SiP Wireless Micro-Power Sensors

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Abstract: *This paper presents the key design challenges encountered in system-in-package (SiP) wireless sensors. These sensors show tremendous promise for the test and evaluation of military equipment. These sensors should be small and autonomous to maximize utility; in this environment, energy management and system integration pose the greatest challenge. Fundamental limits exist on the amount of power required to process and transmit a signal a given distance with given accuracy, and approaching those limits requires careful energy use. Incorporating all necessary components on-chip or in-package will require examining the trade-offs between volume and energy in many cases, as well as processing and packaging technology limitations. To illustrate these constraints, they are evaluated in the context of designing an EMI sensor.*

Keywords: Wireless Sensors; Low-Power Electronics; RF Integrated Circuits; System-in-Package (SiP)

I. Introduction

Wireless sensors have countless uses in military, space, medical, and commercial applications. One particularly useful area is in the test and evaluation (T&E) of military equipment, for example, the effectiveness of EMI shielding of RF-sensitive equipment. Normally, shielding is tested once and put in the field. However, activity can damage or misalign the shielding, causing performance degradation. By studying this degradation *in situ*, more rigorous designs can be created.

This study can be accomplished using discrete, autonomous sensors throughout the system to gather necessary data. To remain non-obtrusive and increase sensor density, they must be confined to a less than 1cm^3 system-in-package (SiP). To remain autonomous, the sensor must include both an in-package energy source and functionality for wireless data transmission with zero maintenance. To be of maximum use, these sensors should have a lifetime of a year or more.

The objective of this paper is to identify the key challenges of working with a small-volume, micro-power system, as highlighted in Section II. Sections III and IV will discuss sensor and wireless transmitter circuitry that address these challenges, and Section V concludes.

II. Key Challenges for Wireless Sensors

A wireless sensor system is shown in Fig. 1. Each sensor has an interface that conditions the signal. One sensor output is selected at a time to be converted into digital form in the analog-to-digital converter (ADC). A micro-controller reads and writes data from and to memory and controls component duty-cycling. A transmitter allows data to be sent wirelessly to a base station, and a receiver processes communication from the base station. The entire system must be contained within a 1cm^3 package and wirelessly transmit stored data periodically for a year or more. These constraints place two main challenges on the designer: energy management and system integration.

Energy Management: The requirement that the system have a long lifetime with zero maintenance places tough limits on energy. The energy source must fit the tiny system dimensions and be autonomous (e.g., no user-initiated recharge). One option is the inclusion of a harvester in the system, which would extract energy from ambient temperatures, vibrations, etc., thus providing a "limitless" source of energy [1]. However, harvesting is not reliable from moment to moment or across environments. An option that can be used nearly anywhere and at anytime at the expense of "limitless" energy is an integrated storage device such as a battery, fuel cell, or ultra-capacitor. These devices can be evaluated in terms of their "energy density," or the amount of total available energy per unit volume, and "power density," or the maximum deliverable power per unit volume. Batteries, such as thin-film lithium-ion cells, are capable of delivering energy at a relatively fast rate (high power density), but quickly lose their state of charge (low energy density). Fuel cells, in contrast, have a high energy density but are very limited in the amount of current that can be drawn (low power density). While some micro-power applications could manage on the limited power capabilities of fuel cells, the addition of telemetry to the sensory system demands fast energy delivery (high power density). To take advantage of the benefits of both battery and fuel cell capabilities, a hybrid power supply is being developed for use in micro-power sensors [2].

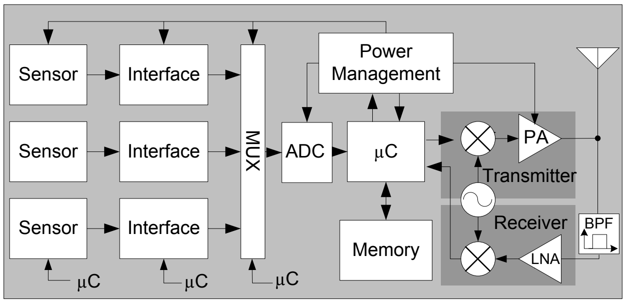

Figure 1. Wireless sensor system.

