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IoT Devices: The Quest for Energy Security

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***Abstract*—Analysts predict that by 2020, more than 50 billion devices to be deployed and interconnected to serve Internet of Things (IoT) applications. However, battery powered devices are vulnerable to periodic battery replacement as their operating time gets limited, and this indicates a high operational and maintenance cost which will affect the economic viability to deploy devices. As a consequence, the energy procurement and energy usage are key factors for sustainability. This paper tackles the energy issue for the IoT devices, and it presents an overview of energy sources and energy harvesting challenges. The paper also proposes recommendations to operate the networked IoT devices in a self-sufficient manner and to acquire the "Place-and-Forget" functionality.**

I. Introduction

The Internet of Things (IoT) is an organization of smart electronic devices that wirelessly communicate in a network without the need for human interaction. Each device, which is uniquely identifiable, circulates information to the internet. These information can be collected from the surrounding environment or provided by the internal structure of the smart object.

RFID products cover applications such as logistics and supply chain management, tracking and tracing, access control, security, library, laundry, animal ID, car immobilizers, toll collection, etc. In [1] we presented a semi-passive smart RFID sensing transponder system with all the requirements for an IoT application. It was composed of a radio transceiver, a sensing unit, a controlling processor, an energy harvesting and storing unit, and a smart energy management unit. Our IoT device represented a radical progress in RFID applications.

The number of IoT devices is expected to be more than 50 billion by 2020 [2]. These smart devices will reform our everyday experiences by affecting many aspects of the quality of life. The IoT will modernize several application domains such as transportation, city management, public security, healthcare, waste management, energy conservation, and many more.

However, in IoT devices, power consumption is a major weakness due to their dependency on the battery as a main source of energy which leads to a limits operating time and increases maintenance cost. The battery-powered nature of IoT devices also harms the environment by causing chemical pollution.Therefore, the deployment of the predicted huge number of devices is a daunting challenge.

In IoT devices, the radio transceiver is typically the most power hungry block with an average power consumption of tens of milliwatts when active. As a consequence, the battery will last for few days if a continuous operation is assumed. Obviously, to prolong battery lifetime, an efficient use of radio transceivers is needed in which they are powered off while not in use. The devices operate then in a duty-cycled mode, wherein the system is active during a short period separated by long idle intervals. In idle intervals, the system enters the low-power or sleep mode.

However, in IoT electronics, batteries still have a finite lifetime and are poor solutions for long-term storage of energy, and depletion often occurs within few months. Therefore, the energy usage of the different components in an IoT device is a key factor for the sustainability of the whole system.

This paper tackles the energy issue for the IoT devices and recommends approaches to operate IoT devices in a self-sufficient manner and to acquire the "Place-and-Forget" functionality.

II. Energy Harvesting and Challenges

Energy harvesting goal is to convert energy from ambient environment into an electrical energy. Various available renewable ambient energy sources exist in nature [3], [4], [5]. The widely utilized ambient energy sources are summarized in TABLE I.

TABLE I: Available Energy Sources

Energy Sources	Power Density	Available Time
Solar Energy	100 mW/cm^2	Day Time (4 ~8 Hrs)
Ambient RF Energy	0.0002~1 µW/cm^2	Continuous
Piezoelectric Energy: Vibration	200 µW/cm^3	Activity dependent
Piezoelectric Energy: Push Button	50 uJ/N	Activity dependent
Thermal Energy	60 uW/cm^2	Continuous

The electromagnetic radiation comprises solar energy and Radio Frequency (RF) waves. While the source in solar energy harvesting is the natural radiation of the sun, in RF harvesting, the source is an intentional electromagnetic radiation by RF transmitter.

Solar energy harvesting using photovoltaic cells has a high power density (TABLE I). It is well-suited for outdoor

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applications such as environment monitoring. As the produced energy is depending on illumination level, it can be limited due to weather conditions such as cloud covers.

