Automated Design of Stable Power Delivery Systems for Heterogeneous IoT Systems

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ABSTRACT

Efficiently and reliably managing high quality power is a primary challenge in Internet of Things (IoT) systems. Based on current projections, future IoT will provide vast interconnectedness of embedded devices and sensors, many of which will be powered up wirelessly from spatially distributed power supplies or locally from energy harvesting sources. The energy budget, constrained by inherently lower quality of power of these non-traditional power sources, will become a critical system resource and a primary limiting factor for scalability of future IoT systems. Distributed on-chip power regulation is necessary for efficiently delivering high quality power to high performance heterogeneous integrated circuits (ICs). A multi-feedback system with distributed on-chip power supplies delivering current to billions of non-linear circuits is characterized by complex interactions among the heterogeneous power supplies and loads. These modern multi-feedback systems exhibit high design complexity and degraded stability. No straightforward method exists to efficiently design a stable multi-feedback power delivery system. An automated design and analysis flow for stable, high quality power delivery is proposed in this work based on the passivity of heterogeneous integrated systems. The algorithm is evaluated based on ISPD benchmark circuits and shows that the generated power delivery system addresses both the quality of power (QoP) and stability requirements. A distributed power delivery system is designed based on the passivity criterion and fabricated in 28 nm CMOS technology. The system is tested under a wide range of load, voltage, and temperature variations that are typical for modern heterogeneous ICs. The system exhibits high performance and stable response.

Keywords

On-chip power delivery; distributed system; LDO regulators; power conversion; stability; IoT; wireless power transfer; energy harvesting

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1. INTRODUCTION

Emerging IoT systems exhibit a wide spectrum of power requirements and switching activity patterns induced by billions of non-linear loads within numerous voltage domains of the individual interconnected IoT devices. Many of these edge devices are expected to be powered by means of energy harvesting (EH) from ambient energy sources and/or by means of wireless power transfer (WPT). Quality of the power supplied by these non-conventional energy sources is significantly lower compared with the traditional power supplies (e.g., batteries and power cords) and poses a critical challenge on efficiently delivering power in heterogeneous IoT systems. A segment of IoT system with interconnected devices powered by heterogeneous, traditional and alternative power sources, is illustrated in Fig. 1. The underlying

Figure 1: IoT power delivery system with interconnected edge devices powered by heterogeneous (EH, WPT, conventional) energy sources.

heterogeneous power delivery system of a single edge device (e.g., smartphone) is illustrated in Fig. 2.

The quality of power (QoP) in modern high performance systems is typically addressed with a point-of-load (POL) power delivery [6, 5, 4, 9]. Modern distributed power delivery system of a multi-core IC typically comprises a power management module, efficient power converters, global power distribution networks (PDNs), and on-chip voltage regulators distributed within local power grids, all delivering power to billions of non-linear loads within multiple power domains, as shown in Fig. 2. The distributed nature of modern power delivery system with many thousands of on-chip electrical components significantly increases design complexity of next generation IoT edge devices. To cope with the design

Figure 2: A typical power delivery system of a multi-core IoT edge device (e.g., smartphone)

complexity in complex analog circuits, automated modeling, optimization, and synthesis techniques are typically considered [8]. To automate the design of a power delivery system in future IoTs, accurate methods to evaluate performance metrics (*e.g.*, quality of transient response and stability) are required.

In a heterogeneous IoT system, the total load of a single power domain within a IoT edge device is shared among all of the parallel connected power supplies. The greatest portion of the total current is supplied by those voltage regulators in close proximity with the current load. This supplied current can be significantly higher than the average current supplied by a single regulator [4]. The current load of each regulator is therefore a strong function of the characteristics of the power delivery system (*e.g.*, PDN impedance, load activity, and number and location of power supplies). A distributed system with multiple low-dropout (LDO) regulators delivering power to a single grid can exhibit degraded stability due to complex interactions among the LDO regulators, power distribution network, and shared current loads. The many challenges involved with absorbing energy from heterogeneous non-conventional EH and WPT sources reduce the reliability of the power supplies within the individual edge devices, further reducing the stability of multi-feedback power delivery systems. The stability of IoT power delivery systems is therefore a primary concern and needs to be accurately evaluated.

A distributed power delivery system with multiple power supplies driving a single power grid is depicted in Fig. 3. The stability of a single closed loop system is traditionally determined by the phase margin of the open loop response. In systems with multiple dependent loops, the open loop approach is not practical because no straightforward method exists to identify the unstable loop. An alternative stability criterion has recently been proposed that imposes a passivity condition on the power grid impedance [10]. Based on this passivity-based stability criterion (PBSC), accurate system requirements for evaluating exponential and marginal stability in distributed power delivery systems are provided. Automation of the design process of a power delivery system is proposed in this work based on the PBSC and parametric circuit performance modeling technique.