Regardless of power delivery method, tiny dimensions translate to tiny power budgets. Working at micro-power levels creates design trade-offs between data quality and lifetime. Analog measurement has fundamental power limitations set by signal bandwidth, signal-to-noise ratio (SNR), and gain requirements [3]; therefore, there is a tradeoff between power and signal distortion due to aliasing, noise, and feedback error. Micro-power design also eliminates some sensors from being used, since either sensing or signal conditioning may require excessive amounts of power. If any signal conditioning, such as linearization, can be done at a later time, it should be postponed until transmitted to a device with more available power. Requiring more power to sense will translate into a lower allowable duty cycle (the percentage of time the sensor can be on).

In contrast, the transceiver system will have the greatest impact on the peak power demands of the system. From the Friis equation, to transmit a signal a distance d to a receiver at a frequency f and bandwidth BW and to ensure a given SNR, the required power from the battery is

$$P_{batt} = \frac{\left(\frac{4\pi df}{c}\right)^2 kT(BW)(SNR)}{\eta_{PA}\eta_{Ant}^2(1-|\Gamma|^2)}, \qquad (1)$$

where η_x is the efficiency of the power amplifier (PA) and antenna, Γ is the reflection coefficient between the PA and antenna, c is the speed of light, and kT is the characteristic energy [4]. For reliable communications, the Shannon theorem specifies a minimum SNR:

$$SNR_{\min} = 2^{BR/BW} - 1, \qquad (2)$$

where BR is the bit rate [4]. Thus, power can be limited only by designing for maximum efficiency and keeping distance, data rate, and duty cycle low. Transmission under 10m, 10kb/s, and less than once per day should be expected.

This analysis assumes the transmitter dominates power budget. In reality, the receiver can equal or surpass the transmitter in micro-power short-range applications because of the increased complexity, linearity, and duty cycle of the receiver [5]. This can be reverted if the sensor need only receive minimal commands from a base station to wake-up and transmit stored data. Further functionality, however, would be required if sensors are to communicate with each other over a network, in which case receiver power needs escalate drastically.

System Integration: Fitting all necessary components into a small package presents a great challenge. As already stated, the energy source must be in-package. While many sensors can be integrated on-chip in a standard CMOS process, others require a MEMS process to fabricate, which may not be compatible with the interface (CMOS) process, requiring a multi-chip solution. Telemetry functionality requires additional off-chip components. At least one antenna must be included in- or on-package. The small dimensions will only allow antennas to efficiently radiate at 30GHz or more, while CMOS circuits are limited to 1GHz or less due to parasitics, resulting in large inefficiency. Many RF circuits also require large passive components for matching, biasing, and resonance. These components must have low parasitic resistance (ESR), expressed as a high "quality factor", Q, to limit power dissipation, noise injection, and signal distortion:

$$Q = \frac{|X|}{ESR}, \qquad (3)$$

where X is the reactance of the component at the operating frequency. While good quality capacitors up to 100pF can be fabricated on-chip, inductors are limited to at most 100nH of $Q < 5$. In contrast, surface mount inductors can provide more than 1μH at a Q of 25-50 [6]. One must thus choose between saving power or footprint.

III. Sensor Sub-System

The power needs of any self-powered SiP wireless sensor must be low enough to sustain reasonable lifetimes. This includes not only the sensor itself but all supporting electronics, including any signal conditioning, analog-to-digital conversion, and memory storage. To increase utility and decrease cost, package dimensions and footprint must conform to micro-chip scale dimensions. The quality of the sensor must also be on par with larger state-of-the-art counterparts.

Most sensors fall into four classes. Transistor-based sensors are low power, system-on-chip solutions. Capacitor-based sensors consume zero power, but are constructed in a MEMS or other exotic process, often resulting in a multi-chip solution. Resistor-based sensors exhibit a trade-off between power and area consumption; since what they are sensing can often also be accomplished using a transistor- or capacitor-based design, they should be avoided when possible. Antenna-based sensors are the most challenging to incorporate into an SiP micro-power system, since they will require an in- or on-package antenna and an RF (high power) front-end.

