SoC Issues for RF Smart Dust

Wireless sensor nodes, each a self-powered system performing sensing, communication, and computation, form reliable mesh networks coordinating efforts to add intelligence to the environment.

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ABSTRACT | Wireless sensor nodes are autonomous devices incorporating sensing, power, computation, and communication into one system. Applications for large scale networks of these nodes are presented in the context of their impact on the hardware design. The demand for low unit cost and multiyear lifetimes, combined with progress in CMOS and MEMS processing, are driving development of SoC solutions for sensor nodes at the cubic centimeter scale with a minimum number of off-chip components. Here, the feasibility of a complete, cubic millimeter scale, single-chip sensor node is explored by examining practical limits on process integration and energetic cost of short-range RF communication. Autonomous cubic millimeter nodes appear within reach, but process complexity and substantial sacrifices in performance involved with a true single-chip solution establish a tradeoff between integration and assembly.

KEYWORDS | Low-power circuits; low-power RF; Smart Dust; wireless mesh networks; wireless sensor networks; wireless sensors

I. INTRODUCTION AND HISTORY

The term "Smart Dust" has come to be used to describe a wide range of wireless sensor network hardware at a small scale down to a handful of cubic millimeters [1]. Each wireless sensor node, or "mote," contains one or more sensors, hardware for computation and communication, and a power supply (Fig. 1). Motes are assumed to be autonomous, programmable, and able to participate in multihop mesh communication.

The genesis of Smart Dust was a workshop at RAND in 1992 in which a group of academics, military personnel, and futurists were chartered to explore how technology revolutions would change the battlefield of 2025 [2]. By this time it was clear that MEMS technology was going to revolutionize low-cost, low-power sensing. Moore's law was accurately predicting CMOS digital circuit performance improvements with no end in sight, and the wireless communication revolution, already firmly established in two-way pagers, was beginning to make its way into handheld cellphones. The confluence of these three technological revolutions in sensing, computation, and wireless communication placed the major sensor mote functions on asymptotic curves down to zero size, power, and cost over time. Furthermore, the potential for cointegration of CMOS and MEMS made single-chip sensors with integrated signal conditioning possible at low cost [3]–[11].

In 1996, the term "Smart Dust" was coined to describe the ultimate impact of scaling and process integration on the size of an autonomous wireless sensor [12]. Several DARPA-sponsored workshops in the mid-1990s fleshed out some of the implementation and application details of the 1992 vision, and key research proposals were written and funded at the University of California, Los Angeles (UCLA); the University of California, Berkeley; and the University of Michigan, Ann Arbor. It was clear to the community at that time that low-cost ubiquitous wireless sensor networks would have a revolutionary impact on military conflict. What was not as clearly anticipated was the potential impact on commercial and industrial applications.

The first wireless sensor motes, called COTS (commercial-off-the-shelf) Dust, were built early in the Smart Dust project using printed circuit boards and off-the-shelf components. It was shown that these inch-scale devices could perform many of the functions predicted in the 1992 workshop, including multihop message passing and mote localization [13]. COTS dust and other macro-scale motes were developed to explore sensor network software and individual mote architecture as well as deploy small scale networks [14]–[16].

