IOT Power Management For Reducing The Dependency On Batteries

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Abstract

Various reports and studies projects that, by 2020, about to 50 billion devices will be connect to internet of things and the global market value will reach $7.1 trillion, which will give the engineers the opportunity to design solutions to several problems such as healthcare, industry, transportation, agriculture, smart homes, etc.

The Internet of Things (IoT) is the network of physical devices, vehicles, home appliances and other items embedded with electronics, software, sensors, actuators, and connectivity which enables these objects to connect and exchange data. Each thing is uniquely identifiable through its embedded computing system but is able to interoperate within the existing Internet infrastructure.

Sensors are the core of the IoT as its collect the data from the environment and then exchange it with a web cloud server through the network (internet) and then send a response to the things (devices) to take actions.

Most of the devices will be connect wirelessly due to the inconvenience, expense or infeasibility of wiring it, and many of them have size constrains with limited battery space and no power cord, so powering these devices (to achieve several months of functioning) become serious challenge. This paper highlights focusing in this challenge and addressing some solutions by using environmental energy to make IoT self-powered such as solar energy, these will decrease and, in some cases, eliminating their dependence on batteries.

Keywords: Internet of Things, Wireless Power Management, Energy Harvesting, Low Power, Solar Energy.

1. INTRODUCTION

By 2020, there will be around 50 billion smart objects connected to the Internet of Things (more than six times the world's projected population at the time), making the IoT one of the fastest growing technology across all of computing [24]. These smart devices will change all aspects of our daily lives and fundamentally change the way we interact with our physical environment, thereby revolutionizing a number of application domains such as telemetry, healthcare, home automation, energy conservation, security, wearable computing, asset tracking, maintenance of public infrastructure, etc., as shown in Figure 1.

One of the biggest challenges to realizing this IoT vision is the problem of powering these tens of millions of IoT devices. Most of these devices will be battery-powered for reasons of cost, convenience, or the need for untethered operation. Despite tight constraints on size and, hence, battery capacity, many IoT devices will be required to have long operational lifetimes (from a few months to possibly several years) without the need for battery replacement, because frequent battery replacement at scale is not only expensive, but often not even feasible in addition to the Alkali effect of the battery on the environment. For example, the Environment Protection Agency reports that more than 3 billion batteries are discarded in the USA every year and that, placed end to end, discarded AA batteries would circle the earth six times. The rapid proliferation of IoT devices will only exacerbate this problem, making the need to address it an urgent priority.

This paper highlights some promising directions for addressing this challenge and makes a case for focusing on two main building blocks: (a) the development of intelligent system-level power management techniques that allow an IoT device to adjust its power consumption in a context-aware manner, and (b) the use of environmental energy harvesting to make IoT devices self-powered, thus decreasing in some cases, even eliminating their dependence on batteries. These building blocks are illustrated using examples of IoT devices, including the QUBE wireless platform, which exploits the characteristics of emerging non-volatile memory technologies to seamlessly and efficiently enable long-running computations in systems that have an intermittent and unreliable power supply.

It is important to recognize that IoT devices have very diverse power requirements and longevity requirements, which have a profound influence on how they are designed. One group of devices, henceforth referred to as Type I devices, are wearable devices.

