Designing the Batteryless IoT

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***Abstract*—Over the past decade, wireless sensor networks have established themselves as a robust technology with a wide range of applications from smart buildings and cities, infrastructure and environmental monitoring, precision agriculture, and the IoT. One of the driving forces that have made applications feasible has been the push to reduce the power consumption of electronic devices. However, the broader problem of how to supply them with the energy they require in an efficient, low-cost, long-term, self-sustainable manner has not yet been adequately solved. Traditionally, systems designers have used bulky, expensive energy storage devices such as batteries and supercapacitors to power a sensor node in a time scale ranging from a few days to a few years. We minimize the storage element in an application-specific manner such that computational progress can be guaranteed with even minimal input power. Experimental results have shown that these devices can operate very efficiently, and with energy-proportionality, even under highly volatile harvesting scenarios.**

I. Introduction

The advances in ultra-low power design over the past decades have significantly extended the lifetime of battery-powered devices. However, the billions of devices in the emerging Internet of Things (IoT) that will be deployed in hardly accessible areas with varying environmental conditions will demand for long-term deployments with virtually unlimited lifetimes. Battery-only designs are not an option, since their limited lifetimes would require expensive maintenance. Energy harvesting and ultra-low power system design are seen as key solutions of that problem and gained increasing research attention in recent years.

Different energy sources can have widely ranging voltage and power levels depending on the environmental conditions. By contrast, the load's optimal voltage only depends on the application and the peripherals it uses. Even when a transducer is large enough to directly power a load, there is high probability that because of adverse conditions, it will harvest only a fraction its maximum power. Because of these reasons, transient systems should have the following properties in order to be considered useful and efficient:

a) Source and load power points are decoupled. *b*) System buffers minimal energy. *c*) Load receives the energy required for task completion.

The first property ensures functionality and maximum power point tracking [2] for a wide range of power and voltage inputs. The second limits the energy that the system can buffer to the absolute minimum, since anything more leads to unnecessary losses. This minimum is defined to be the energy known to be required for the execution of one task. If an application consists of several tasks, the maximum energy level allowed corresponds to the task with the highest energy requirement. The third property implies that when the load is activated, its minimum energy requirement can be guaranteed. Depending on the type of task that is being executed, this can either mean enough energy to complete the entire task (atomic tasks), or enough energy to complete a state-retention mechanism in the case of a power-critical interrupt (non-atomic tasks).

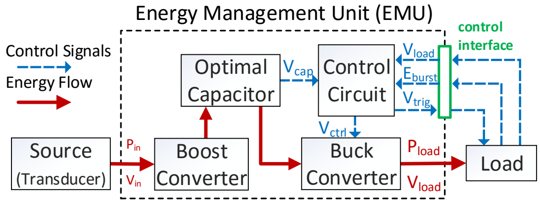

Figure 1. Transient system architecture with EMU. [3]

In this work, we explore the effect that a minimized storage element has on the design, specification, and performance of wireless sensor nodes. To begin, it is important to understand the lower limits of this storage element, which are application-specific, for the new class of transiently powered systems. A second important design consideration is the dimension of the energy harvesting source, which also needs to be minimized for cost and area.

II. Powering the IoT

State-of-the-art systems [1], [4], [5] use a small decoupling capacitance to enable a voltage supervisor to provide a power-critical interrupt and trigger an energy-guaranteed state-retention mechanism. While such mechanisms have a much lower overhead that a traditional checkpointing techniques such as [7], [8], little attention is paid to the full application, which almost invariably includes atomic tasks such as sensor readings and radio transmissions. As was mentioned earlier, the volatility of most harvesting sources requires small storage elements to provide the energy guarantees for either state-retention mechanisms or all other atomic tasks. These are the main challenges in baterыless system design.