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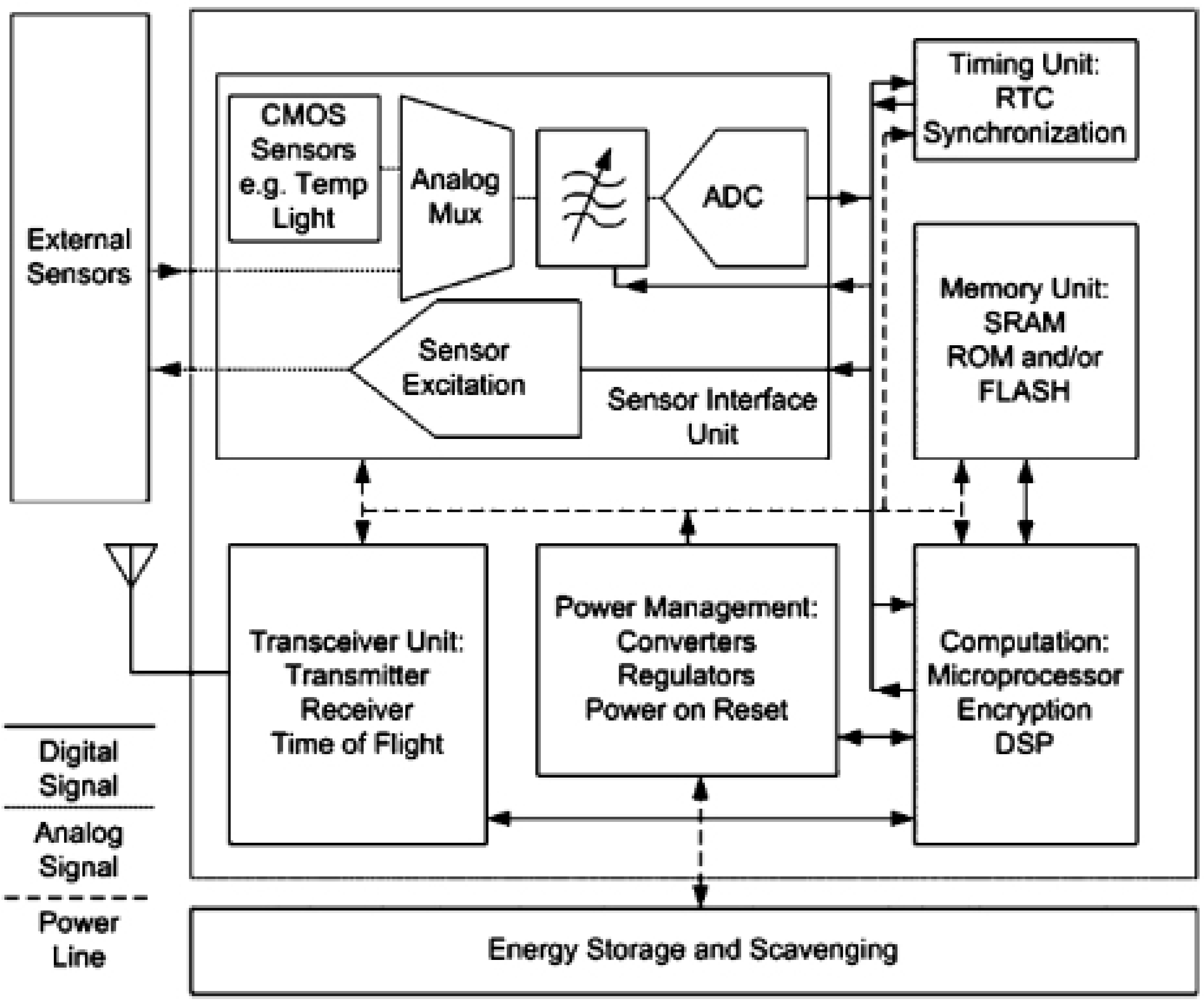

Fig. 1. *Basic block diagram of a wireless sensor node. A complete node will consist of many blocks, most of which can be integrated onto a single standard CMOS die (blocks inside gray box). Energy storage (batteries, large capacitors, or inductors), energy scavenging, and some sensors will likely be off-chip components. The primary integrated blocks include a sensor interface, memory, computation, power management, and an RF transceiver.*

While great strides were made in miniaturization and power reduction of the hardware, perhaps the most important event during this early period was the observation that networks of autonomous sensor motes represented a ubiquitous, embedded computing platform [17]–[20], and they needed a new operating system to match. Proposed in the Endeavour project [21], the TinyOS operating system [22] was developed under DARPA funding and put into the public domain, along with all of the COTS Dust hardware designs, and a thriving open-source sensor networking community was born.

Meanwhile, in 1999 the IEEE formed the 802 working group 15, with a charter to develop standards for wireless personal area networking (WPAN), from which the low-rate WPAN 802.15.4 standard emerged. The 802.15.4 standard was designed from the beginning to be a low-power, low-complexity solution for sensor networking in industrial, automotive, and agricultural applications [23]. A spinoff group from the industrial consortium HomeRF, focused on home automation applications, created the Zigbee standard in 2004. Zigbee 1.0 [24] is based on the 802.15.4 standard radio [25]. With the blessings of the IEEE on a radio standard, a consortium of large companies defining applications, and the help of the venture capital community, a new industry was born.

