12.3 PicoRadios for Wireless Sensor Networks: The Next Challenge in Ultra-Low Power Design

Jan M. Rabaey, Josie Ammer, Tufan Karalar, Suetfei Li, Brian Otis, Mike Sheets, Tim Tuan[1]

Univ. of California Berkeley, CA
[1]Xilinx Inc

An untapped opportunity in the realm of wireless data lies in low data-rate (<10kb/s) low-cost wireless transceivers, assembled into distributed networks of sensor and actuator nodes. This enables applications such as smart buildings and highways, environment monitoring, user interfaces, entertainment, factory automation, and robotics [1]. While the aggregate system processes large amounts of data, individual nodes participate in a small fraction only (typical data rates <1kb/s). These ubiquitous networks require that the individual nodes are tiny, easily integratable into the environment, and have negligible cost.

Most importantly, the nodes must be self-contained in terms of energy via a one-time battery charge or a replenishable supply of energy scavenged from the environment. With the proposed size limitations, battery power alone does not suffice to ensure self-containment. Figure 12.3.1 shows how batteries fare compared to a number of energy-scavenging technologies [2]. At 100µW, 1cm^3 of non-rechargeable Li-Fe battery lasts <6 months. 10cm^2 of solar panel under typical lighting conditions meets the specifications, and so does 2 to 3cm^2 of piezo-electric material. Achieving the ultra-low power-dissipation requires reductions from the system architecture down to the circuit technology. This paper proposes a number of techniques to accomplish this, and outlines venues for further research.

The following functions are to be supported by the wireless node: (1) sensor and actuator interface functions; (2) applications and controller; (3) networking protocol stack; (4) locationing; (5) RF and physical layer; and (6) energy supply chain. While most functions are implemented in CMOS, some components are not (RF passives, antenna, sensor parts and energy train parts). This paper focuses on energy-reduction opportunities in the CMOS-designated functions.

In most wireless systems, the power amplifier dominates the transmit power budget. Transmitting a bit reliably over a distance, d, incurs an energy cost E_t, a strong function of the distance between nodes: $E_t = a + b \times d^{\gamma}$, with γ the path-loss exponent (approaching 4 in indoor environments). For communication distances over 10m, transmit energy rapidly dominates the overall energy budget. Since latency is rarely critical in sensor networks, a multi-hop ad-hoc network is adopted. Partitioning the link by introducing repeater nodes results in a linearization of the energy as a function of distance. The high sensor network density ensures sufficient repeater nodes for message relay. Thus, the average wireless hop length is below 10m, where high-gain PAs are usually not needed.

For integratability, higher carrier frequencies allow small passives and antenna. Yet high-frequency components (mixers and oscillators) increase receive power (from 0.7mW at 170MHz to >100mW at 2.4GHz for existing low-data rate radios). Focussing on energy efficiency (nJ/b) and ease of integration rather than bandwidth efficiency (b/s/Hz) presents opportunity for innovation. Ultra-wide band (UWB) transceivers are attractive. Another option, the sub-sampling receiver of Figure 12.3.2, uses a mostly passive front-end to virtually eliminate the need for active high-frequency components. Passive high-Q narrow-band filters, enabled by recent advances in integratable high-Q (>1000) resonators (FBAR, RF-MEMS), are used to suppress the noise-folding effects associated with these receivers [3,4]. A bank of these filters provides frequency diversity in an “analog” orthogonal frequency division multiplexing (OFDM) style. Orthogonal spreading codes distribute a bit over a set of frequency tones avoiding narrow-band fading effects that hamper simple FM modulation. It also allows for the simultaneous processing of multiple channels without extra components. The energy/bit is reduced to ±5nJ/b, an order of magnitude lower than other architectures at the same carrier frequencies.

The sensor node duty cycle for smart building applications with average aggregate data rates of 300b/s is between 1 and 5%. A traditional media-access (MAC) layer would spend >90% of its energy on channel monitoring. An asynchronous MAC approach that turns the radio on only when communication is needed, rather than scheduling communication between nodes, offers a radically different approach. It uses an extremely low-power “wake-up” channel to remotely wake up a neighboring radio from deep sleep, thus avoiding strict inter-node timing synchronization. This wake-up radio is an extremely simple low bias current (<10µA) RF receiver (e.g. Figure 12.3.3 [5]), or the main RF receiver biased in deep sub-threshold followed by an energy detector.

Additional energy savings are obtained by selecting the appropriate circuit strategy. Configurable protocol implementation fabrics such as the hybrid FPGA/PAL structure shown in Figure 12.3.4, reduce energy consumption by over 40% with respect to low-energy FPGAs, while maintaining the necessary flexibility. To avoid sizeable leakage power, the protocol stack must aggressively power-down idle modules (disconnect or ramp down the supply rail). A power management scheme powers up functions automatically in response to events at their interfaces (Figure 12.3.5). These events can be from external (sensors or wake-up requests) or internal sources (neighboring blocks). A centralized supervisor unit maintains system state, schedules periodic system maintenance, and ensures that blocks do not power down in the middle of communication sessions.

Projected energy consumption in the integrated wireless transceiver node using the proposed techniques is shown in Figure 12.3.6. By balancing the various power dissipation sources, a node consuming <100µW on average is attainable. It combines innovative approaches throughout all layers of the design hierarchy (from system to architecture, circuits, and technology). While this paper presents some lines of attack, further research in all areas is a necessity. Most importantly, a system design methodology supporting exploration and optimization between layers is required.

