Title

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Authors

Chee, Yuen-Hui
Koplow, Mike
Mark, Michael
et al.

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PicoCube: A 1cm^3 Sensor Node Powered by Harvested Energy

Yuen-Hui Chee, Mike Koplow, Michael Mark, Nathan Pletcher, Mike Seeman,
Fred Burghardt, Dan Steingart, Jan Rabaey, Paul Wright, Seth Sanders
Berkeley Wireless Research Center, University of California at Berkeley
2108 Allston Way, Suite 200 Berkeley, CA
510-666-3105, flb@eecs.berkeley.edu

ABSTRACT

The PicoCube is a 1cm^3 sensor node using harvested energy as its source of power. Operating at an average of only 6uW for a tire-pressure application, the PicoCube represents a modular and integrated approach to the design of nodes for wireless sensor networks. It combines advanced ultra-low power circuit techniques with system-level power management. A simple packaging approach allows the modules comprising the node to fit into 1 cm^3 in a reliable fashion.

Categories and Subject Descriptors

B.7.0 [**Integrated Circuits**]: General; C.3 [**Special-Purpose and Application-Based Systems**]:Real-time and Embedded Systems

General Terms

Design, Experimentation

Keywords

Intelligent sensors, energy management, active antennas, advanced packaging, low power, energy harvesting

1. INTRODUCTION

This paper describes the architecture and implementation of the PicoCube, a 1cm^3 wireless sensing device powered by harvested energy. The Cube provides focus and motivation for research into low power technologies by providing a complete integration platform, combining the elements of a sensor node while maintaining a focus on modularity and miniaturization.

One of the main goals of the project was to eliminate the need for long term-energy storage. Sensing systems will become ubiquitous, and will be embedded in everyday materials and surfaces often in very dense collaborative networks. The sensors must live at least as long as the application is in service, which can be decades (for example, in a building). Changing batteries or refueling of this huge number of deployed nodes is impractical, if not impossible.

The 1cm^3 volume of the node contains everything with the exception of the harvesting device. For some applications, such as tire pressure monitoring where the node is mounted on the rim of a wheel, a substantial amount of "mechanical mass" is required to provide the necessary energy. In other applications a large mass may not be needed. For instance, under well-lit conditions cladding the outside of the node with solar cells would provide sufficient energy.

After a short overview of the state-of-the-art in wireless sensor nodes, we discuss the architecture of the Cube, integration challenges, implementation details, tools and design methodology, and experimental data. We conclude by describing some ongoing work related to PicoCube.

2. BACKGROUND

The last decade has witnessed major growth in research and development of wireless sensor nodes and networks, leading to great progress in the domains of ultra low-power wireless, mixed-signal and digital processing, as well as the realization of integrated sensors. In the late 80s and early 90s a number of visionaries pointed out how a combination of technology trends – cheaper and lower power electronics resulting from the continuation of Moore's law, major progress in ad-hoc wireless connectivity, and the availability of mesoscale peripheral devices such as sensors, energy sources and antennas – would lead to a so-called "third wave of computing." However, only recently has this idea become reality [1].

Early sensor nodes were bulky (the size of a coke can), and built from commercial-off-the-shelf (COTS) components [2]. It was not until the introduction of the Berkeley COTS "motes" that the size and the power dissipation of the nodes became small enough that wide scale deployment could be considered. This development combined with the introduction of the TinyOS software platform created a breakthrough, and inspired researchers all over the world to engage in Wireless Sensor Network (WSN) research.

Yet the size and power consumption of the motes (and their derivatives) was still too large to be considered for true ubiquitous deployment. One option to reduce both parameters is a fully-integrated SoC approach. While this leads to the smallest energy and size numbers, it limits usage to a small set of applications (through the choice of processing power, radio bandwidth, sensors, etc). In this paper, we consider an alternative, where very tiny components are combined in a modular fashion using advanced packaging, while maintaining energy efficiency and integration density.

3. ARCHITECTURE

The functional requirements for the PicoCube are simple: take a sample, process the data, packetize the data, and transmit the packet. The Cube does not require external control, so only a transmitter is needed. Major elements of the system include: interconnect and packaging, harvested energy storage, power management, sensor(s), the microcontroller, and the radio.