IoT devices placed in areas deprived of solar power or used in application for which it is impractical to change the batteries such as hazardous industrial monitoring, RF energy harvesting might be an alternative since RF energy is able to travel within different materials. RF energy conversion is well known technique used to power passive RFID transponders from a dedicated RF transceiver (RFID interrogator). Although ambient RF energy transmitted for WiFi, TV, or military broadcasting could be used as another source of energy [6] [7], the actual energy levels are very low that almost no electronic devices can be powered. A rectenna (antenna and a rectifier) is used to convert the received RF power to a usable DC supply. To maximize the power received by the antenna of the IoT device, impedance matching between the antenna and the harvesting circuit is crucial. Moreover, in practice, the conversion presents a certain amount of power loss in the matching circuit and in the RF-to-DC converter.

Vibration energy harvesting is another alternative to power IoT devices attached to vibrating objects such as motors using the piezoelectric effect [8]. IoT wearable devices can also convert the human motion into electrical energy [9]. Using a push button in designing batteryless Radio and WiFi Indoor positioning for hospital nursing has been reported in our prior work [10]. The generated power usually consists of high voltage with a magnitude that varies between 7V and 15V, and low current is resulted in low conversion efficiency values while necessitating the use of voltage regulation circuitry to protect from voltage overshoots [3], [9].

To convert temperature difference into energy, small thermoelectric generators (TEGs) can be used for wearable applications such as healthcare systems. Using thermoelectric generators for body-wearable applications limits the output voltage to ~50 mV for temperature differences of 1–2 °C usually found between the body and ambience. Obviously, it is not possible to use this voltage to directly power CMOS circuits because it is still lower than the threshold voltages of the most standard CMOS technologies. Therefore, a low-startup voltage IC is required to convert the thermoelectric harvested energy to usable output voltages [11]. In the design of the harvesting ambient heat energy system using TEGs with input voltage which is lower than 50mV, the major challenge involves the interactions between the thermoelectric power source, the power stage, and signal-conditioning circuits of the load including DC–DC conversion, the maximum power point tracking (MPPT) controller, and power management control.

III. DIRECTION APPROACHES FOR SUSTAINABILITY

Micro energy harvesting, i.e. the conversion of ambient energy into an electrical supply required for IoT electronics, is a promising perspective as it would make the IoT devices truly energy-autonomous without the need of power grids nor batteries. However, a simple replacement of the battery or the supply cable by a local “micro power plant” will not secure energy for IoT devices. Some power could be made available through energy harvesting but in very small amounts. Therefore, micro energy harvesting relies on a thorough design of the whole embedded system. Therefore, the energy consumption of the system itself has to be minimized to a high extent by appropriate design and system control measures. Moreover, micro energy converters have to be provided with a size and a function which is compatible to the respective application site. Finally, the varying availability of ambient energy will require an efficient smart energy management. Fig. 1 summarizes directions for self-sustaining IoT device. Theses directions are discussed in the following subsections.

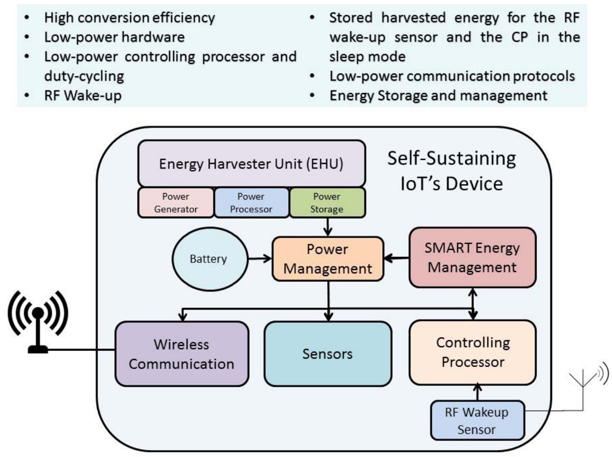

Fig. 1. Directions for self-sustaining IoT device

A. *High Conversion Efficiency*

Harvesting energy from the ambient RF sources needs an optimization of the power conversion efficiency through increasing the sensitivity and reducing the losses in the RF to DC converter. In addition, for the quest of energy from a multitude of RF transmitters transmitting at different frequencies, refined power converter with a dedicated high bandwidth antenna is required. The converters analyze the received power and optimize the matching to maximize the received power and reduce losses by using adaptive matching scheme. A technique facilitating RF energy harvesting at multiple frequencies with a single antenna is described in [12].