II. DEVELOPMENTS IN SENSOR MOTE HARDWARE

The Mica mote (Fig. 2), the most popular mote used in research, was developed to mimic the expected architecture of a highly integrated mote while using off-the-shelf parts mounted on a common PC board to reduce development time. This mote includes a microcontroller, RF transceiver, and the ability to interface to a variety of sensors. The mote is powered by a pair of AA batteries, and these take up the majority of the unit's volume [14]. Similar inch-scale motes utilizing primarily off-the-shelf components are now commercially available from numerous sources [26]–[30].

Development of highly integrated sensor mote components started in the mid-1990s and resulted in multichip systems that could be assembled to create a mote. At UCLA, MEMS devices were combined with commercial CMOS chips that provided sensor control and readout as well as communication [31]. At the University of Michigan, Ann Arbor, a 10 000-mm^3 device containing sensors, computation, and RF communication using multiple chips in a single package was developed and demonstrated [32]. Other wireless sensor multichip units or components have been demonstrated for a variety of industrial, commercial, and defense applications [33]–[42].

To minimize energy, passive optical communication was explored for early Smart Dust motes. The smallest optical mote to date (Fig. 3.) displaced only 4 mm^3 and contained an 8-bit ADC, an optical receiver, a corner cube reflector passive optical transmitter, a light sensor, an accelerometer, a multivoltage solar cell power source, and limited computation [43]. A newer generation sensor mote, called the Spec mote, contained a microprocessor, SRAM, an RF transmitter, and an 8-bit ADC integrated onto a single CMOS die [41]. More recently, highly integrated chips with a complete RF transceiver, microprocessor, ADC, and sensor interface have been reported [44], and even commercialized [45]. Even these highly integrated chips still require an off-chip battery, some passive components, a crystal timing element, and an RF antenna, resulting in a complete package at the centimeter to inch scale.

III. WIRELESS SENSOR NETWORK APPLICATIONS

Today's sensor networks rely on a wired infrastructure to provide power and transfer data. The high cost of running wire for power and communication often dramatically exceeds the cost of the sensors themselves, slowing the adoption of sensor networks for all but the most critical applications. By drastically reducing installation costs, reliable low-cost wireless mesh networking places sensor networks on the same technology curves as the rest of the IT revolution.

Wireless connectivity for sensors has been an attractive option for years, but, due to problems with reliability, adoption has been limited to applications where occasional loss of connectivity and data is acceptable. The current revolution in wireless sensing is being driven by the dramatic improvement in reliability and lifetime possible with wireless mesh networking. This is an echo of the Internet revolution, where point-to-point wired communications were replaced by multihop wired communication. The insensitivity of the Internet mesh to the loss of a path or a node is a key part of what makes the Internet reliable. The same concept applied to wireless sensor networks improves reliability.