Figure 1 shows a functional block diagram. The blocks highlighted in dark yellow are core elements; those required in any

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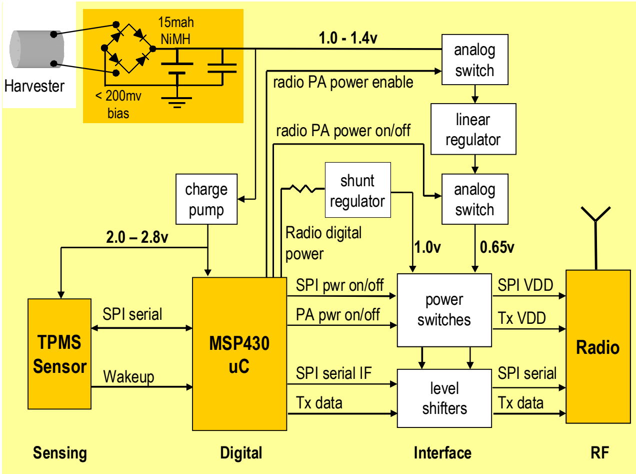


Figure 1. PicoCube architecture

sensing device in one form or another. Anything outside the light yellow area is not part of the Cube. Blocks in white perform power management, a function that requires special consideration in low power devices.

In the next section, we discuss each major element, starting with interconnect and packaging followed by our solution to power management and a description of each printed circuit board (PCB) and how it relates to the functional architecture. Except for power management, each dark yellow block in figure 1 represents one PCB. Power management takes one PCB and half of another.

4. IMPLEMENTATION

The PicoCube uses five vertically stacked PCBs connected by a bus and enclosed in a plastic case (fig 2). All PCBs except the radio board have two metal layers: top and bottom. The terms *board* and *PCB* are used interchangeably in this paper.

For all electrical devices, requirements include efficiency (particularly in sleep mode), small size, supply and signal voltage range compatibility with other devices, a simple electrical interface, and minimal external support needed.

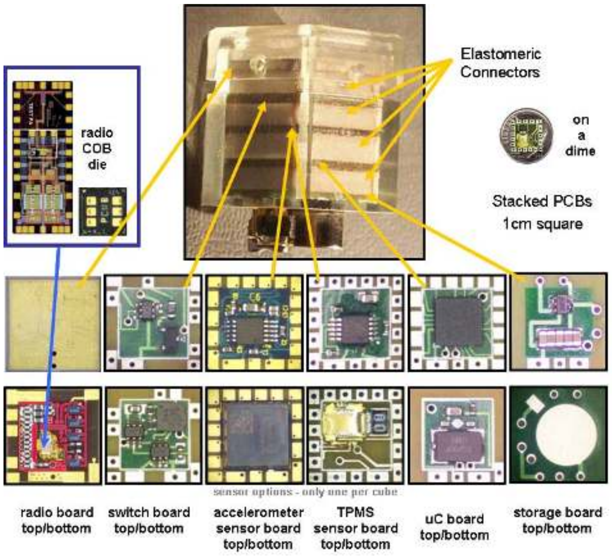


Figure 2. PicoCube anatomy

4.1. Interconnect

Since a board is only 1cm on a side and inter-board spacing is determined by the tallest component, even the tiniest mechanical connector is too large for the bus pin count. Most of the PCB surface area is covered by electrical components and trace routing. Some of these components are COTS which tend to be large. Very little area for interconnect remains.

An interesting technology for making contact with non-solderable terminals such as an LCD panel is the elastomeric connector. One class of these devices look like a rectangular beam with alternating strips of conducting and insulating material, either laminated in the longitudinal direction or wrapped around a core (fig 3). Contact is made by pressure against a metal pad. Pads aligned on either side of the beam are electrically connected.

For our purposes, the advantages of elastomeric connectors are: very small size, fine pitch, and ease of customization. We chose connectors with 0.05 mm gold wires on a 0.1 mm pitch. The standard pad size is 1.2x1.0 mm, allowing multiple wire contacts per pad. In actuality, contact integrity and current capability of the wires was such that even the smallest pad turned out to be larger than needed.

