the wireless sensor can operate throughout its lifetime without the need for any intervention or maintenance by the user. This presentation will give an overview of wireless sensors in IoT applications, highlighting current and future projected trends. Four primary methods of achieving power autonomy for wireless sensors are identified as battery power in case of short lifetime devices, energy harvester powered devices for indefinite operation, inductively coupled wirelessly powered devices for short distances and devices based on passive radio back scattering. This paper summarizes the published doctoral thesis, of the same title, of the first author [1].

In recent years, IoT device markets have been growing steadily as reported in [2], and illustrated in Figure 1. The market growth has largely been driven by connected cities, and in more recent years, increasingly also the industrial internet. Market segments, particularly including wearables and connected vehicles are becoming more significant contributors to IoT grown in recent years. The global IoT connected devices, estimated at 25 billion in 2017 generated revenue of just over 90 billion USD. The number of connected devices is projected to grown exponentially reaching 75 million devices in 2025.

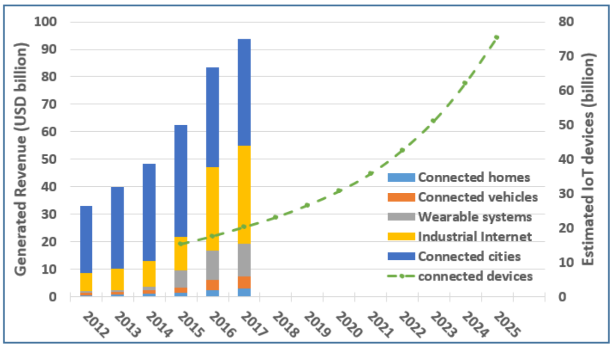

Figure 1. IoT device markets, global revenue by sub-sector (2012-2017) and projected growth (2015-2025) [3].

An overview of a classic wireless IoT sensor system is illustrated in Figure 2. A typical network topology is shown in (2 a.). A number of sensor nodes connect wirelessly to a gateway. The wireless connection can exploit any number of technologies (Bluetooth, NFC, RFID, LoRa, NB-IoT etc.) depending on the range and extent of the network. The gateway receives the network information and relays it to the cloud server over an internet connection (Ethernet, WiFi, LTE etc.) where remote uses can access the data. The hardware architecture of the sensor and gateway electronics is shown in (2 b.). The sensor node consists of the sensor itself and front-end readout electronics. A microcontroller interfaces the sensor, and stores data in memory if needed before relaying it wirelessly using the ratio transceiver. A power supply is included, which can be an energy storage, harvesting or receiving device. On the gateway side, a radio transceiver receives the data, stores to memory if needed and relays to the cloud server.

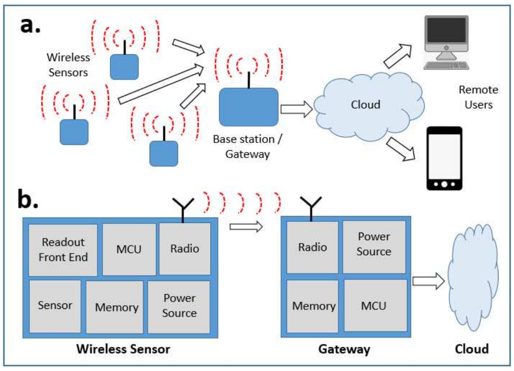

Figure 2. Overview of a wireless IoT sensor system showing (a) a classical wireless sensor network structure, and (b) hardware architecture of the sensor and gateway.

2 Developed Systems

The authors have developed four concrete technical examples of whole system solutions, each exploiting one of the mentioned powering strategies. Namely, (2.1) battery power, (2.2) powered by energy harvesting, (2.3) powered by inductive coupling and (2.4) fully passive radio backscattering.