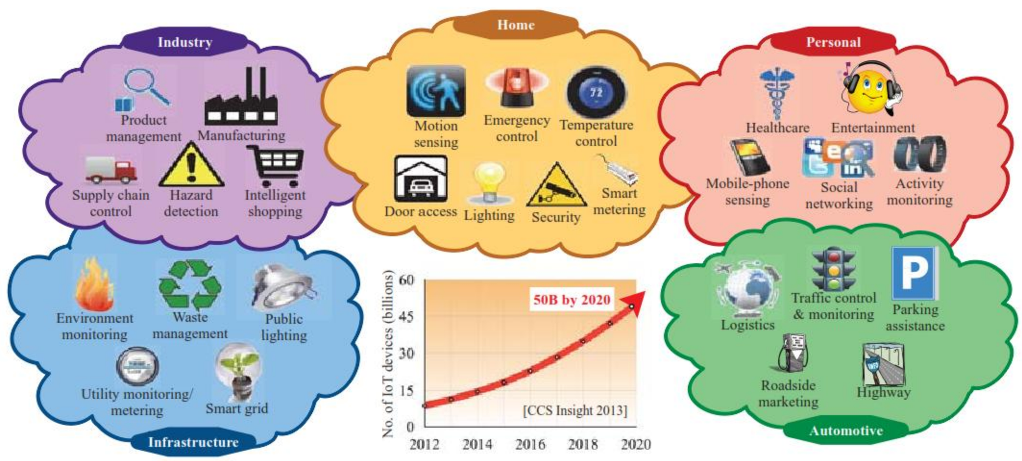


FIGURE 1: A summary of the envisioned applications and growth application for the Internet of Things.

(e.g., smart watches, fitness monitors, connected glasses), which have a longevity requirement of several days because a user is likely to own only a few such devices and can recharge them regularly, particularly with the advent of wireless charging technologies. A second group of devices, henceforth referred to as Type II devices, are set-and-forget devices (e.g., home security and automation sensors, water leak sensors) that a user wants to deploy and then not tinker with for several (2 to 5) years. A user is likely to own dozens of such devices, therefore frequent battery replacement would be very inconvenient and hamper the user experience. A third group of devices, henceforth referred to as Type III devices, are semi-permanent devices (e.g., wireless sensors that monitor public infrastructure such as bridges, highways, and parking structures), where the device is installed and needs to operate for more than a decade. The scale of these devices makes frequent battery replacement simply infeasible. A fourth group of devices, henceforth referred to as Type IV devices, are battery less and passively powered (e.g., RFID tags, smartcards), drawing their power from an external source such as a tag reader. Finally, a fifth group of devices, henceforth referred to as Type V devices, are powered appliances (e.g., smart refrigerators, microwaves, smart TVs) that will always be plugged into a power outlet, eliminating the need for a battery.

2. SELF-POWERED SYSTEMS USING ENERGY HARVESTING

Over the past, energy harvesting has emerged as an attractive and increasingly feasible option to address the power supply challenge in a variety low power systems. The use of energy harvesting significantly prolongs over all system lifetime and has the potential to result in self powered, perpetual system operation, particularly for Type II and Type III IoT devices. Figure 2 shows the power supply subsystem of an energy harvesting device. In this section, we discuss recent advances in the design of each constituent component, namely, the energy harvester (or transducer), the power conditioning unit, and the energy storage element.

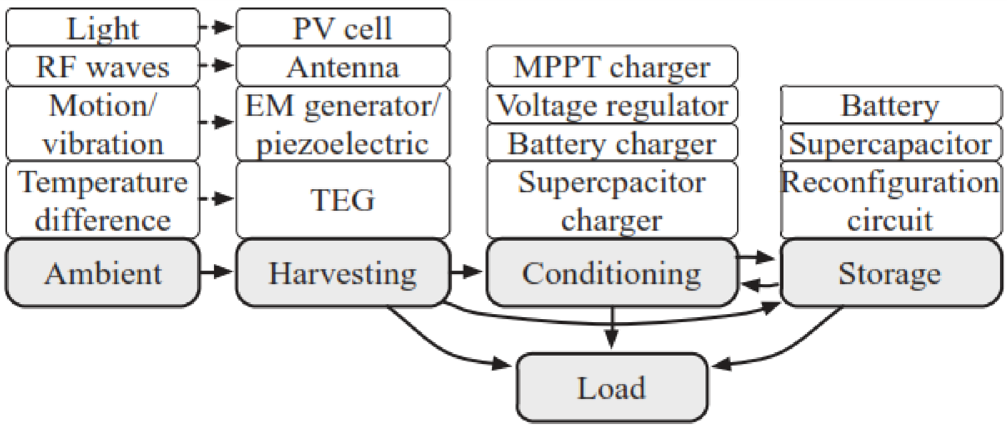


FIGURE 2: The power supply subsystem of an energy harvesting IoT device.

