SiP Integration of Intelligent, Adaptive, Self-Sustaining Power Management Solutions for Portable Applications

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Abstract—**Power management is an essential component of any electrical system, and nowadays a limiting factor in the miniaturization of portable electronic devices. Not only are the battery and power components difficult to integrate but their performance requirements in mobile environments are more stringent. And although point-of-load (PoL) regulation techniques and monolithic controllers are industry standards today, more integration is indispensable. To address these issues, system-in-package (SiP) self-renewable energy source and storage devices are proposed alongside an array of circuit techniques designed to circumvent the shortcomings of such a miniaturized environment, like smart load-sharing schemes, customizable and self-adaptive PoL regulators, active inductor and capacitor multipliers, and robust self-calibrating and self-stabilizing dc-dc converters. On their own, each seeks to push the limits of integration while maintaining and many times improving performance. As a whole, they promise the birth of a new generation of ICs.**

I. INTRODUCTION

The demand for high-performance portable electronic devices such as laptops, cellular phones, and digital cameras continues to grow and expand at an unrelenting pace, forcing ICs to pack an increasing number of functions into ever-shrinking form-factors under severe power and cost constraints. Wireless ad-hoc micro-sensing networks, for instance, embody such stringent demands because miniaturization, optimum performance, and long operational life are all essential. However, power management blocks like switching power supplies and batteries do not conform well to this trend, not to mention that scalability is compromised by large power passives, noisy on-chip switches, and reduced capacity of energy storage and source elements. To satisfy these requirements, system-in-package (SiP) and system-on-package (SoP) integration solutions are not only attractive but also necessary.

Monolithic integration of switching power supplies, built-in energy sources, and point-of-load (PoL) management architectures are today's solutions to increasing system complexities. Current research promises an even greater degree of integration in the future, from *in situ* SiP energy harvesters, micro-fuel cells, and thin-film lithium ion (Li-ion) micro-batteries to high ripple-rejection, customizable, and dynamically adaptive regulators; inductor and capacitor multipliers; and high bandwidth self-learning and self-stabilizing switching dc-dc converters, which will be discussed in the following sections. The basic goal is to push the miniaturization limits of total system integration, circumventing the need for external energy sources and large power passive components.

II. ENERGY SOURCES

Wireless SiP micro-sensors present a driving example of an application that fully benefits from the integration trends of power management blocks. Volume constraints limit the amount of energy that can be stored in chip-compatible micro-batteries, resulting in short operational life. Battery replacement and/or external recharge cycles are impractical because of limited access, spatial distribution,

and sheer number of micro-sensors in a network [1]. Overcoming these challenges requires a long-lasting, self-renewable *in situ* energy source that continuously replenishes the system at the rate the energy is lost [2]. When combined with a micro-fuel cell, the result is a long-lasting, versatile, and efficient in-package energy source compatible with the micro-sensor system, as shown in Fig. 1.
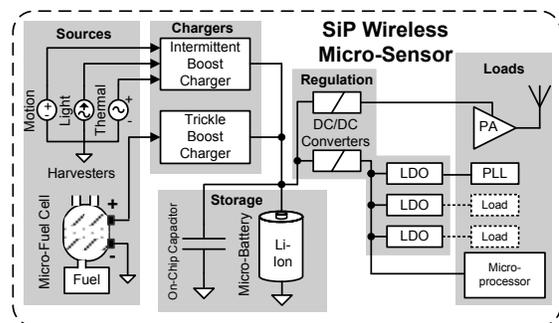

Figure 1.   Proposed system-in-package (SiP) power management architecture.

A. Energy Harvesters

To replenish the system with energy and extend its lifetime, harvesters harness energy from the surrounding environment. Light, vibration, and thermal energy is harvested via state-of-the-art photovoltaic, thermoelectric, and other in-package micro-electromechanical system (MEMS) generators [2-3]. Energy is subsequently transferred and stored in a reservoir (e.g. thin-film Li-ion battery). As a result, energy that is typically lost to the environment is added back to the system, providing a virtually inexhaustible and boundless energy source. In this manner, the lifetime of the micro-sensor is no longer dependent on the amount of energy initially stored but on its wear life.

Given the unpredictable nature of the environment, the harnessed energy manifests itself in irregular, random "bursts." Therefore, a discontinuous, intermittent boost charger is necessary to interface the energy-harvesting devices with the Li-ion battery [2]. The charger must harness sporadic trickles of energy and efficiently store them as usable electrical energy in a micro-battery, while meeting battery voltage and charging requirements. Given the low power levels expected, the high efficiency of the charger is paramount to maximize the amount of usable energy harnessed.