Our approach was to place a ring of pads along all four edges of a board, on both sides (fig 4). All boards in the stack have the same pattern, so pads for a given signal are directly adjacent across the connector. There are 18 pads per side, electrically connected to the opposite side of the PCB with vias. We devoted the outer 1.4 mm of each board to connectors and inner housing, leaving a 7.2x7.2 mm area for component placement and routing.

There is an optimal amount of contact pressure for an elastomeric connector, and they deform but do not compress. For these reasons design rules specify vertical deflection and horizontal deformation. The area needed for a connector must take this into account by providing extra horizontal space beyond the connector thickness and there must be a way to limit the vertical deflection. These issues are considered in the design of the package.

Figure 3. Elastomeric connector

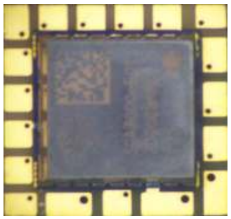


Figure 4. Example of pad ring

4.2 Packaging

In terms of meeting the functional goal for a sensor, packaging, like power management, is not strictly speaking essential for the application to do its job. Of course in the real world something is required to hold the bits and pieces together. Ideally the packaging would take no space i.e. be “invisible”. A compromise is to design the electrical substrates and interconnect as part of the package (fig 5).

Vertical separation between boards is limited by the height of components. An 8x8 mm OD plastic ring, 0.4 mm thick and 2.33 mm high, was used to satisfy three requirements: a vertical deflec-

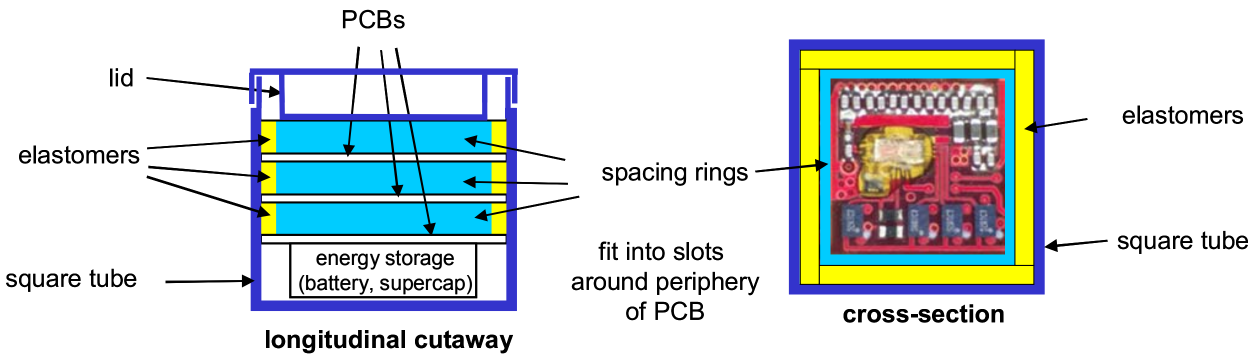


Figure 5: Packaging

tion stop, the inner vertical surface of the connector deformation channel, and an inter-board spacer. The outer vertical surface of the deformation channel was provided by the outer enclosure itself. This "tube and ring" packaging technique provides structural strength, connector housing, board placement control, and an outer protective barrier.

The plastic rings, outer package, and lid were built using stereolithography (SLA), post-processed to create a very close fit around the PCBs; horizontal alignment is a critical parameter to prevent shorts between adjacent contact pads. Compression is maintained by a snap-fit between the lid and the package body.

4.3. Power Management

Energy is wasted any time voltage needs to be stepped up, down, or regulated. In an ideal world, energy from a storage buffer would be applied directly to the electronics. In reality, components usually have different requirements for voltage, noise, and regulation, so additional circuits are required to "manage" the source. These circuits provide no benefit to the application but consume power nonetheless. In fact, since at least one supply is always on, the contribution that management makes to the total system power can be dominant.

The PicoCube requires three power supplies: between 2.1 and 3.6v for the microcontroller and sensor, 1.0v regulated for the radio digital logic, and 0.65v tightly regulated with low noise for the radio RF section. The microcontroller/sensor supply must be available at all times for sleep circuitry and timers. The radio supplies are on for only a short time in each sample period, so efficiency is less important than size.