2.1 Harvesting Ambient Energy

An energy harvester, in our context, is a device that converts power from ambient sources, such as electromagnetic radiation (including light and RF waves), thermal gradients, mechanical motion, etc., into electrical power. Of these modalities, solar energy harvesting through photovoltaic conversion is the most mature and well-studied, in part because it has a higher power density (output power per unit area or volume) than other ambient power sources. Solar harvesting is well suited for IoT devices that have substantial exposure to light, such as the Flood Beacon [5], which is an outdoor environment monitor. Flexible photovoltaic cells [34] could possibly also be integrated into clothing and used to recharge wearable IoT devices.

Kinetic energy harvesting converts the mechanical energy of motion or vibration into electrical energy through electromagnetic induction [28] or the piezoelectric effect [39]. It is particularly attractive for wearable IoT devices that are powered by human motion and for devices attached to vibrating objects such as engines or motors. For example, the Pavegen [6] is an energy harvesting floor tile that can be installed on a sidewalk to gather energy from footsteps, which could be used for advertising, way finding solutions, etc. Intelligently scavenging energy from routine human activities could play a prominent role in improving the battery lifetime of IoT devices. RF energy harvesting uses the power received from incident RF waves for powering a device. This technique is commonly used in passive RFID systems. The source of the power can either be dedicated RF waves generated for wireless charging (e.g., the Qi wireless charging standard) [31], or ambient RF signals that are transmitted for wireless data transfer (e.g., WiFi or TV signals) [14]. Energy harvesting from ambient WiFi signals has been demonstrated [30], although the amount of harvested power that can be harvested is often minuscule.

Thermoelectric generators (TEGs) translate a thermal gradient between two surfaces into an electrical potential [51]. TEGs are suitable for powering IoT devices that are in contact with hot surfaces. Wearable IoT devices, such as smartwatches, can also use TEGs as a power source by exploiting the difference between the body’s surface temperature and the ambient temperature.

In summary, the choice of harvesting modality for a particular IoT device is dependent on its operating environment, form factor constraints, as well as its power budget.

2.2 Power Conditioning

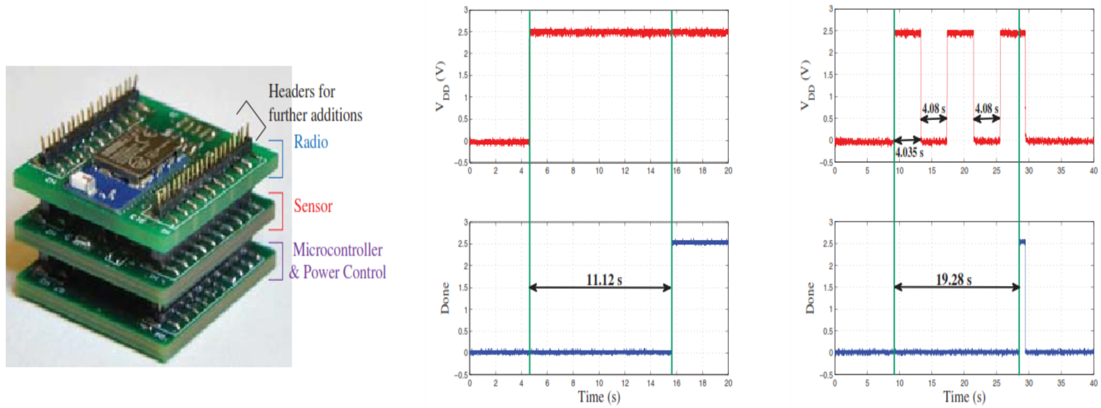
Electronic circuit components require a stable DC power supply to operate reliably. However, the output voltage of an energy harvester often varies significantly depending on the strength of the ambient power source (e.g., the light intensity or the amplitude of vibration). Therefore, the output of the harvester needs to be converted into an appropriate (and stable) voltage level through the use of a power conditioning circuit before it can be fed to an IoT device or transferred to an energy storage element. However, power conditioning for energy harvesting is not straightforward. For example, due to the stringent form factor constraint in most IoT devices, the output power of the harvester is very small, often only a few mW. The conditioning circuit should deliver as much of this power as possible to the IoT device with minimal loss, which requires extremely careful design. Further, some harvesters generate only tens of mV at their output, such as TEGs in body worn devices. In such cases, a boost regulator that accepts an ultra low input voltage is required [19].