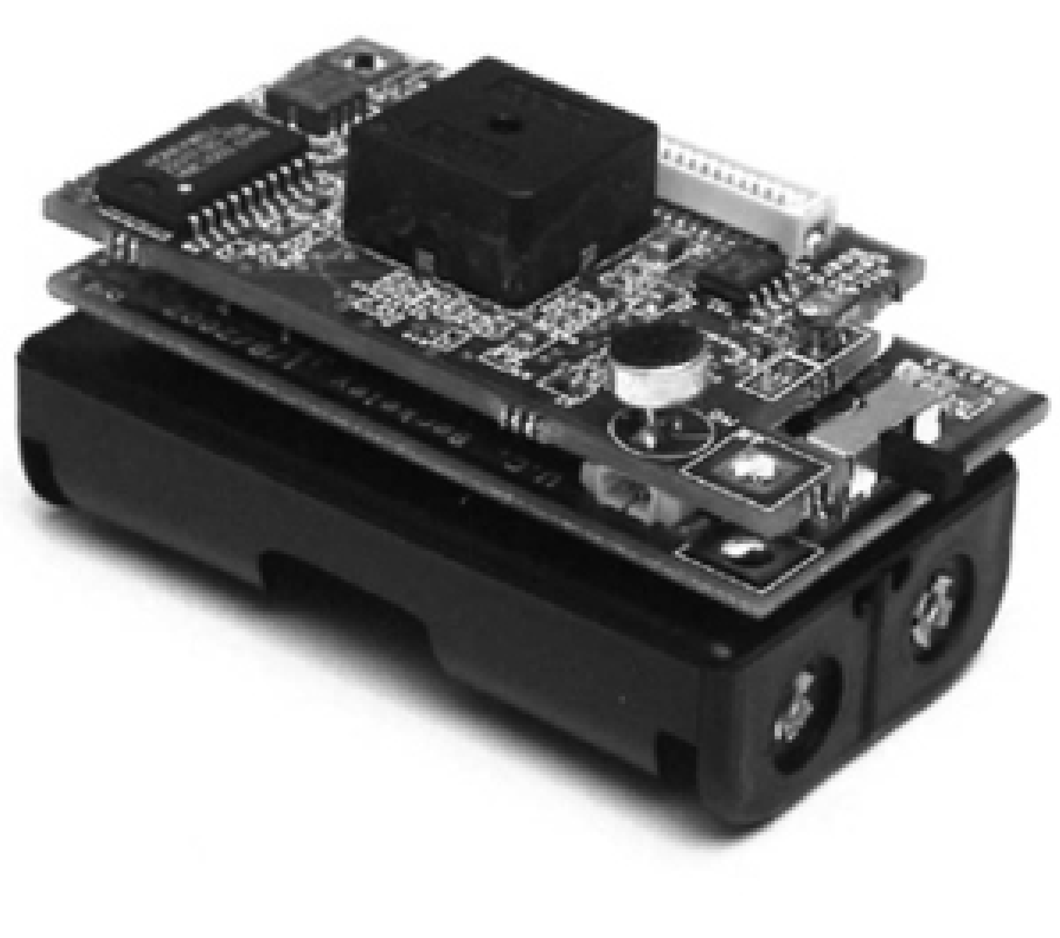

Fig. 2. *The Mica mote combines sensing, power, computation, and communication into one package using off-the-shelf components.*

In commercial and consumer applications, motes can be used to eliminate the wiring cost for light switches, thermostats, and fire alarms. Fig. 4 illustrates the wireless routing mesh blueprint from an actual sensor network deployment. In this application, motes were installed throughout a health clinic in just 2 h to implement a low-cost air temperature and energy consumption monitoring system with a simple Web browser based control interface [46].

In applications such as inventory monitoring, motes will not be fixed in space. A primary concern of the network will be determining the location of motes on boxes or pallets on demand and this requires location discovery capability to be built into the network [47].

In some entertainment applications inertial sensing motes may be worn by humans to detect and interpret movements as communication gestures or control signals [48]–[52]. Similarly, wearable motes have been used to interpret human motion as musical gestures, allowing users to create music interactively in real time [53]. In these systems the latency requirements are more stringent than in typical monitoring scenarios and, since humans will be wearing the sensor mote, a small form factor is important.

Defense applications drove much of the initial research in sensor networks. The Igloo White system was a wired sensor network employed from 1966 to 1972 along the Ho Chi Minh trail during the Vietnam War. In a more modern military application, wireless sensors were distributed throughout a mock urban battlefield to pinpoint a sniper's location by acoustically detecting the arrival time of the muzzle blast at several different points in the field [54]. Sensor networks have also been proposed for position tracking and identification of people and fast-moving vehicles in both civilian and military scenarios [55].

IV. APPLICATION REQUIREMENTS AND HARDWARE IMPLICATIONS

Applications for wireless sensor networks can be broken down into two categories: wire replacement and wirelessly enabled. In the former case, the cost of hardware for a wireless solution is generally dramatically lower than the comparable cost of running wiring. Once secure, reliable, low-power solutions are demonstrated in this domain, adoption is limited by caution, rather than cost. Wirelessly