PERPETUAL CUBIC-MM WIRELESS SENSOR NODES

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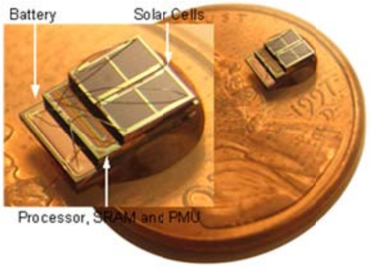

Figure 1. 0.5nW 9mm^3 node with temp. sensor, processor, solar and battery developed at UofM [1].

(i) Background and experience of the participants – Our team at the University of Michigan has a history of collaboration and several years of experience developing technology for energy-constrained wireless sensor nodes. Our team has combined expertise in CMOS imagers and solar arrays, energy-efficient digital circuits, wireless circuits, sensor node networking and applications, dissemination, and time synchronization. Dennis Sylvester and David Blaauw recently demonstrated a 9mm^3 sensor node (Figure 1) complete with solar harvesting, battery, and processing that consumes 7.7μW in active state, and 550pW in a data-retentive sleep state [1]. This work has built on nearly a decade of experience in sub-threshold digital circuits and memories. These power levels are sufficient for perpetual lifetime under moderate lighting conditions. David Wentzloff has recently demonstrated an all-digital UWB transmitter that consumes 12pJ/bit [2], as well as integrated patch antennas at 60GHz and a wake-up radio architecture to harvest a wireless synchronization pulse from existing GSM broadcast signals. Prabal Dutta co-developed the Epic [3] open mote platform and fostered the dissemination of these motes into nearly 100 applications. He has recently published several papers with Thomas Schmid on time synchronization and networking of wireless sensor nodes [4][5].

(ii) Vision of the participants – As of today, there exists no complete sensor node including harvesting, sensing, battery, computing, and wireless communication in a cubic-mm form factor. Even given the rapid scaling of ICs, and proliferation of MEMS sensors, integrating a complete system including the aforementioned functionality is limited to 1cm^3 and larger form factors. This is partly due to the challenges of engineering the technology small enough to fit these form factors, but is largely due to the power requirements, energy storage, and system integration challenges. There is a tight coupling between underlying technology, the peripherals, and the application, all of which ultimately factor into the minimum size of the sensor node. We envision the following technological and integration challenges to realizing true cubic-mm sensor nodes:

1. Energy resources and power consumption – the primary factor impeding the realization of 1mm^3 nodes is the mismatch between the energy consumed by node resources and the energy stored and harvested on the node. Batteries in today's systems are typically >100× larger than we require, and energy harvesting is underpowered to achieve lifetimes of even a few days.

2. Node standby power and retentive memory – sensor nodes spend most of their time in standby mode, monitoring for a wakeup event, rather than in an active mode. Because of the relative time spent in standby, standby energy dominates the energy budget. To minimize standby power, circuits are typically power gated, however this causes the contents of volatile memory to be lost. Non-volatile (NV) memory can be employed to save state between wakeup intervals, but the write energy of NV-memory is much higher than that of RAM, and complex peripheral circuits are needed for the NV write process.

3. Wireless communication – wireless radios typically consume relatively high active power, and require time synchronization between two isolated nodes, both significantly draining battery resources. Additionally, antenna size and efficiency are dictated by radio frequency, with little dependence on the technology. Antennas therefore pose lower limits on the node geometry given a desired frequency range.

4. Software – writing software for this new computing class presents a number of challenges. The two classes of SRAM (volatile and NV) requires data partitioning and low-level memory management. The high time and energy cost of paging underscore the need to track dirty data to reduce unnecessary write-backs. Limited energy requires an energy-aware OS scheduler. High concurrency from communications, image processing, and memory management, coupled with a small memory renders thread-based programming infeasible and event-driven programming preferable.

(iii) Evidence that pursuing this vision will lead to major advances in the field – The technology being developed by our team at Michigan seeks to push the frontiers and enable the applications envisioned possible when perpetual, cubic-mm, wireless sensor nodes transitioned from science fiction into reality. Our team is collaborating with biologists, medical doctors, and other engineering disciplines to define applications that will benefit from pervasive, cubic-mm computing. Specific applications include intra-ocular and intra-cranial pressure sensing, intrusion monitoring, and investigating the biotic effects of climate change on targeted animals. As cubic-mm platforms are adopted by the sensor network community, many new and exciting applications will no doubt be realized by researchers years ahead of market forces. To that end, we identify the following three application themes that we seek to sufficiently support to enable third party research. *Sensory skins* cover surfaces with a dense deployment of small, stick-on nodes that monitor the properties of the manifold itself or its surroundings including: detection and tracking of movement [6], detecting corrosion across metal surfaces [7], or monitoring EEG signals [8]. *Thinking and linking* gives everyday static and mobile objects sensing, computing, communication, and tracking ability. For example, tiny tags can be stitched into clothing for in-home elder care [9], smart waybills can report on the temperature fluctuations a shipping package experiences [10], active baggage tags can locate a bag in an airplane fuselage [11], asset tracking can become as commonplace as asset tagging [12]. *Implantable intelligence* gives visibility and voice to deeply embedded physical and biological processes. New applications will be enabled, like cancer and tumor growth monitoring [13], novel human-computer interaction systems that couple biological and computational processes, and smart band-aids for ECG or EMG [14].

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