B. Hybrid Energy Supply and Storage

Although energy-harvesters theoretically provide an inexhaustible energy source, their intermittent nature and low power levels preclude them from fully supplying the power needed. A combination of different energy sources and storage elements is therefore necessary to accommodate the widely variable loading demands.

SiP-compatible micro-fuel cells, thin-film Li-ion batteries, and capacitors comprise the proposed hybrid solution. Micro-fuel cells fabricated on a silicon wafer via MEMS technology promise to provide high energy densities, surpassing the capabilities of other micro-storage technologies [4-5]. The major drawback is their relatively low power density, as shown in Fig. 2(a), which is effectively the result of high internal resistance. Thin-film Li-ion batteries, on the other hand, have higher power densities with relatively low self-discharge and long cycle life. They are capable of supplying the "burst" power loading demands that the micro-fuel cells cannot [6]. Finally, the ultra-fast load currents that neither technology can sustain are supplied by capacitors, which have low energy densities.
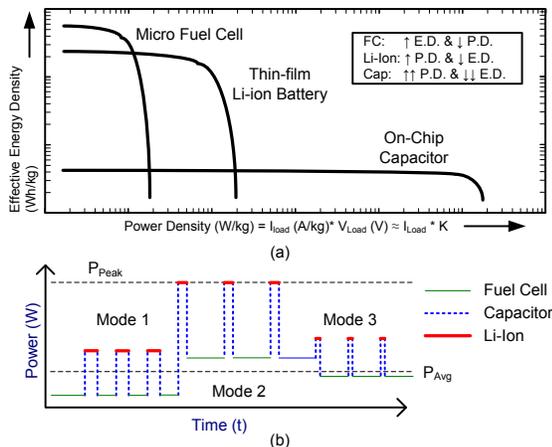

Figure 2. (a) Ragone plot and (b) a typical pulsed-power load profile.

Each energy source features complementary energy-power characteristics, which are combined and conformed to match the various load modes [7]. For example, micro-fuel cells can source the average power required by the system (Fig. 2(b)). When the load drops below the average (e.g., Mode 1), the power difference is used to charge the Li-ion battery through a trickle boost charger. Conversely, when the load exceeds the average output power (e.g., Mode 2), the Li-ion battery supplies the difference. Meanwhile, all fast transients are handled by a capacitor. The end result is a hybrid solution that is capable of handling both low and high load currents at maximum energy levels and, when combined with energy-harvesters, a versatile, virtually self-sustaining solution is realized.

III. POWER MANAGEMENT

A. Point-of-Load (PoL) Regulation

Point-of-load (PoL) architectures are a means through which diverse performance specifications are addressed while simultaneously decoupling noise generators from noise-sensitive blocks in a highly integrated environment [8]. In this strategy, a number of switching and/or linear regulators provide power to individual system sub-blocks at their respective sites. Each PoL regulator can be customized to cater to the critical needs of their specific loads, thereby enhancing power efficiency (i.e., long battery life) and supply performance (i.e., load requirements). The PoL strategy naturally distributes the power sourcing and therefore the heat generating devices, providing the added feature of a thermally balanced package. To illustrate how PoL can filter noise and reduce power losses, a noise-sensitive (e.g., phase-locked loop – PLL) and a power-intensive (e.g., power amplifier – PA) block are discussed next.

1) High PSRR Supply for PLLs:

Noise suppression in a component-dense environment, typical of portable devices, is critical for more efficient and controlled power management. For example, noise in the power supply of a voltage-controlled oscillator (VCO) produced by the switching action of the phase-frequency detector and charge pump is a significant cause of PLL jitter [9]. For this reason, the VCO-dedicated regulator must exhibit high power supply rejection ratio (PSRR) performance over a wide band of frequencies. Since a noise-free output is critical, a linear regulator is best suited than its switching counterpart. However, the regulator's loop gain and output capacitor shield the output from supply ripple only at low and high frequencies, respectively. PSRR performance severely degrades at intermediate frequencies, near the vicinity of the regulator's bandwidth. As a result, a charged-pumped NMOS cascode device is proposed, as seen in Fig. 3 [9-10]. Charge pump CP_C boosts the voltage at the cascode transistor's gate to circumvent the undesired gate-source voltage drop and reduce the power-consuming on-resistance of the NMOS. The low current-carrying RC network filters the charge-pump and supply noise before it reaches the NMOS gate.
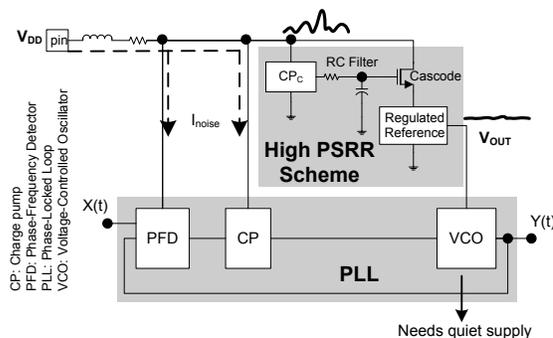

Figure 3. High PSSR PoL reference/regulator PLL system.