2.1 Swallowable Capsule (Battery powered)

One system included in this work [3] develops a wireless swallowable capsule for in-vivo electrochemical analysis of the gastrointestinal tract, with wireless communication at 433 MHz. The system includes and electrochemical e-tongue sensor for detecting non-specific markers of gastrointestinal tract disease such and Crohn's disease and ulcerative colitis. The device includes a potentiostat and current acquisition circuit. A PIC microcontroller controls the measurement, digitizes the signal and relays the data to a Melexis TH72015 radio transmitter. The radio signal is coupled to an electrically small loop antenna, which is Q-degraded and matched to the in-vivo environment. Transmission is at 433 MHz for good coupling through the body. The device lifetime is limited to 72 hours, so power autonomy can be achieved using battery. A LiMnO2 battery with 165 mAh allows a 28-second measurement cycle to be conducted every 2 minutes for the 72-hour lifetime. The capsule, illustrated in Figure 3 is implemented on a rigid flex PCB substrate with 12 mm FR4 modules interconnected with a polyimide flexible connection (3 a.). The structure is folded in a pleat fashion as shown in (3 b.) and encapsulated in a biocompatible silica material as shown in (3 c.).

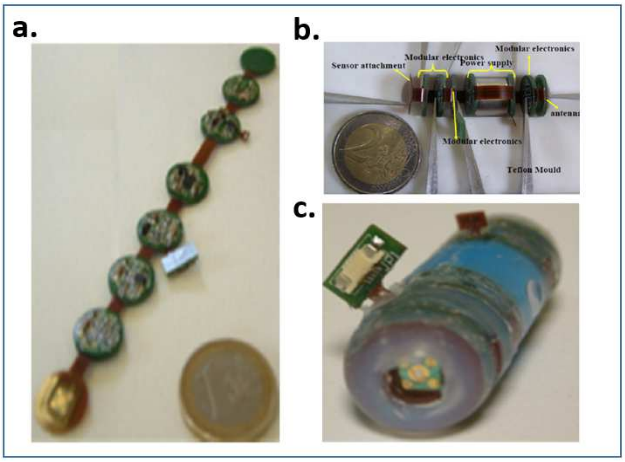

Figure 3. E-tongue capsule (a.) implementation on rigid-flex, (b.) folding to capsule form and (c.) encapsulation in silica based material [2].

The developed capsule was tested in a laboratory environment. The e-tongue sensor and readout electronics were compared with a commercial PalmSense potentiostat and shown to perform well. The radio system was tested by placing the capsule in a Plexiglas 'water cooler' container filled with saline solution to model the dielectric properties of human tissue. The radio link was shown to be reliable to a 2.5 m range, ample for the application requirements. The system was set running for 72 hours, on battery power and shown to meet the maximum measurement time requirement.

2.2 Energy harvester powered

A second system [4] developed in this work is for industrial condition monitoring using an acoustic emission sensor and a communication system at 2.45 GHz. The sensor detects micro fractures in a petrochemical valve by detecting minute vibrations at 110 kHz using a MEMS acoustic emission sensor. The signal is represented as a varying capacitance, which is RMS converted to represent to magnitude of the emissions, the turbulence and therefore the level of deterioration of the valve. The system enables power autonomy by utilizing a proprietary ultra-low power wake-up radio based on passive down conversion of an incident wake-up signal. On the sensor node, the incoming wake-up signal is received on a carrier of 2.45 GHz, and passively down converted to 125 kHz using a diode envelop detector. The 125 kHz signal is used as a pulsed subcarrier, down converted to 1 kbps signal that addresses a trigger to a low frequency wake up chip. The wake up receiver in listening mode needs power only for the diode bias and the low frequency wake up chip, totally measured as 6.8 uA. After wake up, the sensor communicates with gateway of the 2.45 GHz link. Energy for the sensor node is harvested using a thermoelectric generator from the temperature difference between the petrochemical payload and the ambient environment. In this case, for seamless deployment the gateway also utilized energy harvesting by tapping current from an industrial current loop. Figure 4 illustrates a block diagram of the sensor node and gateway.

