Demo Abstract: M3: A mm-scale Wireless Energy Harvesting Sensor Platform

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ABSTRACT

In this demo, we explore the critical role that power plays in the development of a mm-scale system. We argue that any practical deployment of a mm-scale system must have a significant energy harvesting component. We demo the newest M3 system, a self-contained, 1 mm^3, energy-harvesting computing platform capable of short-range (order cm) wireless transmission. Finally, we present some of the M3's innovations that enable its current basic operation and discuss some of the open problems that remain before a smart dust network becomes operable.

Categories and Subject Descriptors

C.5.m [**COMPUTER SYSTEMS ORGANIZATION**]: Computer Systems Implementation—*Miscellaneous*

Keywords

Energy harvesting, Ultra-Low Power, Smart Dust

1. INTRODUCTION

The call for "Smart Dust" was delivered to the research community two decades ago. While the prevalence of intelligent, embedded devices is growing, the vision of pervasive, networked, intelligent millimeter-scale devices remains a fiction. In developing the M3 platform, we seek to push boundaries and test the hypothesis that technology has finally advanced to the point where Smart Dust can be realized.

We begin by presenting energy considerations at millimeter-scale. Our goal is to motivate discussion and recognition of the importance of energy harvesting technologies to the effective realization of sub-centimeter computing. We then present our M3 node, the state-of-the-art in general-purpose millimeter-scale computing. Finally, we close with a discussion of the pieces that remain missing to realize an energy-neutral M3 as well as some thoughts on the types of advances that will be required before energy harvesting nodes can successfully integrate with general-purpose sensor networks.

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2. POWER AT MM-SCALE

Nearly all of the design challenges in the creation of a "dust-scale" sensor network system can ultimately be traced back to one common root: power. Storing power is expensive in terms of volume, but to provide an effective wireless sensor node, several power-hungry activities must be supported: a variety of sensing modalities, computation for at least basic data processing, and communication to share sensed data.

2.1 The Case for Energy-Harvesting

In motivating their attempt to develop battery-less nodes, Yerva et al. make a critical observation: as the principal node dimension shrinks, the surface area available for energy harvesting shrinks quadratically while the available volume for energy storage shrinks cubically [3]. Given the limits of energy storage density, there is an inflection point at 1 cm^3 where it becomes necessary to rely on energy harvesting to build a node with a reasonable ($\geq$ 7 years) lifetime. At the mm-scale, this problem is exacerbated even further. Indeed, to achieve the target volume of 1 mm^3, the M3 system only has enough volume for 20 μWh of energy storage[1].

The optimistic power budget of a fully active M3 system is 10 μW; the target power budget for a sleeping M3 node (with active timers) is 5 nW. For a simple, lightly loaded collection network, state-of-the-art duty cycles in mesh networking collection protocols range between $0.23 - 0.43\%$ [1]. Assuming a network of M3 nodes are able to replicate this performance, at a 0.23% duty cycle the M3 node would last for only 700 hours (about one month) on battery alone. To have enough energy to sustain a year-long deployment, the M3 system would require a 245 μWh battery. This 12× increase in energy storage would require a 26 mm^3 battery, well over an order of magnitude larger than the system itself.

2.2 Achieving Energy-Neutrality

Assuming the same 0.23% duty cycle and power figures, an M3 node has an average power draw of 28 nW. This means the energy harvesting subsystem of a M3 node must also achieve an average of 28 nW of harvested energy to reach an energy-neutral steady state. Our early experiments with new GaAs solar cells find that they are capable of harvesting about 78.2 $^{\text{nW}}/_{\text{mm}^2}$ in "average indoor light" (loosely defined as about $350 - 500$ lux). Reaching 28 nW would require only 0.36 mm^2 of area, well within the M3 size budget.

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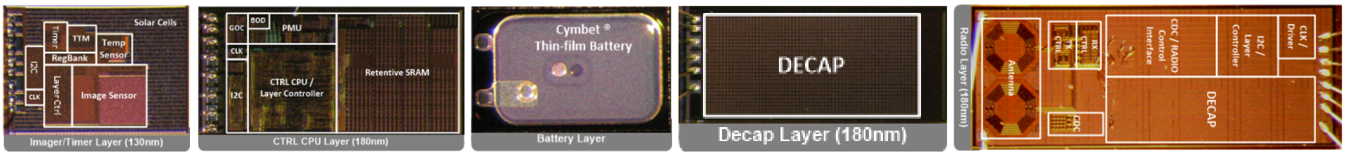
[1] Erring on the side of excess stored energy for this argument: A 5 μAh battery at 4 V yields 20 μWh of energy.