For the EMI sensor, the chosen topology is an antenna-based RF power detector (Fig. 2a). Incident EMI is amplified, rectified into a DC signal, and then logarithmically compressed and subtracted from a reference signal to compute attenuation. To measure the state of the system, transistor-based temperature and capacitor-based pressure sensors are also included. The temperature sensor is based on the temperature dependence of the voltage across a diode (PTAT), and can be implemented as a fully-CMOS design at very low power levels (Fig. 2b). The pressure sensor is a MEMS membrane whose distance from the substrate (and thus capacitance) changes inversely with pressure (Fig. 2c).

The rest of the system is made up of an interface for each sensor, which provides gain to allow for efficient rail-to-rail operation and increase the signal's dynamic range, and an ADC. Analog-to-digital conversion is important as it allows the largest power consumer – the transmitter – to be duty-cycled since data can be stored in a robust form for later retrieval. Other signal conditioning, such as offset reduction, linearization, and temperature compensation, should only be performed if it can be done without consuming power (for instance, improved transistor matching). Otherwise, it should be delayed (if possible) until transmitted to the base station. Since the signal bandwidth of EMI, temperature, and pressure are assumed to be quite low (and in general, most other parameters of interest will be below 100Hz), a serial topology is chosen for the ADC, since fewer components mean less power when operating at low clock rates (for example, an 8-bit ADC would require only 25kHz when dealing with signals below 100Hz). In particular, Sigma-Delta modulation schemes are most attractive because of accuracy and resolution and simplicity and resulting compactness, which translates to low power demands and, consequently, longer life [7].

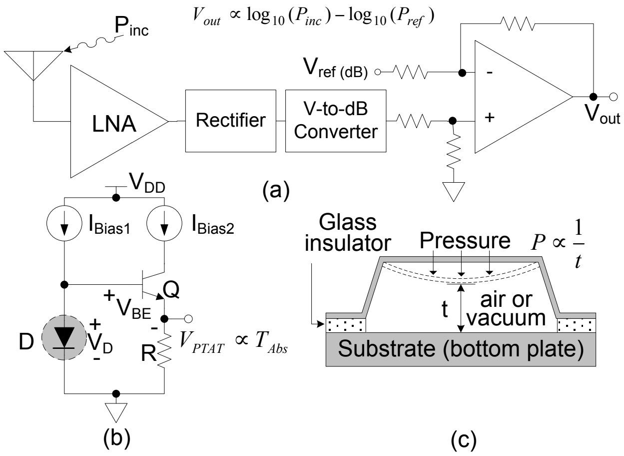

Figure 2. (a) EMI Detector; (b) PTAT temperature sensor; (c) MEMS pressure sensor.

IV. Transmitter Sub-System

To relay the information gathered by and facilitate communication with the sensor, an in-package telemetry function must be included. The transmitter generates a carrier signal, modulates it with stored information, and drives it onto an antenna [8]. From equation (1), the most crucial components in terms of power and/or area are the PA and antenna.

Modulation: Tight power budgets considerably limit modulation frequency and scheme [4, 6]. Current low-power protocols utilizing "spread spectrum" techniques, such as Bluetooth and Zigbee, were developed for portable devices whose power source is generally a rechargeable battery, which can support the microprocessors required for implementation. Given the expected low distance, data rate, and duty cycle, however, simpler schemes, though spectrally wasteful, save energy at the expense of (unnecessary) bandwidth [9].

Of these simpler schemes, On-Off Keying (OOK) and Frequency Shift Keying (FSK) are the most promising. OOK uses less power since it is implemented by either transmitting the carrier or not, depending on the bit state [8]. In contrast, FSK, which switches between discrete frequencies to represent information, requires more power and chip area to implement, but is more robust in the presence of noise [10]. Since it is known the EMI sensor will be operating in a low-interference environment, OOK is the best selection for simplicity and power consumption.

Modulation requires an oscillator to generate a carrier and a mixer to add information to it. Harmonic (LC tank) oscillators are very efficient; however, this efficiency comes at the expense of required off-chip, high-Q inductors. Since package area is severely limited, a ring oscillator, consisting of an odd number of CMOS inverters in feedback, is an area-efficient option, albeit with poorer performance and possibly greater power consumption. Mixing can be either passive or active; passive mixers (switches) have a low input impedance, but are preferred in many cases due to a lower power consumption and noise injection and higher linearity.