In addition to voltage regulation, power conditioning also plays an important role in maximizing harvesting efficiency. Most energy harvesters have an optimal operating point (called the maximum power point or MPP) at which their power output is maximized. Since the MPP changes dynamically based on ambient conditions, the power conditioning unit should continuously maintain operation at the MPP, a process referred to as MPP tracking. MPP tracking is a feature available in many commercial power conditioning ICs [55, 38]. Design considerations for MPP tracking are described in [42, 36]. In [57], MPP tracking is done by modulating the average power consumption of the device, without a dedicated power conditioning unit.

2.3 Energy Storage

Since the amount of power available from an energy harvester is dynamic and unpredictable, an energy storage element is needed in IoT devices for uninterrupted operation when ambient power is not available. Often, the energy storage element is the bulkiest part of an embedded system. Therefore, energy storage elements with a high energy density are highly desirable for IoT devices to maximize lifetime and minimize device size.

Batteries are the most widely used energy storage element in untethered devices. A solid state thin film battery that uses solid electrolytes is a promising battery technology for IoT devices [47]. It has low power density but high energy density, making it suitable for long lasting low power IoT devices. Such a thin, bendable battery can also be easily integrated into small IoT devices [27]. A solid state battery can be manufactured in conventional IC packages or even be integrated with an IC in a single package, such as Cymbet's EnerChip [22]. This enables a significant reduction in size and system integration cost. Compared to batteries, super capacitors have a much higher cycle efficiency and extremely long cycle life. However, they require the power conditioning unit to be able to cope with their large voltage variation, in particular, the very low voltage during cold boot. Dynamic reconfiguration of multiple supercapacitors can mitigate the voltage variation issue and improve cold boot speed [20].



(a) (b) (c)

FIGURE 3: (a) Qube: A modular embedded platform (1” by 1”) that facilitates easy prototyping and addition/removal of features through modules, (b) Time taken (11.12s) to complete RSA encryption of 128 characters on Qube in the presence of continuous power supply. The Done signal is raised at the end of the computation, and (c) QuickRecall implemented on Qube. RSA encryption is successfully performed across multiple power cycles with negligible overhead (19.28s − 2 × 4.08s = 11.12s).

Recent advances in nanotechnology have also enabled flexible supercapacitors on a thin film substrate, which are well suited for wearable applications [44].

3. LOW POWER HARDWARE FOR THE IOT DEVICES

The most effective way to improve the battery life of an IoT device is to decrease the power consumed by its constituent hardware components. Even in IoT devices such as Driblet [3] and SPAN [10] that are powered through energy harvesting (discussed in Section 2), it is imperative to use low power hardware to achieve near perpetual operation. It is useful to note that many IoT devices are architecturally similar to wireless sensor node platforms [25, 45] and low power design techniques used for these platforms are equally applicable to the design of IoT devices [21, 49]. The following subsections discuss recent advances in low power hardware for the computation and communication subsystems of an IoT device, respectively.