Most currently available COTS switching or linear regulators are not designed for extreme low power and consequently have high quiescent currents. Alternatively, a charge-pump, or switched capacitor converter, either doubles or inverts a voltage without regulation and generally with low drive capability. The advantages of charge-pumps include low quiescent current and high efficiency under light loads: the operating regime of the Cube.

Our controller/sensor supply uses a TI TPS60313DGSR charge pump with very low quiescent current due to a special low-power mode. It is located on the top side of the sensor board. The radio digital section demands so little power that a controller I/O signal fed through a shunt regulator is sufficient. The radio RF section is more demanding in terms of current, noise, and voltage so we use a LT3020EDD linear regulator gated on both input and output by solid state switches. Both of these supplies are located on the switch board.

The PicoCube supplies have been integrated onto a single die. Section 7.1 discusses this chip in more detail.

4.4. Harvested Energy Storage

The Cube requires an AC source that meets specifications determined by the storage and management blocks, but is otherwise source agnostic. This paper focuses on the Cube itself, so harvesters will not be covered here [3,4,5].

The energy delivered by a harvester is not directly usable by device electronics due to mismatches in, for example, voltage level, voltage range, and impedance. Therefore, some means of buffering between energy source and load is needed.

Depending on the design and technology, capacitors can store significant amounts of energy and can deliver power in bursts. However, voltage is directly related to state-of-charge which may be inconvenient due to the potential of additional need for voltage matching interface hardware (DC-DC). Furthermore, capacitor energy density is considerably lower than that of battery technologies; for example, 220 J/g for a NiMh battery vs. 10 J/g for a super capacitor or 2 J/g for a typical capacitor. On the other hand, batteries typically exhibit poor burst current performance relative to capacitors. This can be addressed by using bypass capacitors.

A NiMH battery was chosen for two reasons. First, its discharge characteristics provide a nominal 1.2v that is stable until just prior to full discharge, and 1.2v is close to optimal for generating the required supply voltages. Second, NiMH can be trickle charged for an indefinite period at one-tenth the capacity (C/10) without damage. This eliminates the need for complex charge control circuitry.

4.5. The Storage, Controller, Sensor, and Switch Boards

These four boards are simple in design and the current version of the Cube uses COTS parts for these functions. In the next version, the switch board and microcontroller and sensor supply will be replaced by the custom power management chip.

We assume a harvester that produces an AC signal. Everything downstream expects DC, so the first thing in the power train is a full bridge rectifier. The rectifier is mounted on top of the storage board along with several filter capacitors. The battery is attached to the bottom of the board with silver epoxy.

Digital processing in a sensor node ranges from very simple data formatting to complex DSP algorithms or protocols. There is no single solution for all applications: a small state machine may do for a fixed task; programmability or dynamic reconfiguration may be required for something more complex. Configurability comes with an energy cost, however. We chose the TI MSP430-F1222 microcontroller in part because it provides a sub-microwatt deep sleep mode.

Most signals on the bus originate or terminate on the controller board and routable area is minimal, so signals are routed to the PCB pad closest to the uC package pin. Therefore, this board determines pad to signal mapping for the bus.

Microcontroller code was written in ‘C’ and is entirely interrupt driven. No operating system support was required for this simple application.

Two sensor boards are available for the Cube. The first board contains an SP12 TPMS device from Sensonor. This device has sensors for tire pressure, temperature, acceleration, and supply voltage. Its package is too big for the PCB, but we were able to obtain bare die (one analog and one digital). The die were attached and bonded using chip-on-board (COB) technology. The digital die generates an interrupt every six seconds - between events, only an internal timer is running and the MSP430 controller is in deep sleep mode. The interrupt initiates a sample/format/transmit cycle that takes about 14ms.

The second sensor board contains a single packaged accelerometer (SCA3000-E01-10). This device, 7x7 mm, *just barely* fits within the placement boundary.

The switch board contains power gating switches and the two power supplies dedicated to the radio. The output of the 1.0v shunt regulator is switched to ensure a clean rising edge with no overshoot. The 0.65v power amp supply is switched at its input to avoid quiescent losses and a short time later is switched at its output to ensure a clean rising edge.