Maximum power point (MPP) algorithm is used to maximize the harvested power and hence increase the efficiency. Basically, it consists of selecting a load impedance of the harvesting circuit to present an impedance that is equal to the impedance of the transducer. Different techniques are proposed, such as in [13] and [14].

Harvesting a small amount of energy needs the use of a boost converter. The maximum power and the oscillator clock frequency relationship has to be investigated to maximize the power by optimizing the clock frequency. Also, the design of a low-power oscillator allowing the clock frequency selection has to be considered.

Moreover, the design of an oscillator with a controllable output pulse-width needs to be explored. The output pulse width of the oscillator to maximize the power can be selected by monitoring the available voltage on the load which is an indication of power availability using a voltage supervisor and voltage divider.

B. *Low-Power Hardware*

Energy harvesting unit allows the device to be self-powered and creates its own energy. However, to achieve a self-sustainability, selection of efficient hardware with the lowest power consumption is required. In Integrated Circuits (ICs) design, the designer should consider low power consumption as a top priority and should consider low-power analog and digital design approaches. Although reducing the power consumption of CMOS digital circuits can be achieved by reducing the supply voltage [15], this will not apply to analog circuits. Weak inversion affords several advantages that can be exploited in designing low-power analog circuits [16].

C. *Low-Power Controlling Processor and Duty-Cycling*

The controlling processor (CP) is considered to be the heart of every embedded system including the IoT devices. Therefore, it is imperative to select a CP with low-power consumption in idle state and during the active mode as well. As mentioned earlier, the duty-cycling is used to save power and extend the battery lifetime. Also, in duty-cycling, transceiver is switching between listening-transmitting and sleeping states.

Most of the CPs feature multiple low power modes (sleep modes). For example, the microcontroller PIC from Microchip has a power down state of about 7µA since a timer is running to allow the microcontroller to awake from the sleep mode. It has been reported in [17] that the power consumption in deep sleep mode can be down to 78nA using a proposed Duty-Cycle Controlling (DCC) technique (Fig. 2) where the microcontroller is awake from its sleep mode by an external event. This low current consumption can be achieved since the timer is disabled.

Another approach consists of dynamically adjusting the duty cycles to adapt to the availability of ambient environment energy sources.

D. *RF Wakeup*

An efficient approach to extend the battery life time of the IoT device, is by using RF wakeup sensor as shown in Fig. 1. It converts a small RF input signals into a DC signal to trigger the communications. We advocate the use of such RF wakeup sensor for proximity detection as reported in [17] and [18]. It has been shown that using a wakeup interrupt, an extremely low power was achieved thanks to the extension of the sleep mode time as shown in Fig. 2.

In another version, a wakeup command can be used. When the wakeup sensor receives such command, it generates an interrupt for the controlling processor which in turn wakes up the main transceiver. A simplest version of this approach consists of an antenna, a rectifier, and a data extractor.

The wakeup sensor is constantly active. Therefore, wakeup interrupt approach can be adopted only if the energy consumption of the wakeup sensor is insignificant compared to that of the main transceiver.

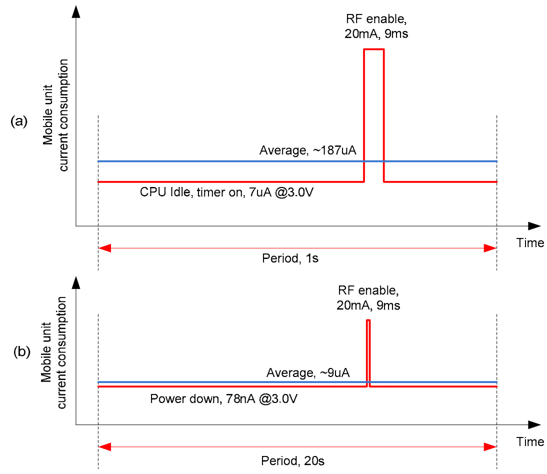

Fig. 2 (a) Basic functionality by periodically enables the radio communication, without the DCC technique (b) Using the DCC technique, extremely low power is achieved by extending the power-down state

E. *Stored Harvested Energy*

The harvested energy from ambient environment can be used as a main energy source to power the IoT device. However, ambient energy sources are sometimes fleeting and variable in nature. If the stored harvested energy is below the required level to power the IoT electronics, we propose to use it as a backup energy source to supply the RF wakeup sensor for example.