2) Dynamically Adaptive Supplies for PAs:

Within portable wireless devices, the power amplifier (PA) generally consumes most of the power and energy available, and its efficiency therefore significantly affects the operational life of battery-driven low-power applications, as in the case of a self-sustaining transceiver sensing node. Linear PAs unfortunately exhibit relatively low power efficiencies, especially when considering that the radio frequency (RF) signals they process have a non-constant envelope [11-13].

To increase PA efficiency, an envelop-tracking switching regulator can be inserted between the input supply and the linear PA. In this fashion, PA power consumption is reduced during low power conditions [12-13]. However, for high bandwidth envelop signals, the regulator's efficiency is compromised by high switching losses. Power tracking, which adjusts the supply voltage of the PA according to the average power of the RF input signals, is a middle-of-the-road solution because, on the average, PA efficiency is increased (but not as much as the envelop tracked PA) and supply bandwidth and therefore switching losses are reduced. Some signal peaks, however, are clipped under this scheme, inducing a tradeoff between power efficiency and bit error rate (BER). To mitigate this tradeoff, the nonlinear, dynamically adaptive PA supply shown in Fig. 4 is proposed. The scheme reduces the power tracking levels of the main low bandwidth path by having a fast nonlinear path handle the peaks, thereby increasing efficiency and maintaining signal fidelity.
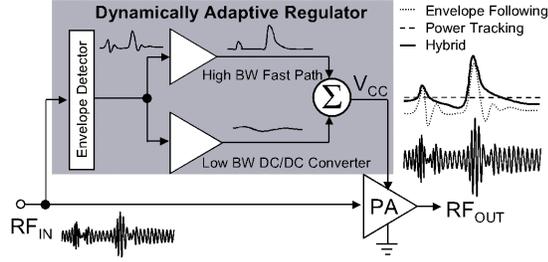
Figure 4. Nonlinear, dynamically adaptive PA switching supply.

B. Power Passives

1) Physical Integration:

A complete, self-contained micro-sensor solution, like most other systems, requires the integration of large, bulky power passive components. These components must be carefully placed alongside the active circuitry to minimize parasitic effects and therefore decrease power losses. Consequently, the integration of power passives within the application package does not only help miniaturize the system but also increase efficiency and as a result extend battery life.

Fabrication techniques to integrate inductors are currently under development in industry and academia [14-16]. Adding magnetic layers to standard CMOS processes has produced inductors of hundreds of nano-henries with various equivalent series resistances (ESR). Integrating the largest possible inductor, however, is not necessarily the best solution because it usually implies higher ESR and consequently higher conduction losses. Larger inductors also typically saturate at lower currents, a property that makes them poorly suited for high power applications. Enhancing the effects of smaller integrated inductors with active circuitry is therefore proposed.

In its simplest form, when applied to a switching regulator, a ripple current cancellation circuit is used to decrease the output current ripple and therefore increase the effective inductance of a small integrated inductor, which is the inductor multiplier shown in Fig. 5. In this way, the low resistive and soft saturation characteristics of smaller inductors can be exploited in practical applications. Similarly, this multiplicative effect can also be applied to capacitors [17]. A few authors have already documented this ripple canceling approach [18-20] but only recently has it been applied to test them in fully integrated switching regulator applications [21-22]. The main drawback is the power consumed by the current-canceling circuit, which of course decreases efficiency. In the end, however, the adverse effects on efficiency are offset by the feat of integration, which by any other means would have incurred even poorer efficiencies. A practical, fully integrated solution has not yet been realized but improvements in both inductor process technology and multiplier circuit techniques will extend this range until a practical, fully integrated switching regulator is possible.
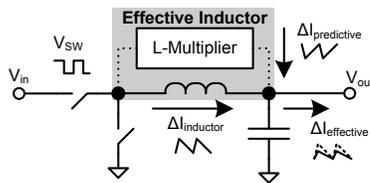

Figure 5. Active power inductor multiplier.

