Powering the Internet of Things[*]

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ABSTRACT

Various industry forecasts project that, by 2020, there will be around 50 billion devices connected to the Internet of Things (IoT), helping to engineer new solutions to societal-scale problems such as healthcare, energy conservation, transportation, *etc.* Most of these devices will be wireless due to the expense, inconvenience, or in some cases, the sheer infeasibility of wiring them. Further, many of them will have stringent size constraints. With no cord for power and limited space for a battery, powering these devices (to achieve several months to possibly years of unattended operation) becomes a daunting challenge. This paper highlights some promising directions for addressing this challenge, focusing on three main building blocks: (a) the design of ultra-low power hardware platforms that integrate computing, sensing, storage, and wireless connectivity in a tiny form factor, (b) the development of intelligent system-level power management techniques, and (c) use of environmental energy harvesting to make IoT devices self-powered, thus decreasing – in some cases, even eliminating – their dependence on batteries. We discuss these building blocks in detail and illustrate case-studies of systems that use them judiciously, including the QUBE wireless embedded platform, which exploits the characteristics of emerging non-volatile memory technologies to seamlessly and efficiently enable long-running computations in systems that experience frequent power loss (*i.e.,* intermittently powered systems).

Categories and Subject Descriptors

C.3 [**Computer Systems Organization**]: Special-purpose and application-based systems—*Real-time and embedded systems, Microprocessor/microcomputer applications*

Keywords

Internet of Things; Low Power; Power Management; Energy Harvesting; Perpetual Systems; Wearable Computing

1. INTRODUCTION

It is projected that, 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 technologies across all of computing [24]. These smart objects will pervade all aspects of our daily lives and fundamentally alter 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 billions 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 days 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. The battery-powered nature of IoT devices also has significant environmental implications. 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 three main building blocks: (a) the design of ultra-low power hardware platforms that integrate computing, sensing, storage, and wireless connectivity in a tiny form factor, (b) 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 (c) 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,
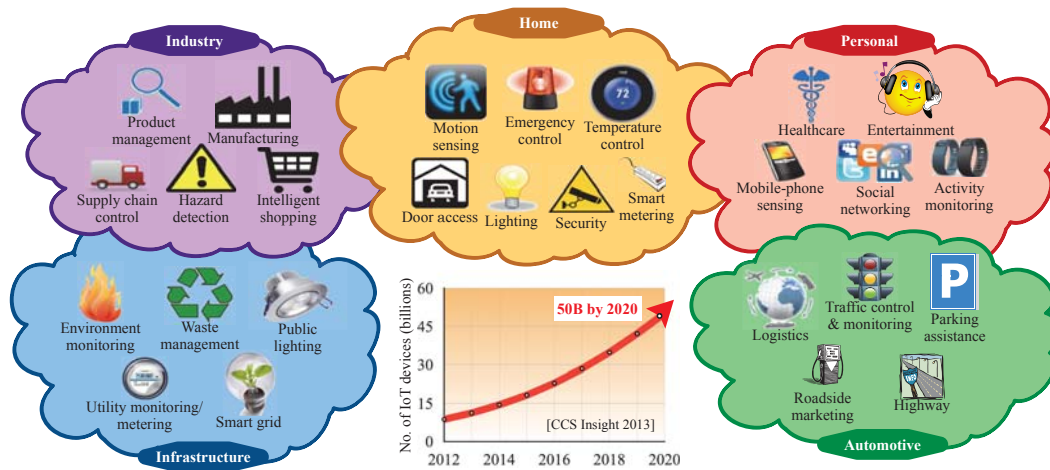
Figure 1: An overview of the envisioned applications and growth forecast for the Internet of Things.

are wearable devices (*e.g.,* smartwatches, 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 (5 to 10) 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 batteryless 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) that will always be plugged into a power outlet, eliminating the need for a battery.

2. LOW POWER HARDWARE FOR THE IOT

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 3), 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.