3.1 Computation Subsystem

Microcontrollers (MCUs) are at the heart of every embedded system that interfaces to (and interacts with) the real world, including IoT devices. As described in Section 1, many of these systems need to operate unattended for several years without the need for battery replacement [43,46]. Achieving such long operational lifetime requires extreme levels of energy efficiency. Fortunately, many sensing applications operate in a heavily duty cycled mode, wherein the system is active only for very short bursts of time (of ten, only milliseconds) separated by long idle intervals (of ten, many tens of seconds) during which the system can be placed in a low power, sleep mode. Since the system spends greater than 90% of its time in the sleep mode, the cumulative energy spent in this mode is often the bottleneck for battery lifetime. Therefore, it is important to select an MCU that has a very low power consumption in idle state in addition to being power efficient during active computation. To minimize idle mode power consumption, most MCUs feature multiple low power (or sleep) modes. For example, the STM32L1 series of MCUs (based on the ARM Cortex M3 core) supports up to 7 different sleep modes. The sleep modes found in MCUs are of two types. The first is a shallow sleep mode, in which the MCU core is stopped, peripherals are disabled, and clock sources are turned off. However, the MCU stays powered up, which means that state information (consisting of the MCU registers and the contents of on chip SRAM) is preserved during sleep. Although waking up from shallow sleep is very fast, it is (as expected) not the lowest power sleep mode possible. Hypnos [33] addresses this problem based on the observation that the minimum voltage required for SRAM data retention is often much lower (by as much as 10x) than the minimum operating voltage of the MCU. By lowering the supply voltage when the MCU is in sleep mode to just above the SRAM data retention voltage, Hypnos achieves dramatic reductions in sleep mode power. The second type of sleep mode is deep sleep, in which the entire MCU, including the on-chip SRAM, is powered down. While this results in the lowest power consumption possible during sleep, it does not preserve SRAM state. Therefore, the contents of the SRAM need to be saved to non-volatile storage such as the on-chip Flash of the MCU before entering this mode. When the MCU wakes up next, the saved state is restored from the Flash to the SRAM and the MCU resumes execution. Unfortunately, due to the high erase/write time and power of Flash, the energy overhead of saving and restoring state is substantial. Recent work [32] to address this problem uses emerging non-volatile memory (NVM) technologies such as magnetoresistive RAM.

Processors and MCUs (Freq = 8 MHz)

Product	Architecture Family	Current Active (mA)	Current Sleep (µA)
MSP430F5438A	MSP430	1.84	0.1
STM32L051x6	ARM CM0+	1.55	0.29
STM32L100C6	ARM CM3	2.16	0.3
SAM4S	ARM CM4	4.5	1.8
PIC24FJ128GC010	PIC	1.5	0.075

Wireless Standards

Standard (Product)	Current Tx (mA)	Current Rx (mA)	Current Sleep (µA)
WiFi (TI CC3200)	229	59	4
IEEE 802.15.4 (Atmel AT86RF231)	14	12.3	0.02
Bluetooth Smart (Nordic nRF8001)	12.7	14.6	0.5

Sensors

Sensor	Product	Current Active (µA)	Current Sleep (µA)
Temperature	TMP102	85	0.5
Humidity	SHT21	300	0.15
Accelerometer	ADXL362	13	0.01
Light	ISL29033	65	0.01
Proximity	AD7150	100	1

TABLE 1: Power consumption of a few representative hardware components used in IoT devices (sourced from datasheets).

(MRAM) [37] or ferroelectric RAM (FRAM) [26]. These memories combine the flexibility and endurance of SRAM with the non volatility of Flash, all at a very low power consumption. Low power MCUs with these emerging NVMs integrated are already available [48, 61]. In these MCUs, software can save the processor state and the contents of SRAM to the NVM before the MCU enters sleep mode, avoiding the need for keeping the SRAM powered during sleep. Building on this idea, recent research has led to the emergence of a new class of processors called non volatile processors [35, 53]. In these processors, NVM memory elements are distributed throughout the MCU such that it can automatically save the contents of all the registers in these NVM elements before it is shutdown, resulting in a (nearly) zero power sleep mode with state retention and rapid wakeup.