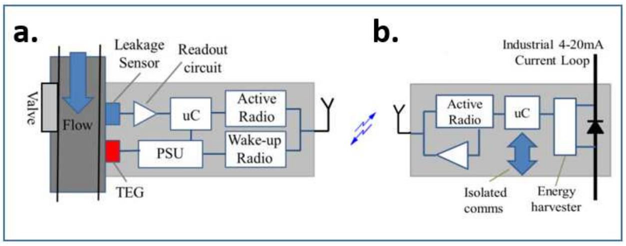

Figure 4. Block diagram illustration of the valve leakage detection system showing (a.) sensor node connected to the valve and (b.) gateway generating wake up signals.

The acoustic emission sensor and readout electronics were tested against a commercial piezoelectric device and shown to perform well. The wake-up radio receiver was tested in terms of successful wake-ups, indicating the whole wake up packed is correctly received. The packet error rate (PER) was tested in an indoor corridor and outside and found reliable to a range of 16 m indoors and 21 m outdoors. The sensor's thermal energy harvester was shown to harvest 44 uW, 450 uW and 5 mW at respective temperature differences of 6, 10 and 46 K showing enough energy at 6 K for a measurement every 10 hours. The gateway current loop harvester provided 250 uW and 1.26

mW at loop currents of 4 and 20 mA respectively, with 250 uW providing enough energy for a measurement every 5 minutes allowing the required 256 nodes to be measured every 12 hours.

2.3 Inductively coupled wireless power

A third system [5][5] was developed for powering a soft caterpillar type robot utilizing inductively coupled wireless power transfer at 8.5 MHz. The system utilized shape memory actuators (SMAs), which are essentially a spring that contracts when a current is passed through it. The actuators are coupled to wireless power receiver coils that are fabricated on a polyimide flexible substrates. Two coil-SMA pairs are used, a required minimum to provide forward movement. The SMA actuators are independently controlled by tuning their resonant frequency to 8.25 and 8.75 MHz and controlling the frequency at which power is transmitted. The power is transferred to the SMA actuators from a single transmitter coil made from copper litz wire between two PET plates. The transmission coil was driven by a 75 W E&I A-075 linear amplifier controlled by signal generator. The caterpillar movement was controlled by sweeping the transmitted signal enabling alternate contraction of the two SMAs. A photo of the robotic caterpillar, with receiver coils assembled is shown at the top of Figure 4, while the bottom shows a diagram of the wireless power transmission and reception.

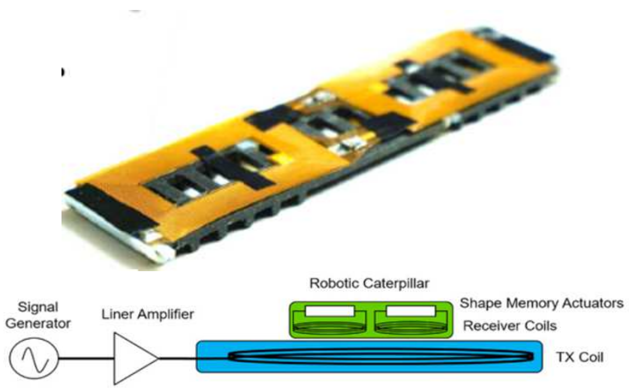

Figure 4. Inductively powered wireless soft robotic caterpillar (top) and the power transmission diagram (bot)

The wireless power transmission system was optimized and a 17 turn, 200 um track/gap coil was found as optimal. Coupling coefficients of 0.15 and 0.09 we found for distances of 4 and 24 mm from the transmitter coil. Power transfer efficiencies of 34 and 37 % were measured for the SMA actuator with receiver coils resonant at 8.31 and 8.71 MHz, with fixed frequency power transmission. The transmitter signal generator was set to sweep from 7.5 to 10.5 MHz at 100 kHz steps, with 100 ms dwell time giving a total sweep time of 2 seconds with a 1-second pause between sweeps giving the SMAs time to cool and fully relax. An actual force generated in the SMA actuators was measured as 41 g at 8.45 MHz and 51 g at 8.85 MHz for the SMA-coil pairs resonant at 8.31 and 8.71 MHz respectively. The movement of the caterpillar was tested under the same sweep parameters, with the same SMA-coil pairs resulting in a motion of 7.5 cm /minute.