The rest of the paper is organized as follows. The stability criterion for distributed power delivery is reviewed in Section 2. Automated design of a stable distributed IoT power delivery system is described in Section 3. Experimental results are presented in Section 4. The paper is concluded in Section 5.

Figure 3: Model of distributed LDO regulators and power distribution network.

2. PASSIVITY-BASED STABILITY OF DISTRIBUTED SYSTEMS

Understanding the effects of the frequency domain parameters on the time domain characteristics provides significant insight into the transient behavior of complex systems. Traditionally, the phase margin of the output response determines the transient stability of a single LDO regulator. Similarly, a criterion is required for determining the stability of a *distributed* power delivery system.

A distributed power delivery system with two or more power supplies driving a single power grid is depicted in Fig. 4(a). In this distributed system, the power supplies can be combined into a single power delivery system, yielding an equivalent single port network, as shown in Fig. 4(b). Note that the output impedance of the equivalent single port network, Z_{TOT} in Fig. 4(b), is the parallel combination of all

Figure 4: Power delivery system (a) with two or more distributed power supplies, and (b) reduced single port network.

of the output impedances $Z_i, i = 1, \dots, N$ of the individual power supplies shown in Fig. 4(a). Similarly, the output impedance of a distributed power delivery system is based on the individual output impedance of the parallel connected elements. The open loop transfer function, traditionally used to determine the stability of a lumped power delivery system, cannot be applied to a distributed power delivery system with multiple control loops. An alternative criterion for evaluating the stability of a multi-feedback path system composed of distributed power regulators has recently been proposed [10] that describes sufficient conditions for stability of a distributed power delivery system. These conditions are based on the observation, that a linear, time-invariant (LTI) system is stable when coupled to an arbitrary passive environment if the driving point impedance is a passive system. A distributed power delivery system is therefore stable if the equivalent output impedance Z_{TOT} satisfies passivity requirements, yielding the following passivity-based stability conditions:

- $Z(\omega)$ has no right half plane (RHP) poles.
- The phase of $Z(\omega)$ is within the $(-90^\circ, 90^\circ)$ range.

A distributed system is, therefore, exponentially stable (converges within an exponential envelope) if the impedance of the system satisfies these passivity requirements, marginally stable (oscillates with constant amplitude) if the voltage and current phasors are shifted by precisely 90° , and unstable otherwise. The phase of the output impedance is an efficient alternative to determine the stability of these distributed systems, since the traditional phase margin approach is not practical due to the multiple control loops.

3. CIRCUIT PERFORMANCE MODELING

Existing automated techniques for designing analog circuits are based on numerical optimization and evaluation engines [8]. Parametric models characterize the performance of an analog circuit (*e.g.*, gain, bandwidth (BW), slew rate (SR), or phase margin (PM)) based on circuit design variables (*e.g.*, device sizes and voltage biases) [8]. The performance of an individual power supply is typically determined by a set of parameters, such as the DC gain, phase margin, DC offset, slew rate, and power. Alternatively, a distributed power delivery system should be evaluated based on both the performance of the individual power supply and additional performance metrics of the combined system, such as the *passivity of the output impedance*. To reduce the design complexity of modern distributed power delivery systems, the proposed PBSC is integrated within an automated design methodology.

An automated flow for designing a stable distributed power delivery system is shown in Fig. 5. The first stage of the proposed flow is based on a standard parametric performance modeling technique [8]. During this stage, an LDO regulator is synthesized based on the specific LDO topology and design objectives. The output of the first stage is used during the second stage to determine the number and location of the parallel connected power supplies in the proposed distributed power delivery system. During this second stage, a distributed power delivery system with a different number and location of voltage regulators is iteratively evaluated based on the proposed PBSC and distributed power

Figure 5: Automated PBSC-based design flow for a distributed power delivery system.

supply placement algorithms [4]. During each iteration, the worst case load sharing scenario is determined for the specific power delivery system. The PBSC of the distributed system is evaluated based on the individual current loads. If required, the number and location of the power supplies are updated. Finally, the number and location of the parallel connected power supplies that satisfies both the QoP and stability requirements of the distributed power delivery system are determined.