(a) Solar/Imager (b) CPU/RAM (c) Battery (d) Decap (e) Radio

Figure 1: **Individual chips of the M3 system**— These five layers are stacked to build the complete node shown in Figure 2.

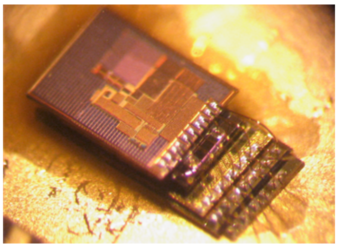


Figure 2: **The complete M3 stack**— The field of dark grey surrounding the perimeter of the top chip is the solar harvesting cells. The center area contains the 128 × 128 pixel imager, a temperature sensor, and the timer subsystem.

3. DEMO

The previous section describes the research ambition for the M3 system. The system demoed in this work has not yet achieved the energy neutral threshold. This demo presents the first integrated, functional M3 “stack”. The M3 node is made up of several subsystems, shown in Figure 1.

The M3 subsystems are:

Solar/Imager: Solar cells and a 128 × 128 pixel imager
CPU/Memory: ARM Cortex M0 CPU, 3 kB of RAM
Decap: Bypass capacitors for radio transmissions
Radio: The RF transmitter

These individual components are assembled into a single system by stacking them one atop another. A complete, assembled M3 stack is shown in Figure 2. The active power of the demoed system is about 40 μW. The sleep power (with timers) is 8 nW. In indoor lighting, this solar harvester is capable of delivering about 1 nW of power to the M3 node.

4. DISCUSSION

We divide our discussion into two sections: first, we consider the aspects of M3 that require further attention and the research directions required to achieve our desired power numbers; second, we address some of the wider questions that surround the interoperability of energy harvesting systems.

4.1 M3 Power Budget

A shortcoming of the current M3 node is the solar harvester. The performance of this first-generation harvester does not achieve what will be required to reach our energy goals. The solar layer is also the oldest layer. Since its design new investigations into a replacement GaAs cell have been very promising. Coupled with improvements in the battery charging circuit, the new generation M3 harvester is projected to harvest $8 - 9$ nW of usable energy. As the solar cells only occupy minimal area in the M3 stack (0.16 mm^2), for only a modest increase in area, an initial goal of 28 nW for “daytime energy-neutral” seems within reach.

Improvements have been made to active power as well. In particular, a new, custom-designed inter-chip bus protocol reduces the number of running clocks in the system and is expected to drop the active power by as much as 10 μW.

4.2 Networks of Energy Harvesting Nodes

Much of the discussion on power in this paper focused on how to adapt existing wireless mesh protocols to energy harvesting nodes and what the requirements would be for energy harvesting nodes to interoperate with existing networks. Columbia’s EnHANTs project takes a different tack, observing these challenges and instead designing a custom communications stack from the physical layer up to facilitate networking between their energy harvesting tags [2]. While we still believe that interoperability is a laudable notion, we also recognize that current mesh protocols were not designed with energy harvesting nodes in mind.

In particular, a node such as M3 that is designed to run on indoor photovoltaic energy could run continuously if exposed to sunlight Harvesting communication protocols whose nodes are exposed to periodic “high-energy” windows could duty cycle more aggressively, absorbing the cost of the longer idle listening times with these free energy periods and modifying demand to meet supply.

Conversely, harvesting nodes operating near their energy-neutral thresholds are dependent on the continued availability of harvestable power to maintain traditional duty cycles. Conventional mesh protocols are willing to pay a relatively higher cost for initial synchronization under the assumption that further communications will preserve the synchronization (at the cost periodic messages and a running timer, whose stability is also a function of power) and amortize this cost. For a network that loses all its available energy at sundown, perhaps this trade-off needs to be reevaluated.

5. REFERENCES

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