A Single-Stage, Single-Inductor, 6-Input 9-Output Multi-Modal Energy Harvesting Power Management IC for 100µW-120mW Battery-Powered IoT Edge Nodes
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Abstract
A 25MHz switching, event driven, 6-input and 9-output single inductor Energy-Harvesting PMIC (EHPMIC) with multi-modal harvesting capability from DC & AC sources delivers up to 120mW with a peak efficiency of 81.7% and only 120µW control power overhead. The high-frequency, high-bandwidth design optimally trades off EHPMIC conversion efficiency with inductor/capacitor size & transient response speed to enable the fast power state transitions demanded by the SoC in a compact IoT edge node, thus minimizing the overall platform size & energy consumption.

Introduction
IoT edge nodes continue to integrate increasingly complex sensing, compute, and connectivity capabilities into smaller form factors, while pursuing energy autonomy through multi-modal harvesting. Although average power demands of edge nodes can be reduced to µW levels, peak power & power complexity often remain high. A complex edge node platform needs 0.5V to 5V operating voltages for a variety of sensing, processing, IO and radio functions, with instantaneous power levels ranging from a few µW to 100s of mW [1]. In addition, it needs the ability to quickly transition between high power active states and low power idle/sleep states to conserve the limited amount of available energy.

High-frequency, high-bandwidth switching voltage regulators (VR) are needed to reduce inductor/capacitor size & enable fast power state transitions and supply high di/dt loads (Fig. 1a). At the same time, the conversion efficiency must be sufficiently high across a wide range of voltage & current loads. Unlike traditional VRs optimized mainly for maximum conversion efficiency [2-4], it must be traded off optimally with transient response to minimize overall edge node energy consumption & size.

In this paper, we present a single-stage, event-driven EHPMIC switching up to 25MHz and featuring fast response, high rail count multi-rail power delivery spanning wide voltage & current ranges, with multi-modal AC (Piezo) & DC (photovoltaic or PV) energy harvesting. The single-inductor, 6-input, 9-primary + 10-gated output (MISIMO) EHPMIC delivers 120 mW peak power to output rails ranging from 0.5V to 5V, with integrated battery (Fig. 1b). The 2.3mmX2.3mm 1800µW single inductor ISVC switching up to 25MHz, initially triggered by load demands, and the inductor current waveform demonstrates how the controller manages events while minimizing power overhead with minimal external component count.

Event-Driven MISIMO EHPMIC
The EHPMIC power stage (Fig. 2) consists of 17 switches to 3 DC PV harvesting inputs, one AC Piezo harvesting input, a battery, a super-capacitor for providing actively-managed power-boost, and 7 primary output rails. Three of these outputs supply an additional 10 power-gated rails for fine-grained power management in the edge node SoC [1]. The power switches are 5V NMOS/PMOS driven from the highest voltage rail (Vctrl) regulated at 5V. Whenever the MISIMO controller detects either load power demand or harvester power availability, the system generates an inductor pulse that transfers energy from one or more of the input sources (e.g. the battery/supercap or harvesters) with available energy to one or more sinks (e.g. output loads or the battery/supercap itself) that need energy (Fig. 2). The controller accepts event requests even when the inductor pulse is already ON, and arbitrates the requests to maintain all output rails in regulation as long as the total power demand is below the 120mW maximum supported by the 9.9µH inductor. The sequencing modalities of the power switches accommodate opportunistic buck-boost, using either a buck or boost average voltage transformation within each current pulse dictated by the adaptive ON-time. Within every pulse, any number of loads and/or sources can be serviced. The hysteretic comparators decide when each source or load is 'satisfied', and the controller then hands off to the next one. Any remaining energy in the inductor after satisfying all loads is returned to the battery. A zero current detector (ZCD) terminates the power transfer pulse. The controller uses ZCD events to optimize the ON-time and minimize power-return to the battery.