Furthermore, when adopting the duty cycling to save energy, the system spends an extensive time in the sleep mode. For example as shown in Fig. 2a, the transceiver is active during 9 ms within a period of 1 second. The system spends greater that 99% of its time in the sleep mode while the cumulative energy is still significant and has also to be reduced or powered by a viable source different from the battery. While asleep, the CP must maintain its state while consuming little power and shutting down or disconnecting all peripherals. To reserve the battery power during the sleep mode, the harvested energy can be used.

As a consequence, if the required energy of the wakeup sensor and the CP during sleep mode is provided by the harvested energy, this will preserve the battery and extend its lifetime.

F. *Low-Power Communication Protocols*

In the Internet of Things (IoT) concept, electronic devices communicate wirelessly in a network and connect to the Internet. Therefore, selecting power-efficient wireless technology is primordial.

In IoT applications using RFID readers with low data rate, RFID-based communication can be used. The advantage is that the transponder harvests energy from the nearby reader's RF transmissions.

The Bluetooth Low Energy (BLE), IEEE 802.15.4, can be an appropriate choice for some IoT applications. Selecting the BLE standard for the IoT devices will allow the communication with smart phones which are Bluetooth-equipped. This represents an advantage for applications such as smart positioning applications. For example, in the TI CC2640, the average current consumption is 6 mA in Rx mode and 9 mA in Tx mode.

ANT protocol is another ultra-low power and flexible network protocol for 2.4 GHz ISM band communication. Compared to BLE which is standard protocol, ANT is a proprietary (but open access). It is conceptually similar to BLE, but is oriented towards usage with sensors which is key advantage for the IoT sensing and monitoring applications such as sports and fitness. ANT was designed for low bit-rate and low power sensor networks, in a manner conceptually similar to BLE [19]. ANT can be configured to spend long periods in a low-power sleep mode. For example, the Nordic nRF24AP2-1CH average current consumption is 54 µA for Broadcast Tx at 2 Hz message rate, 42 µA for Broadcast Rx at 2 Hz message rate, and 5.9 mA for 20 kbps Burst mode.

WiFi wireless standard has a high power consumption compared to the above technologies. Therefore, the preferred wireless communication standard for the IoT applications are still the above presented technologies. However, an additional gateway is required to connect to internet.

G. Energy Storage and Management

Due to the varying availability of ambient energy, a serious question arises which is how a widely distributed network of IoT devices should be supplied with energy. Obviously, the device requires efficient intermediate energy storage.

Solid-state rechargeable battery can be used for micro energy harvesting. It allows thinner product packaging and enjoys the advantages of rapid recharge and charge acceptance at currents as low as 1µA.

A battery charger for micro energy harvesting has been used in [1]. Depending on the available ambient energy, the battery charger allows the CP to select the current charge level and the battery end-of-charge by a trimming method. The trimming circuit was chosen by means of a binary weighted switch network with 11 bits resolution.

In addition, providing a backup power and a smart energy management will ensure self-sustainability. Associated with energy harvesting and storing, designing an efficient smart energy management to transfer the electrical energy among all subsystems in an optimal way and to execute actions depending of the available energy is fundamental.

IV. CONCLUSION

This paper presented the energy security challenge in the IoT devices. The efficient energy conversion and usage are the key factors for the sustainability of the whole system of an IoT device. We recommended approaches allowing the design of autonomous IoT systems. Earlier design consideration of the above matters will ease the deployment and enable a fast endorsement of devices to serve for IoT applications.

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