The operation of the second stage of the automated PBSC-based design flow is demonstrated here based on the ISPD placement benchmark suite circuits [2]. The floorplan of the superblue5, superblue10, superblue12, and superblue18 circuits is illustrated in Fig. 6. Each of the circuits is composed

Figure 6: Floorplan of ISPD circuits [2] (a) superblue5, (b) superblue10, (c) superblue12, and (d) superblue18.

of thousands of fine grain rectangular shapes. To reduce the complexity of the circuit evaluation, the fine grain shapes are combined into larger rectangular nodes. Out of the combined nodes only the largest nodes are considered, exhibiting a reduced floorplan. Magnitude of the distributed load currents is determined proportionally to the size of these nodes with a total load current of 1 A. The location of each of the current loads is determined in the center of the corresponding rectangular node. The number of the fine grain shapes, large nodes, coverage of reduced floorplan, and power grid data is listed in Table 1. Note, that the nodes in the reduced floorplan occupy more than 85% of the total active circuit area.

Ideally, a constant voltage is distributed to all of the current loads within a circuit. Practically, the QoP is degraded in modern circuits due to parasitic on-chip impedance. The voltage drop map of the superblue5 circuit without on-chip power supplies is shown in Fig. 7, yielding a maximum voltage drop of 23.4%, assuming off-chip voltage supply of 1 V.

Table 1: Properties of ISPD benchmark circuits.

circuit	Number of fine grain shapes	Number of large combined nodes	Coverage of reduced floorplan	Power grid size	Number of nodes in the power grid
superblue5	29,736	129	85.0 %	774 × 713	551,862
superblue10	2,318	30	89.2 %	638 × 968	617,584
superblue12	3,578	15	98.4 %	444 × 518	229,992
superblue18	6,776	71	99.5 %	381 × 404	153,924

Figure 7: Voltage drop map of the superblue5 circuit.

To address the quality of on-chip power supply, power delivery systems with a single on-chip power supply (case 1), six on-chip power supplies (case 2), and twelve on-chip power supplies (case 3) are considered. For each of the three cases, IR drop of the distributed power delivery system is analyzed based on the IR drop algorithm for a power grid with multiple power supplies and current loads [3]. The location of power supplies in cases 1 and 2 is modeled as a mixed integer nonlinear programming problem [4], and optimized based on the general algebraic modeling system (GAMS) [1]. In case 3, the power supplies are uniformly distributed on-chip. Stability and quality of power are evaluated in each of the three cases based on, respectively, the PBSC and voltage drop.

The map of the voltage drops and phase of the output impedance within superblue5 with different number of on-chip power supplies is shown in Fig. 8. A distinct peak for the case with a single LDO regulator corresponds with the physical location of the LDO, pulling up the supply voltage locally in the network. The voltage peaks that correspond with the physical locations of the LDO regulators are reduced in cases 2 and 3. The QoP is therefore efficiently enhanced with increasing number of power supplies, exhibiting maximum voltage drop of, respectively, 9.17 %, 3.11 %, and 1.11 % with a single, six, and twelve on-chip power supplies.

The output load of the individual regulators also changes with the number of power supplies, affecting the phase of the output impedance and stability characteristics of the distributed system. Based on the proposed stability criterion, the superblue5 circuit with the evaluated power delivery system is stable with a single power supply and six power supplies (the phase of the output impedance is within the $(-90^\circ, 90^\circ)$ range), and unstable with twelve power supplies (the minimum phase of the output impedance is $-95.1^\circ < -90^\circ$), as shown in Fig. 8(b). While the distributed power delivery system with twelve power supplies exhibits higher QoP than systems with fewer power supplies, this system

Figure 8: Superblue5 circuit with a single, six, and twelve on-chip power supplies, (a) map of voltage drops, and (b) phase of the output impedance.

is shown to be unstable under step response. Thus, a stable system with smaller number of power supplies should be preferred to deliver power to the superblue5 circuit while addressing both QoP and stability challenges.

The second stage of the automated PBSC-based design flow, shown in Fig. 5, is implemented in Matlab. Pseudocode of the Matlab algorithm is summarized in Algorithm 1. A typical LDO model [7] is used to describe a small signal response of the on-chip power supplies, and evaluate the output impedance of the power supplies and overall power delivery system.

Power delivery systems for the ISPD benchmark circuits superblue5, superblue10, superblue12, and superblue18 have been generated and evaluated based on this algorithm. The

Algorithm 1 Automated PBSC-based design flow.