2.1 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 (often, only milliseconds) separated by long idle intervals (often, 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 (MRAM) [37]

Processors and MCUs (Freq = 8 MHz)				Wireless Standards				Sensors			
Product	Architecture Family	Current Active (mA)	Sleep (µA)	Standard (Product)	Tx (mA)	Current Rx (mA)	Sleep (µA)	Sensor	Product	Current Active (µA)	Sleep (µA)
MSP430F5438A	MSP430	1.84	0.1					Temperature	TMP102	85	0.5
STM32L051x6	ARM CM0+	1.55	0.29	WiFi (TI CC3200)	229	59	4	Humidity	SHT21	300	0.15
STM32L100C6	ARM CM3	2.16	0.3	IEEE 802.15.4 (Atmel AT86RF231)	14	12.3	0.02	Accelerometer	ADXL362	13	0.01
SAM4S	ARM CM4	4.5	1.8					Light	ISL29033	65	0.01
PIC24FJ128GC010	PIC	1.5	0.075	Bluetooth Smart (Nordic nRF8001)	12.7	14.6	0.5	Proximity	AD7150	100	1

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

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.

2.2 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-efficient 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 *Revolv* [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 powerline 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 smartphones, 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 smartphones and tablets.

Other IoT applications such as manufacturing and asset tracking could use RFID-based communication. Passive RFID technology allows devices such as batteryless 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 batteryless 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.

3. SELF-POWERED SYSTEMS USING ENERGY HARVESTING

Over the past decade, energy harvesting has emerged as an attractive and increasingly feasible option to address the
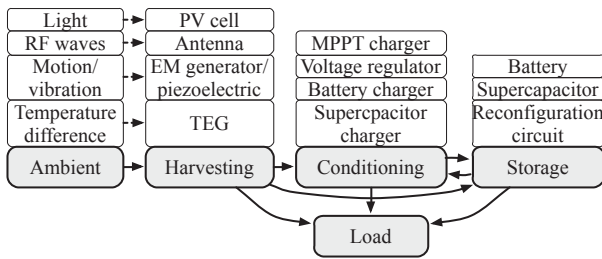
Figure 2: The power supply subsystem of an energy-harvesting IoT device.

power supply challenge in a variety of low power systems. The use of energy harvesting significantly prolongs overall 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.

3.1 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 (*e.g.*, hot water pipes). 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.

3.2 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.

3.3 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, supercapacitors 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].
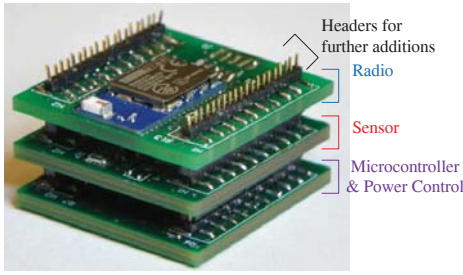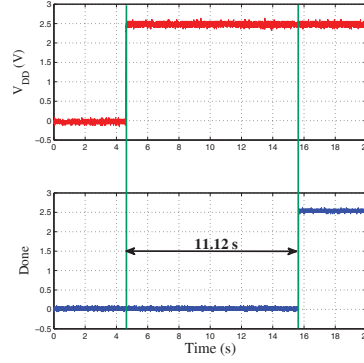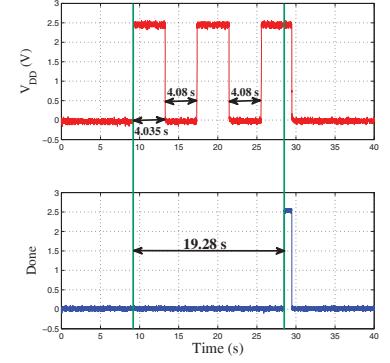
Figure 3: (a) QUBE: A modular embedded platform (1" by 1") that facilitates easy prototyping and addition/removal of features through modules, (b) Time taken (11.12s) to complete RSA encryption of 128 characters on QUBE in the presence of continuous power supply. The Done signal is raised at the end of the computation, and (c) QUICKRECALL implemented on QUBE. RSA encryption is successfully performed across multiple power cycles with negligible overhead ($19.28s - 2 \times 4.08s = 11.12s$).

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

4. HW-SW CO-DESIGN FOR LOW POWER

In addition to each hardware component being optimized for low power, system-level considerations about power consumption and management have to be carefully integrated into both the hardware and software development cycle for IoT devices.