4.6. The Radio Board

Low power radio front-ends are key components of BWRC research, so we had several home-grown options to choose from [6-12]. The Cube uses a 0.8dbm transmitter based on Film Bulk Acoustic Resonator (FBAR) technology for RF carrier generation [11]. An FBAR is a MEMs device that behaves like a capacitor except at resonance, where it has Q > 1000. The FBAR is a separate die, wire bonded to the transmitter.

Baseband data is modulated onto the carrier using OOK by power cycling the FBAR oscillator and the low power amplifier via its foot switch and gate bias respectively. Transmitter properties include a 1.863GHz channel, 46% efficiency @ 1.2mw transmit power, 650mv supply, and direct modulation. The die is 1.2x0.8 mm in 0.13um CMOS. With 50% on-off keying (OOK), power consumption is 1.35mW at data rates up to 330kbps.

Radio PCB design was one of the most challenging tasks in building the Cube due to limited area for an antenna. In keeping with the 1cm^3 goal, even the antenna had to be within that volume. After evaluating several topologies we settled on a patch antenna on the top metal layer with carefully place feed and ground attachments. In order to achieve acceptable efficiency, the patch-ground layer needed a dielectric constant of over 10 with a thickness of 70 mils. Unfortunately, maximum thickness for the most suitable dielectric material (Rogers 3010) was 50 mils. Attempts to fabricate this design by bonding a 50 mil and a 20 mil layer failed in subsequent layer attachment due to debonding between the two Rogers layers. A board redesign compromised efficiency by using a single 50 mil layer.

The board that we ultimately built has four layers: bottom, route, ground, and antenna. All electronics are on the bottom surface, including the radio, FBAR, level converters in tiny CSP packages (to voltage shift the controller signals for the radio logic), an antenna matching network, and bypass capacitors on the 0.65v supply. The top surface is devoted entirely to the antenna. Total thickness is 64.8 mils, surface metal is gold, and the radio and FBAR die are attached using COB. Transmitted signal strength is about -60dbm at 1 meter.

5. TOOLS AND PROCESSES

Initial test boards for elastomer evaluation were designed using ExpressPCB and PCB123, which are free schematic capture and layout tools with built-in ordering and design submittal. Both are low-cost services with short turnaround time, suitable for quick prototypes that do not require precision or small line widths. The storage, microcontroller, pressure sensor, and switch boards were ultimately build using PCB123, but in retrospect this entailed risks that were unnecessary. For instance, minimum unplated via size was 20 mils and minimum line width was 10 mils, making layout and routing more difficult. Large through-hole vias in the bus pads significantly reduced contact area for the connector, which was a concern. Ultimately this did not cause problems, but subsequent Cube versions will have additional bus signals, leading to smaller pads with tighter tolerances.

The radio board required a much more sophisticated fabrication process. It was designed using Cadence Allegro with schematics in Capture HDL and layout in PCB Editor.

6. TESTING AND DEMONSTRATION

Average Cube power consumption using the TPMS sensor is 6 µw, dominated by quiescent losses from the power management circuitry. Figure 6 shows the power profile for a single “on” cycle. The JTAG pins on the controller are remapped to bus signals after boot-up, so the Cube cannot be tested in-system. Test jigs were built for PCB top side up and PCB top side down. The 18 signal bus is pinned out to headers.

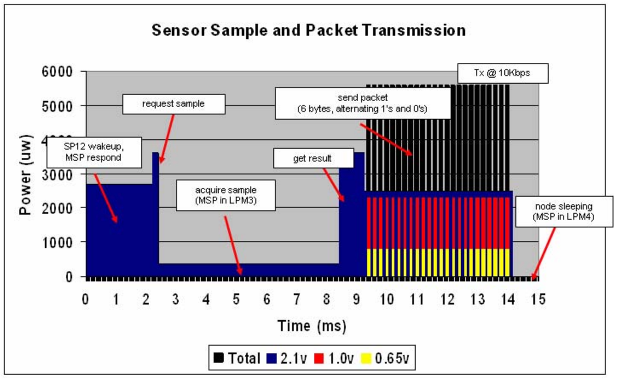


Figure 6. Power profile during “on” cycle

We used the IAR Embedded Workbench to program and debug the MSP430. For all boards except the radio, standard bench test equipment was sufficient. For the radio, we also used an Agilent S4855A spectrum analyzer to measure signal strength. Several power management circuits were prototyped before the design was finalized using ExpressPCB.