Direct Coupling: In directly-coupled systems, the transducer is dimensioned such that it can directly power the load given sufficient energy. Transitions between high and low energy harvesting scenarios can be detected by monitoring the voltage level on a decoupling capacitor. This event can be used to trigger a state retention mechanism and guarantee program progress. Several works have studied these topologies, and proposed different methods to save and restore the state of a volatile processor to reliable, on-chip non-volatile memory [1], [4], [6].

One of the main drawbacks of directly-coupled systems is its inability to harvest and utilize energy when the power harvested is below the minimal power consumable by the load. In order to overcome this handicap, the system needs to buffer at least the amount of energy needed to bridge the power deficit in order to guarantee the completion of a single task. Attempting to use a buffer that stores more energy than the minimum inevitably leads to high losses due to power harvesting costs, self-discharge, and converter inefficiencies. It is important to carefully manage the optimized energy buffer with a burst-like behavior, namely, and event-triggered load.

Energy Bursts: When the input power is not high enough to sustain continuous operation, the only way to guarantee program progress is to buffer the energy required for the atomic execution of one program step. Ideally, this 'step' should be as small as possible, which we call an atomic task. As has been mentioned earlier, several tasks can have different optimal operating points. To operate efficiently, a feedback loop is required to dynamically adjust the load's operating point. This technique, called Dynamic Energy Burst Scaling (DEBS) [3], minimizes energy consumption at the task-level.

The advantage of DEBS is that the power point of the load and the source are completely decoupled. This allows harvesting the maximal possible power from the energy harvesting source, whereas each task is supplied with the lowest possible supply voltage to minimize the energy consumption for each task. Fig. 2 shows three plots of an EMU-based node. The top plot shows the input power harvested using MPPT with respect to time. The middle plot shows now much energy is stored in the buffer capactor. The bottom plot shows the power consumed by the load, which executes an atomic task at its optimal operating point. Note how the frequency of these bursts increase with the input power.

III. Conclusions and Future Work

In this work, we have argued that batteryless systems can offer all the necessary guarantees to build reliable sensor applications, even with high-power peripherals. As opposed to battery-based devices, these systems are energy-driven and thanks to their energy-proportionality, they can operate efficiently even in very variable and adverse harvesting conditions. We have shown how an energy management unit (EMU) can be used to decouple the harvesting source from the application and efficiently generate energy bursts. By accumulating only the minimum amount of energy in an optimally-sized buffer, the EMU is able to supply generic loads predictably and efficiently, even when harvesting only a small fraction of the load's active power consumption.

The concept of the EMU is a promising approach to build IoT nodes with minimized energy storage and harvesting requirements. However, this concept is fairly new and many questions remain unanswered. The task scheduling and the energy management in bateryless systems can be improved. In particular, more intelligence can be added to the EMU in order to increase the efficiency of the system, or to optimize the scheduling of tasks.

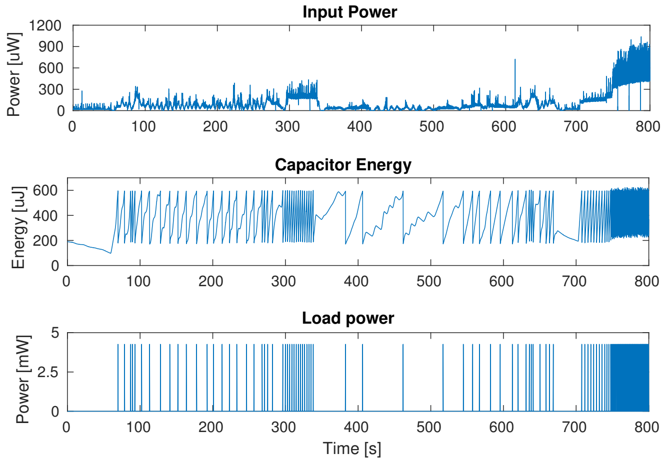

Figure 2. Burst-generation schemes integrate low input power to trigger short, high-power bursts.

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