Dynamic power management has been a well-studied technique for reducing power consumption [54]. Software controlled frequency selection of the processing unit, in conjunction with a well-designed power management unit helps in decreasing energy consumption. Modern day microcontrollers, such as TI's MSP430F5438A, have a programmable power management unit that provides software designers the option of selecting the frequency of operation according to the supply voltage used. The frequency of operation is crucial for batteryless IoT devices such as transiently powered computers (TPCs) [52] that eschew the use of voltage regulators for overhead reasons. As the power supply capacitor discharges during system operation, care must be taken to ensure that the operating frequency never exceeds the maximum frequency allowed for the current supply voltage level.

In addition to frequency scaling, another powerful technique for power management is power gating. Power gating at the system-level can be executed by careful planning of the hardware and software architecture. For IoT devices, power islands could be assigned based on functionality. For example, if the device needs to read a sensor, only the microcontroller and sensor need to be powered and other components can be power gated. As an example, QUBE (Figure 3(a)) is a wireless embedded platform that supports upto four different MCU-controlled power domains. The different functional modules make up different layers of the QUBE stack with power gating hardware residing on each module. Advances in low power circuit design have resulted in commercially available power-gating switches that consume only nanowatts of power, which is negligible compared to the active and idle mode power consumption of the modules that they power gate.

In addition to power gating, other hardware-software techniques can be used for reliable operation of IoT devices in power-constrained environments. Consider TPCs that were discussed earlier. To successfully perform computations across power cycles, TPCs resort to saving the processor and program states via checkpointing before an imminent power loss. Additional challenges are introduced by the high erase and write latency and energy overhead of Flash memory that is used in conventional microcontrollers. QUICKRECALL [32] is an *in-situ* checkpointing technique for TPCs that use an FRAM-enabled MCU. This approach is complementary to the idea of non-volatile processors discussed in Section 2. An *in-situ* checkpointing scheme decreases the checkpointing overhead by reducing the amount of data that needs to be explicitly checkpointed. However, as described in [32], a modified boot sequence is required while using such an approach. Experiments show that the latency overhead of checkpointing in QUICKRECALL is as low as 20 μs per power cycle which is over 100x lower than the corresponding overhead using Flash memory. Figures 3(b) and 3(c) show how a long-running application (in this case, RSA encryption) can be executed successfully across multiple power cycles with negligible overhead.

Communication in TPCs is a challenge as power may be lost in the midst of a transmission. As the nature of the power source is unpredictable, it is imperative to define new solutions to provide reliable communication. Bit-by-bit backscatter [60] aims to solve this problem by adaptively sizing the μframe length. Additionally, it features optimizations for decreasing the energy per backscatter operation and increasing the communication range. Another solution is to gauge the energy available and execute tasks adaptively as power requirements are satisfied [59].

For many IoT devices, maintaining a stable notion of time is critical. Conventionally, a real time clock (RTC) is used for this purpose. In addition to time keeping, the RTC is also used to perform synchronization and trigger periodic interrupts that wake the system from sleep mode. It is of utmost importance that the RTC module receives an uninterrupted power supply. Recent advances in circuit technology have seen the advent of off-the-shelf sub-threshold RTC modules that consume less than 100 nA [15]. Such low levels of cur-

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rent draw facilitate the use of energy harvesting to power the RTC perpetually.

Many IoT devices operate either in event-triggered mode (*e.g.,* Belkin *Wemo* [1], Quirky *Wink* [8]) or in periodic activation mode (*e.g., CubeSensors* [2], *Sensor Tags* [13]). These applications allow the user to set the trigger threshold, monitoring frequency, *etc*. The system designer's task involves considering such scenarios and architecting a power-optimized system architecture. For event-triggered systems, a hierarchical multiprocessor architecture [50] could be used, wherein a smaller MCU (which has lower power consumption than the main processor) monitors the sensor till an event is triggered, following which the main processor is woken up for further processing and communication. The smaller MCU is duty-cycled for energy efficiency according to the desired sampling frequency of the sensor and powers off when the main processor takes over. An alternative approach is to utilize MCUs whose analog components monitor the sensors without having to keep the entire MCU awake [18].

5. CONCLUSION

This paper presented some key directions to address the problem of powering the next generation of devices that form the IoT. We believe that a comprehensive solution to this problem involves three main building blocks including the design of ultra-low power embedded hardware platforms and intelligent system-level power management techniques. The third (perhaps, most promising) direction 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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