2.4 Passive radio backscattering

The final system [6] developed in this work represents a wireless sensing platform that enables fully passive sensors. The 'Zero Power Sensor' readout is based on radio backscattering at UHF RFID frequencies and exploits third order intermodulation for down converting incoming signals to stimulate resonant sensor nodes. The sensor node includes an antenna, matching circuit, non-linear element, high-Q quartz oscillator and a capacitive sensor element. The antenna receives the incident signal, while a non-linear diode mixes the frequencies to couple their difference to the quartz. The capacitance of the sensor element pulls the resonance frequency of the quartz from its precise nominal value. At the reader, two frequencies are transmitted where their difference is set around the expected resonance frequency of the quartz. The difference is swept, and the reader monitors the backscattered signal. Where a maximum is found, the resonance of the sensor node is identified and the sensed parameter is calculated by extracting the pulling capacitance knowing the properties of the quartz. While the concept can work at any frequency, UHF RFID (885 and 867 MHz) were selected for the availability of radio frontend components and antenna. The technique presents a platform on which a wide range of sensor elements including temperature, pressure, acceleration, inclination etc. The contribution of this work relates to the development of the reader device, shown in Figure 5. Two reader optimizations are presented. One to maximize the sensor resolution with an advanced frequency sweeping technique, and another to maximize the readout range by minimizing the self-intermodulation of the reader.

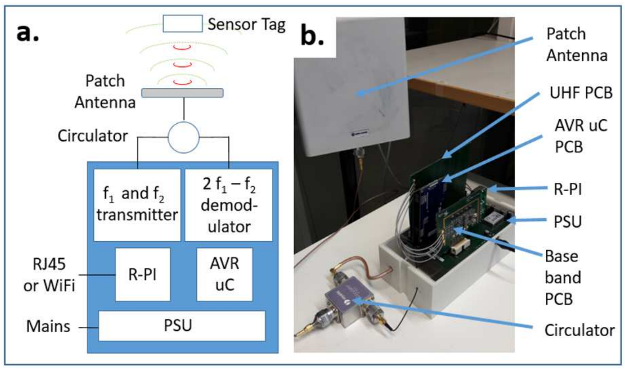

Figure 5. The developed 'Zero Power Sensor' reader device. (a.) block diagram and (b.) photograph

The readers self-intermodulation was characterized as the key limiting factor in the readout range, and numerous measured were taken to minimize this parasitic effect. An improvement (i.e. decrease) of the self-intermodulation of 24 dB was achieved, which enabled a maximum of 15 m readout distance between the sensor and the reader antenna while using the double said band frequency sweeping technique. The double side band frequency sweeping technique provides only a 4.8 Hz frequency resolution, translating to 2.2 % resolution on a 1 pF sensor capacitance. An alternative, single side band frequency sweeping technique was developed that allowed an 8-fold increase in the resolution at the cost of reduced power received and therefore reduced range. The result was a frequency resolution of 0.6 Hz corresponding to 0.3 % on a sensor element of 1 pF, at a cost of a maximum readout range of 10 m.

3 Discussion

The problem of power autonomy and wireless communication in sensor systems was identified as key to the enhancement of the adoption of IoT sensor systems. This work presents four very different system level solutions to address these two problems. The systems here presented cover the most prominent bands terms of radio communications (433 MHz, 868 MHz, and 2.45 GHz). Similarly, the work investigates the most promising methods of powering (battery, energy harvesting, inductively coupled and passive backscattering). This work highlights that there is no universal solution for achieving power autonomous wireless sensors. Rather, a holistic and system level approach needs to be taken where the application requirements and operational environment are considered. In the case of short lifetime devices, it is clear that battery power provides the most sensible solution. Considering cases where measurements need to be taken over a very long period, at long intervals, energy harvesting provides the most interesting option. In the case of short distances, and relatively high powers inductive coupling provides the best solution. In some specific cases, where a sensor element can manifest in a small changing capacitance a backscattering approach utilizing third order intermodulation offers an attractive solution.

6 Acknowledgements

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