Minimizing power consumption in active mode has been extensively investigated for the past few decades and numerous techniques such as dynamic voltage and frequency scaling (DVFS), voltage islands, etc., have been proposed and shown to be effective in reducing power consumption. Continued voltage scaling has led to the emergence of near threshold and subthreshold processors [17, 58] that aim to operate at an optimal energy point. For example, the Phoenix processor [29] is an event-driven subthreshold processor that has an sleep power consumption of only 30 pW. The use of such ultra low power MCUs, if applicable, will provide a significant boost to the battery life of IoT devices.

Table 1 shows the active mode and sleep mode power consumption of a few off-the-shelf hardware components (including MCUs, radios, and sensors) that are commonly used in IoT devices. As seen, most of these hardware components feature highly power-efficient sleep modes in which the power consumption is decreased by several orders of magnitude compared to the active mode.

3.2 Communication Subsystem

The IoT concept fundamentally depends on the fact that devices will communicate either directly with each other or with a cloud based service accessible through the Internet. Hence, reliable wireless communication is an integral component of any IoT device. Typically, wireless communication is more power hungry than other tasks such as sensing or computation. In addition, different types of IoT devices have different communication requirements depending on their deployment locations, longevity constraints, traffic patterns, etc. Therefore, choosing an appropriate wireless technology that is power effcient is a vital design choice.

Despite its relatively high power consumption, WiFi is the preferred wireless standard for many IoT applications due to its near ubiquitous nature WiFi hotspots are present in most homes, offices, and public spaces and the fact that it enables convenient and straightforward access to the Internet. Advances in wireless communication have also seen the development of numerous low power wireless standards such as Bluetooth Smart, IEEE 802.15.4, etc. The IEEE 802.15.4 standard targets low data rate applications (e.g., remote monitoring and control systems) and defines the physical and medium access control layers upon which the Zigbee and 6LoWPAN network stacks are built. The standard allows for multi-hop wireless topologies and several power efficient IEEE 802.15.4 compliant radios are commercially available. However, one disadvantage of using IEEE 802.15.4 for IoT applications, compared to WiFi, is the need for an additional gateway device to achieve Internet access (if required). Particularly for Type II IoT devices, it is difficult to converge on the use of a single wireless standard due to the varying nature of applications as well as the large number of product vendors involved. Hence, it is likely that future smart homes will use IoT hubs such as Revolve [9] or Ninja Spheramid [11] that support a variety of wireless standards such as WiFi, Bluetooth Smart, Zigbee, Z-Wave, Insteon, etc. In addition to existing wireless standards, innovative approaches such as using the existing power line wiring in the home as an antenna have also been proposed [12].

Bluetooth Smart is an enhanced version of the well known Bluetooth standard that was designed for low power communication [16]. Bluetooth based IoT devices, such as Estimote Beacon [23], Lively [41], tado Cooling [56], etc., can directly communicate with smart phones, which are already Bluetooth equipped. This is a key advantage that will likely cement Bluetooth Smart’s position as the wireless standard of choice for IoT devices that need to frequently communicate with mobile devices such as smart phones and tablets.

Other IoT applications such as manufacturing and asset tracking could use RFID based communication. Passive RFID technology allows devices such as battery less smart tags to operate using power harvested from a nearby reader’s RF transmissions. Recent work [40] proposed the idea of ambient backscatter, a novel technique that allows two battery less devices to communicate with each other by backscattering existing wireless signals from TV stations and cellular transmissions. Although the technique is mainly intended for low throughput applications, it is a significant step forward because it enables tiny IoT devices to exchange small amounts of information without the need for a battery or a nearby RFID reader.

4. CONCLUSION

This paper showed some guidance to address the problem of powering the devices that form the IoT. We believe that a comprehensive solution to this problem involves two main building blocks including intelligent system-level power management techniques and (perhaps, most promising) is to make IoT devices self powered by harvesting energy from their operating environment. Doing so raises the possibility of perpetual operation of these devices, thus decreasing their dependence on batteries and the need for frequent battery replacement.

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