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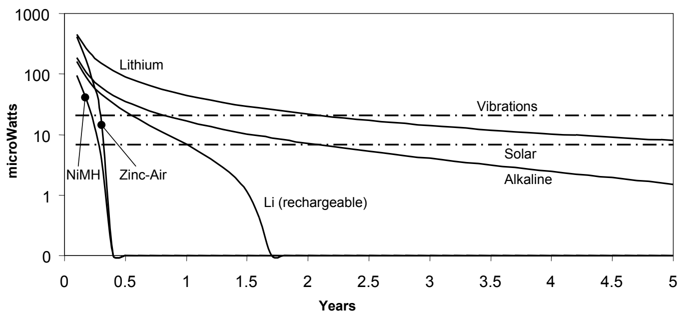

Figure 12.3.1: Battery lifetime (0.5cm³), compared to continuous power sources (1cm² solar cell, 1cm² vibration converter).

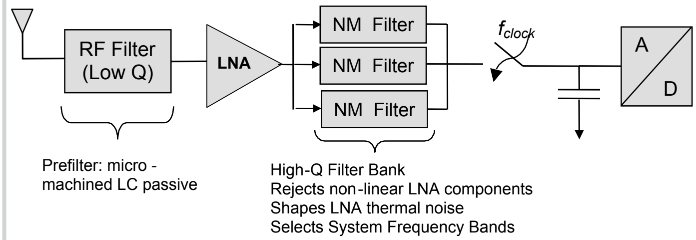

Figure 12.3.2: Sub-sampling RF front-end employing high-Q resonators.

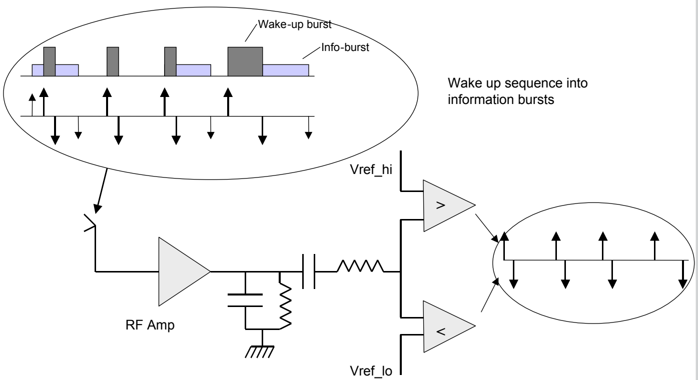

Figure 12.3.3: Reactive radio combines wake-up sequence with information bursts.

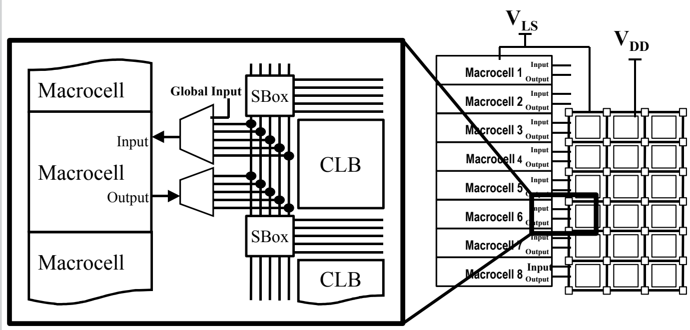

Figure 12.3.4: Hybrid programmable logic array for flexible low-energy implementation of protocol stack.

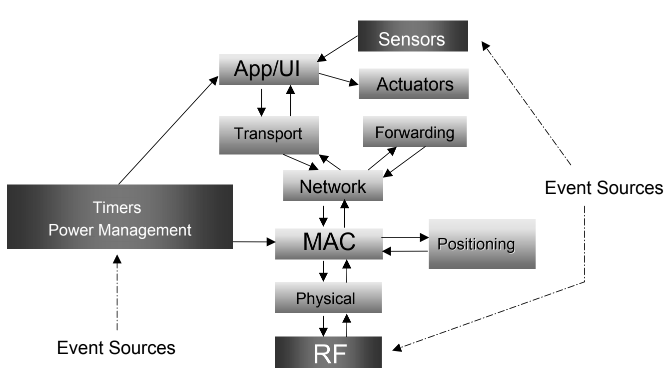

Figure 12.3.5: Block diagram of sensor node.

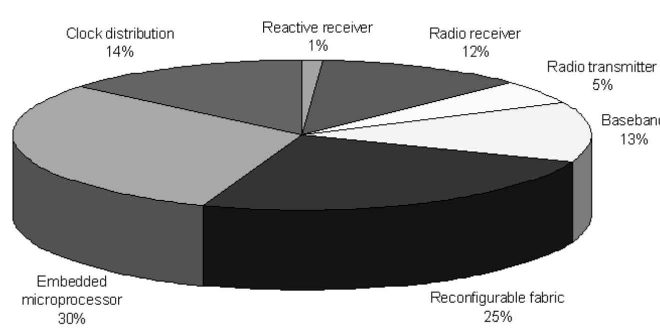

Figure 12.3.6: Projected distribution of energy-consumption.

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