Power Amplifier: To drive the signal onto an antenna, a power amplifier is used (Fig. 4a). PAs can be either linear or non-linear. Linear PAs such as classes A and B utilize analog devices, operating with high linearity at the cost of efficiency. However, OOK and FSK modulation require little linearity due to their constant-envelope nature, and thus efficiency can be gained by using the input device as a switch, as in classes D and E/F. Class D PAs resemble digital inverters, and require no off-chip components to implement (Fig. 4b). However, they can become lossy at RF frequencies. Class E/F PAs attempt to eliminate switching losses by adding passive components to tune current and voltage waveforms in such a way that there is no overlap when the active device is switching (and thus no real power loss). This requires the introduction of large capacitors and inductors, however, demanding off-chip components. Since area in our system is tight due to the integrated fuel cell, a class D PA is chosen.

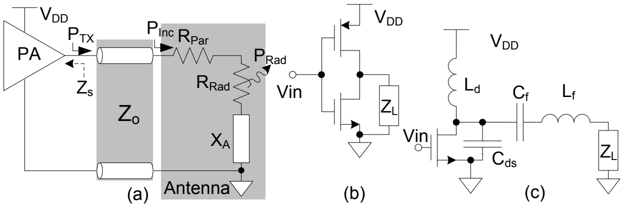

Figure 3. (a) Antenna model; (b) class D and (c) E/F PAs.

Antenna: The radiation efficiency of an antenna is determined in large part by its geometry; if the length is equal to or greater than the driving wavelength, a majority of incident energy will be radiated (high radiation resistance). When limited to 1cm^3, however, this specifies a carrier frequency of 30GHz or more. From a circuits perspective, this high frequency will entail a high operational frequency (and thus high power); further, CMOS technology limits useful device operation to around 1GHz. A compromise that also meets FCC requirements places operation in the 900MHz ISM band.

Here, efficiency will be limited to 10% or less [11]; if better efficiency is required, then a more expensive GaAs or SiGe process will be necessary.

V. Conclusion

Discrete, autonomous sensors can be employed throughout a system for data gathering. To remain non-obtrusive and increase sensor density, they must be confined to a 1cm^3 package or less. To remain autonomous, the sensor must include both an in-package energy source and functionality for wireless data transmission with zero maintenance with a long lifetime. These restrictions place two main challenges on the designer: energy management and system integration. While micro-power design techniques can greatly lessen required power, there are fundamental limits set by accuracy and transmission distance requirements. Some sensors will require MEMS or other processes that result in a multi-chip solution, and telemetry functionality will require an antenna and possibly (high quality) off-chip inductors.

An EMI sensor is considered in such an environment. The sensor itself is antenna-based, requiring an in- or on-package antenna and an RF (high power) front-end. To more fully assess the environment, atmospheric temperature and pressure may be measured. Temperature is sensed in a transistor-based sensor, which can be small and low power and is the best sensor class for micro-power, SiP systems. Pressure is sensed via a capacitor-based sensor, which consumes no power but may pose a challenge to integration. Very little signal conditioning is done in-package due to power limitations. Gain is provided to increase processing efficiency and dynamic range, and analog-to-digital conversion is performed to allow for duty-cycled transmission. The ADC is a serial, sigma-delta topology, preferred for low power consumption and simple architecture.

To relay the data to a base station, telemetry functionality is included. The selected protocol is OOK, since it consumes minimal power and has a simple implementation. The bandwidth efficiency of “spread spectrum” techniques is unnecessary in the low-data-rate, low distance communications expected. Receiver architecture is kept to a minimum to reduce power consumption. The transmitter consists of a PA, oscillator, mixer, and antenna. The PA is a switching (high-efficiency) class D amplifier. Class E/F can deliver higher efficiency, but at the expense of package volume due to required off-chip components. For similar reasons, a less efficient, but more compact, ring oscillator is chosen in favor of a harmonic oscillator. The antenna must be in or on-package, which translates to small wavelengths. However, since the desired process is CMOS, the carrier frequency is limited to 900MHz (ISM band), resulting in a lossy antenna.

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