In order to ensure fast response to a large number of possible events while minimizing power overheads, the digital MISIMO controller is designed to operate as fast as 25MHz in a robust asynchronous manner, along with event clocker and dynamic-biased comparators. An event-detector reliably monitors 32 input signals from hysteretic input/output voltage comparators, zero-current detection, ON-time generation, etc., without a sampling clock (Fig. 1b). Each input signal change is converted into an ‘event’. Each event is XOR-detected with meta-stability filtering by the detector inside the event clocker, and held until processed by a clock pulse. A tree arbiter passes events alternately, and requests a clock for each event. When the clock generator issues a clock pulse, the events are already stable and can be clocked into the control FSM. The end of the clock pulse prompts the arbiter to move to the next event. With this event abstraction and robust synchronization, the digital control state machine can process events synchronously in reference to the internally generated event clock. When there's no event, no clock pulses are generated, keeping power consumption low in light loads. The hysteretic comparators are designed to be fast enough for load tracking while minimizing power overhead at light load (Fig. 3). Dynamic bias-assist during transients & cross-coupled gain stages are utilized to improve power-speed tradeoffs. The supply current scales dynamically with a 6-bit binary current DAC to support response times ranging from <20ns in heavy load to 100ns-2µs under light load. At the start of an inductor pulse, all comparators are switched to their lower threshold to synchronize power delivery and replenish other outputs, thus preventing frequent inductor triggers. The hysteretic comparator uses two parallel offset channels with an output mux, so that the threshold can switch without being affected by settling of the other channel.

EHPMIC Measurements
Fig. 4a shows the series of on-demand event clock pulses at about 25MHz, initially triggered by load demands, and the inductor current waveform demonstrates how the controller manages events to satisfy both 1.8V and 2.5V outputs in a single cycle. All outputs are maintained within ±1/-7% regulation window during a 4mA to 30mA loading and unloading transient on the 1.8V output rail. Droop and cross-regulation are bounded by the regulation window due to the inherent single-cycle capacitance stored in the control circuitry (Fig. 4b).

A dual-rail enable event is demonstrated where 0.65V & 0.75V rails are brought up while the 1.8V rail is maintained, thus enabling quick transition from stand-by to active modes without affecting overall system operation (Fig. 4c). On rail disable events, the EHPMIC recycles the charge on the output rails back to the battery (Fig. 4d). Output regulation on a 0.75V rail is demonstrated for a SoC load in active mode executing instructions (Figs. 4e & 4f).

PV fractional Voc harvesting is demonstrated (Fig. 5a) where the EHPMIC periodically samples open-circuit voltage for MPPT. Measurements demonstrate standalone piezo AC harvesting (Fig. 5b), and simultaneous multi-source (DC+AC) harvesting occurring within one inductor cycle (Fig. 5c), enabled by the fast controller. An inductor pulse is started to first extract energy from the PV down to pVoc, and then
switch to the AC input whenever it’s ready to harvest, with the peak detection circuit indicating that the maximum voltage has been reached. Energy is extracted until the voltage reaches 0, and then delivered to the battery.

The EHPMIC is optimized to deliver high-performance energy for fast & fine-grain power management of complex edge node SoC’s. The highest-power 1.8V & 2.5V rails achieve 81.7% & 76.3% maximum efficiencies, respectively, for 5mW-120mW output power (Fig. 6). The combined power efficiency with all rails ON and supplying proportional power is 71.9%, including control losses. Single-cell PV harvesting efficiency of 50% is achieved with 6mW delivered to the battery, including all overheads of maintaining essential voltage rails. This fully featured compact EHPMIC meets a comprehensive set of energy harvesting, power delivery & fast/fine-grain power management requirements for complex IoT edge nodes [1].

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References
[1] T. Kamik et al., ISSCC, to be presented, Feb. 2018

Figure 1: (a) SoC-type loads from real silicon (b) EHPMIC System diagram showing on-die functional blocks and all external components.

Figure 2: MISIMO Power stage schematic showing inductor waveform & possible power switch configurations for the typical events handled by the EHPMIC.

Figure 3: Dynamic Comparator Design

Figure 4: Measured event clocks, multi-rail start-up/delivery/recycling and regulation with real SoC loads.

Figure 5: Measured multi-modal energy harvesting

Figure 6: Measured regulation and harvesting efficiency, die photo, board and Comparison Table