2) Self-Learning and Self-Calibrating Converters:

The integration of high-value power passives for moderately powered portable applications (i.e., 1-5 A) may not be feasible in the near term, not to mention that an external power L-C filter is also attractive for design flexibility at the board level. If these L-C values were preset and known, the compensation network and current-sensing circuits, which are traditionally implemented off-chip, can be developed monolithically. In practice, however, the IC designer cannot predict what the board designer will require, given the application-specific nature of the various systems, which makes monolithic integration of the compensation network and current-sensing circuit difficult. Similarly, if a system-on-package (SoP) micro-sensor approach is undertaken, power passives will be fabricated separately and attached to the sensor package and their values will unfortunately vary widely over process and temperature, making it equally difficult to design for. To overcome this variability, self-learning current sensing and self-stabilizing converter circuit techniques are proposed.

High-performance portable devices demand intelligent, monolithic, lossless, and accurate current-sensing circuits for protection and feedback control of switching regulators [23]. Lossless schemes require solutions to predict currents exclusively from node voltages (sensing current is itself the problem) and, for accuracy, branch impedances must be known (Ohm's law) [23]. Matching an L-ESR filter response to an internal g_m-C filter response during start-up amounts to measuring the impedances above mentioned, which is what is proposed in [24-25] (Fig. 6). First, the bandwidth is *tuned* by forcing a triangular current into the inductor and having the circuit match its internal g_m-C filter pole. After this step, the filter gain is *calibrated* by forcing a dc current into the inductor and adjusting the gain of the internal filter until they again match, after which the low-pass filter is ready to indirectly measure inductor current. Since the current-sensing circuitry is lossless (only voltages are sensed during normal operating conditions), system efficiency and consequently battery life improve.
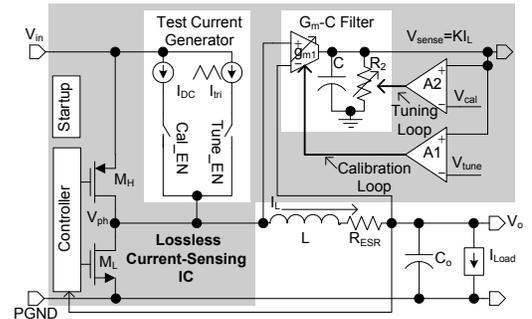

Figure 6. Proposed self-learning, accurate, and lossless filter current-sensing IC.

3) Robust and Self-Stabilizing Converter:

While measuring L-C values is one way of circumventing their variable nature, optimally and naturally adapting is another, and more specifically, self-stabilizing the converter to its L-C filter [26-27]. Simply designing for the worst-case combination implies low bandwidth and therefore poor transient response. A good solution would have its bandwidth self-adjust to the L-C environment while maintaining stability, which is what is proposed here [28].

The dual-mode, asynchronous sigma-delta ($\Sigma\Delta$) boost converter shown in Fig. 7 self-adjusts to its L-C load, which is a combination of a main low frequency signal path for steady-state operation and a bypass high-bandwidth path for fast transient events [29]. The main path yields a low steady-state ripple voltage with high efficiency

whereas the bypass path is only activated during fast transitions. Key to the fast loop is increasing the inductor current quickly, over-riding the main signal path. A smart mode-transitional block is required to smooth out the hand-shaking events of the two paths. The main speed limitation to this scheme is the slew-rate of the inductor itself, which is a fundamental constraint. Stable operation without any compensating network is observed for a wide range of L-C values, for more than 10x variation in both inductance and capacitance. The stability of a fully integrated dc-dc converter is therefore guaranteed, irrespective of the power L-C filter used.
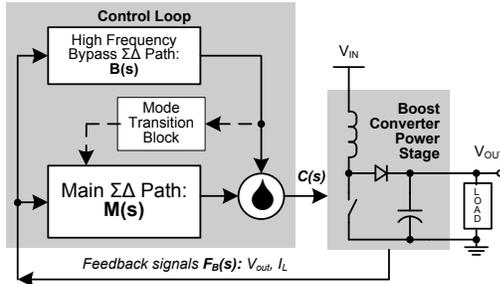

Figure 7.   Block schematic of dual-mode sigma-delta scheme.

IV.   CONCLUSION

Next-generation portable electronic devices such as micro-sensors with wireless transceiver capabilities in an ad-hoc network demand integrated power solutions that neither limits performance or battery life. To this end, a smart, power-efficient, and self-renewable system-in-package (SiP) hybrid energy source is proposed to extend the operational life of the device while flexibly supplying a wide range of power loads. Conditioning and self-adapting the power delivered at the point-of-load (PoL) improves efficiency and regulating performance. With regard to integration, exploiting the beneficial aspects of smaller integrated inductors by multiplying their effective inductances is promising, but not always viable in moderately powered portable applications, where self-learning current-sensing and self-stabilizing converter circuits can overcome the variability of external power L-C components. Real-izing a truly SiP portable solution is complex and addressing its challenges require scrutiny and careful system design. The work proposed in this paper represents the various ways in which some of these hurdles can be potentially overcome.

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