In order to demonstrate functionality, we used the accelerometer sensor board programmed in motion mode. The demo setup included the Cube, a custom-built receiver board using another BWRC research radio as receiver [12], an oscilloscope showing the raw and processed baseband signal, the spectrum analyzer showing the transmitter signal and receiver tone, and a laptop with a graphical display of sensor values (figs 7 and 8).

This sensor has an interesting operating mode from a demo perspective: for each axis, a threshold can be set that, when exceeded, causes an interrupt to the controller. If the Cube is sitting motionless on a table it is in deep sleep mode. In the demo, the Cube is placed on a table where visitors are invited to play with it. When picked up and moved around, it generates sample data that is plotted on the laptop. If held still or placed on the table, the plotting stops. Range is about 1 meter depending on orientation of the antenna.

The node was also demonstrated in combination with an energy scavenger mounted on a bicycle wheel.


Figure 7. Demo at BWRC retreat, 2007

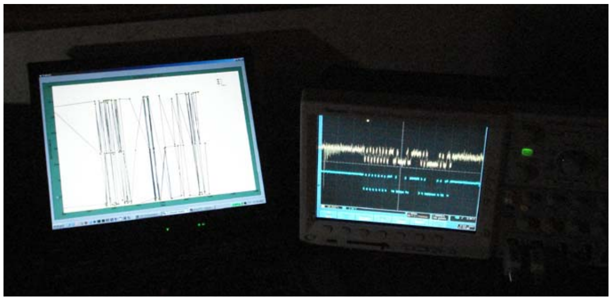


Figure 8. Laptop display of X,Y,Z data values and o'scope display of baseband waveforms for one sample.

7. ONGOING WORK

As mentioned above, the PicoCube is a development platform suitable for a wide range of applications as well as a prototyping platform for emerging research technologies. A number of ongoing research efforts at BWRC are making use of the platform.

7.1. Advanced Integrated Power Management

Switched-capacitor (SC) converters are ideal for wireless sensor node power management. They can easily be integrated in silicon and operate efficiently over large load ranges by varying the switching frequency. To date, only simple fixed-ratio SC converters have been implemented and used in industry. However, large-ratio conversions are possible through topologies in [13]. In addition, variable-ratio inverters can be used to both efficiently create an AC waveform and to also efficiently rectify a varying waveform from an energy scavenger. Such an advanced SC converter can efficiently rectify low-voltage sources such as MEMS vibration generators and other miniature sources to charge energy buffers. In addition, SC converters can provide load voltage conversion, regulation and switching for all the loads of a wireless sensor node.

We have built and demonstrated a power interface IC for conversion and management of the PicoCube. The architecture of the power interface IC is shown in figure 9. The synchronous rectifier interfaces the electromagnetic shaker (scavenger), which puts out a pulsed waveform to the battery. Two switched-capacitor power converters convert the battery voltage, nominally 1.2 V, to 2.1 V for the microcontroller and sensors and to 0.7 V to power the radio. A linear regulator is used as a post-regulator to more precisely set the radio voltage to 0.65 V and to smooth the ripple from the switched-capacitor converter.

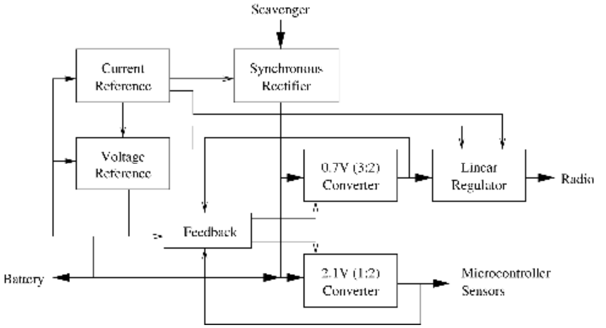
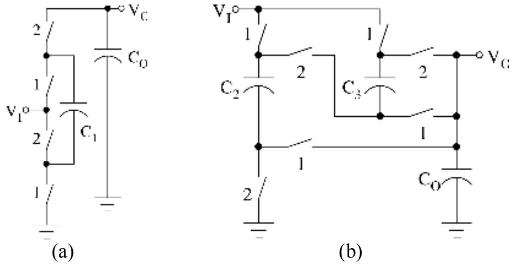


