27.1 A 65nm Energy-Harvesting ULP SoC with 256kB Cortex-M0 Enabling an 89.1uW Continuous Machine Health Monitoring Wireless Self-Powered System

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This paper presents a system-on-chip (SoC) that enables commercial self-powered systems (SPSSs) by flexibly managing application needs, harvesting energy from multiple modalities, coordinating low-latency/high-density network communication, and optimizing power across the system. To scale to a trillion IoT nodes, devices must untether from batteries by achieving energy autonomy. A SPSS must balance harvested power (PH) with load power (PL) to enable continuous operation, which becomes challenging in real-world harvesting conditions for applications with stringent functional needs. While this SoC can support many IoT applications, we demonstrate the SoC in a machine health monitoring (MHM) product that uses multi-modal sensors to forecast motor failure to minimize downtime.

Figure 27.1.1 shows a system block diagram for the SoC in the MHM product, which has a 49x48x81mm3 enclosure including the antenna, and enables continuous sensing even in poor harvesting environments. Multiple mechanical interfaces enable flexible attachment of the node onto a motor. The SoC has an ARM Cortex-M0 microcontroller (MCU) to execute application code, clocked by a crystal oscillator (OCXO) at 32.768kHz for low power. An integrated PLL scales the clock for higher speed computation and for streaming sensor data by a direct memory access (DMA) block. A 7.3728MHz OCXO provides a reference for the SoC to enable continuous operation, which becomes challenging in real-world harvesting conditions for applications with stringent functional needs. While this SoC can support many IoT applications, we demonstrate the SoC in a machine health monitoring (MHM) product that uses multi-modal sensors to forecast motor failure to minimize downtime.

The MHM product requires near-continuous assessment of the state of a rotating machine to observe potential problems in its operation or environment, but voluminous data, high transmit power, and low harvested power (PH) can preclude streaming raw data as a generic solution. To support the MHM product with its large data volume, high transmit power, and relatively low harvestable power, the authors propose a new multi-modal energy-harvesting power management unit (EH-PMU) with supercapacitor management to enable reliable batteryless operation from an electromagnetic (EM) coil, photovoltaic (PV) cell, thermoelectric (TEG), vibration, or RF energy harvesting.

An RF switch connects the WRX and TRX to one antenna for improved system interference robustness, data payload, and protection against energy or replay attacks. If the digital baseband correlates the received sync word above a threshold, it issues a fast wakeup to the MCU. For secure wakeups, the baseband demodulates a header in the physical layer and passes the secure payload through a cryptographic checksum before issuing a wakeup. The WRX also provides clear-channel assessment (CCA) and RSSI for network link quality tracking.

To enable flexible control of the node’s P0, the SoC supports DFVS into sub-V0, wide range clock control, extensive clock/power gating, accelerators for edge compute, and low voltage I/Os. The power balance in an SPS makes power optimization often more important than minimum energy, emphasizing slow low-voltage operation. The SoC includes an ADC and SRAM (Fig. 27.1.5) to operate robustly and at low power across the DFVS range. Fig. 27.1.5 shows how the SRAM combines product features like BIST and redundancy with circuit/architecture techniques (e.g. 8T cell, decoupled R/W, peripheral assist features) to enable reliable operation down to sub-V0.

The SoC is fabricated in 65nm CMOS (Fig. 27.1.7) and provides a comprehensive solution for networked self-powered nodes. Fig. 27.1.6 compares the SoC to other SoCs when using AES. Compared with duty-cycled high-power TRXs with clock drift, an always-on WRX provides lower power time synchronization for dense low-latency networks, especially with shorter intervals between WRX beacons. However, a correspondingly higher uplink packet rate increases the uplink collision rate, requiring retransmission and raising average power in the sense node. A wideband WRX beacon also provides initial frequency synchronization between gateway and sense nodes, allowing the gateway to frequency hop.

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References:
Figure 27.1.1: System block diagram showing the SoC in a commercial self-powered sense node for continuous machine health monitoring (MHM).

Figure 27.1.2: State flow diagram and measured self-powered system current profile for an application example of machine health monitoring, which uses multiple sensors to detect, analyze, and report machine status.

Figure 27.1.3: Energy-harvesting power management unit (EH-PMU) with measured cold-start waveforms from TEG and PV harvesting modalities.

Figure 27.1.4: Simulated performance of the network protocol with the proposed physical layer and supporting WRX architecture.

Figure 27.1.5: SRAM banks and 8T bitcell for DVFS into sub-V, with tables enumerating SRAM and SoC power saving features.

Figure 27.1.6: Performance and comparison table with other ULP and SPSs.
Figure 27.1.7: Die photo of the 65nm self-powered SoC.