Figure 9. Block diagram of the converter IC

A number of analog blocks provide support to the power electronics by providing references and control signals. A self biased current source (reference) supplies bias current to the chip via a current mirror. It is biased at 18 nA independent of VDD and mildly dependent on temperature. An ultralow-power sampled bandgap reference provides a reference voltage to both the converter feedback circuitry and the linear regulators.

Power conversion between the battery and the loads is performed using on-chip SC converters with size-optimized devices and level-shifting gate drivers. A 1:2 ratio converter, shown in figure 10a, provides a doubled voltage for the microcontroller and sensors. The minimum supply voltage for these components is 2.1 V. A 3:2 ratio converter, shown in figure 10b, provides a lower voltage to supply the radio, nominally at 0.65 V. The converters exceed 84% efficiency [14].



(a) (b)

Figure 10. Switch-level diagram of a) 1:2 converter, b) 3:2 converter

The synchronous rectifier replaces the junction diodes characteristic of a bridge rectifier with transistors. The transistors are actively controlled by comparators to eliminate the large forward drops of a diode rectifier. The synchronous rectifier achieves 96% of the efficiency of an ideal rectifier at 450μW input.

The converter IC was implemented using a 0.13 μm CMOS process provided by ST Microelectronics. The nominal 1.2V working voltage matches the battery voltage perfectly, and the process provides 2.5 V transistors and high-density capacitors, the latter used in the switched-capacitor converters. The die is approximately 2 mm on a side, significantly smaller than off-the-shelf implementations. In this IC, the leakage current was approximately 6.5 μA, partially attributable to the pad ring.

Significantly, this architecture is suitable for generating IP cores. We envision a library of parameterizable management cores that can be utilized as black boxes in any chip design, eliminating the need for separate packages. These cores would be tailored to the needs of the chip, or even sub-blocks of the chip, while taking an insignificant amount of real estate.

7.2. Thin-film Batteries

Thin-film batteries have shown promise for the past decade, but low capacity per area and high processing temperatures are still obstacles. Thick-film approaches will improve capacity, but a compatible, effective solid-polymer electrolyte has yet to be deployed commercially [15] because packaging costs and environmental constraints are generally prohibitive for liquid phase electrolytes on-chip. We are developing a low cost, direct write printing method which integrates the capacitor and battery micropower system directly on a device. The dispenser printer consists of a three-axis micron resolution stage and a pneumatic regulator. It is able to print particles at micron to nano scale suspended in a polymer binder onto a substrate. Films of 30 to 100 μm of these various materials have been printed with little surface roughness. A great benefit of this approach is the ability to design storage to fit the consumer, for example, a specific voltage range.

7.3 Ultra-low Power Wireless

One exciting development that can help to reduce the power of the node even further is the wakeup radio [16]. This radio contains an extremely low-power receiver that listens full-time for a wake-up signal, then starts a more complex (and more power hungry) receiver for data transfer.

8. CONCLUSIONS

The PicoCube was intended to impose real constraints on research technologies through interaction in a real system, and it was very successful in doing so. When systems are compressed into smaller and smaller volumes with more and more complexity, weaknesses in design practice become apparent.

More specifically, the PicoCube design brought into the foreground: 1) the challenges of integrated power management for miniature systems such as sensor nodes with multiple operational modes and voltages; 2) the challenge of integrating interfaces such as antennas into such a small volume. The lessons learned provided invaluable insights for future research. At the same time, the resulting PicoCube has become a unique combination of innovative solutions and technologies.

As a final comment, it is apparent that further development of the node requires the introduction of advanced packaging technologies such as stacked die, both from a miniaturization as well as a reliability perspective - living in harsh environments such as the automobile tire, nodes must be durable and robust.

9. ACKNOWLEDGEMENTS

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