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1: LDOModel; // A typical LDO model [7]
2: CircInfo; // Supply voltages, load currents and locations
3: CircNodes; // All nodes in the evaluated circuit
4: NumRegsList; // List of numbers of LDOs to evaluate
5: PreferredNumRegs  $\leftarrow$  0; // Preferred number of LDOs
6: PreferredLocs  $\leftarrow$  N/A; // Preferred location of LDOs
7: PreferredIRDrop  $\leftarrow$  1; // Maximum allowed IR drop
8:
9: for all NumRegs  $\leftarrow$  NumRegsList do
10:  for all RefNode  $\leftarrow$  CircuitNodes do
11:    // Find optimal LDO locations [1]
12:    OptLocs  $\leftarrow$  OPT_LOC(CircInfo, NumRegs);
13:
14:    // Analyze IR drop in a power grid [3]
15:    IRDrop(RefNode)  $\leftarrow$  CALC_IRDROP(CircInfo, ...
16:                                     OptLocs, ...
17:                                     RefNode);
18:
19:    // Calculate the output impedance of the LDOs
20:    for all LDO  $\leftarrow$  LDOs do
21:      ISupply  $\leftarrow$  Current delivered by the LDO;
22:      ZOUTLDO(LDO)  $\leftarrow$  CALC_ZOUT(LDOModel, ...
23:                                     ISupply);
24:    end for
25:
26:    // Calculate the output impedance of the system
27:    ZOUTSYS  $\leftarrow$   $\left( \sum_{LDOs} \frac{1}{Z_{OUT}^{LDO}(LDO)} \right)^{-1}$ ;
28:
29:    if  $\max\{|\angle Z_{OUT}^{SYS}|\} < 90^\circ$  then
30:      if  $\max\{IRDrop\} < PreferredIRDrop$  then
31:        PreferredIRDrop  $\leftarrow$   $\max\{IRDrop\}$ ;
32:        PreferredNumRegs  $\leftarrow$  NumRegs;
33:        PreferredLocs  $\leftarrow$  OptLocs;
34:      end if
35:    end if
36:  end for
37: end for

```

maximum *IR* drop and stability results are listed in Table 2. Based on the evaluated benchmark circuits, the maximum voltage drop is significantly reduced with the increasing number of on-chip power supplies. Alternatively, stability of the distributed power delivery system is a function of specific load distribution and changes with number of parallel connected power supplies. The proposed automated PBSC-based design flow generates a distributed power delivery system that addresses both the QoP and stability requirements.

4. EXPERIMENTAL RESULTS

A distributed system with six LDO regulators has been designed for IoT power delivery and evaluated based on the proposed PBSC. The system has been fabricated in an advanced 28 nm CMOS technology. The area occupied by the LDO with all capacitors is $85 \mu\text{m} \times 42 \mu\text{m}$. The regulators are distributed around the perimeter of the on-chip circuits, as shown in Fig. 3, regulating the power grid at reference voltage of 0.7 volts with an input voltage of 1.0 volt and maximum load current of 788 mA. The on-chip regulators simultaneously drive a power network, delivering current to the

on-chip loads of an IoT edge device. To evaluate the system response under different load conditions, controllable current loads are integrated onto the test circuit. These current loads can be activated separately or simultaneously, exhibiting different current loads at individual LDO regulators. A die microphotograph of the LDO, and measured transient response for an aggressive load current ramp (from 52 mA to 788 mA in 5 ns) and nominal input and output voltages at 25 °C is illustrated in Fig. 9.

Figure 9: Experimental results, (a) die microphotograph of a single LDO regulator and current generating circuit, and (b) measured transient response for a load current step from 52 mA to 788 mA in 5 ns.

The load current of a single LDO regulator significantly varies in different configurations as compared to the nominal current. To evaluate the effect of voltage, temperature, and load sharing variations on the stability of a power delivery system, the system is measured with different line, load, and temperature configurations. The total load current of the distributed power delivery system with six LDO regulators is aggressively ramped in 5 ns from 17 mA to 309 mA (slow corner), from 52 mA to 441 mA (typical corner), and from 420 mA to 900 mA (fast corner) for, respectively, -25°C , 25°C , and 125°C . In the typical corner, the system is also evaluated under $\pm 10\%$ line variations. The DC voltages and voltage droop for a transient response of the experimental distributed system are listed in Table 3. Based on these experimental results, the system of six parallel LDO regulators yields a stable response and voltage droop of less than

Table 2: Properties of ISPD benchmark circuits.

circuit	No regulators		A single regulator		Six regulators		Twelve regulators	
	IR drop	Stability	IR drop	Stability	IR drop	Stability	IR drop	Stability
superblue5	23.4%	N/A	9.17%	Stable	3.11%	Stable	1.11%	Not stable
superblue10	23.0%	N/A	10.8%	Stable	4.75%	Stable	2.43%	Not stable
superblue12	23.6%	N/A	10.7%	Stable	6.39%	Stable	4.88%	Not stable
superblue18	22.7%	N/A	10.7%	Stable	4.43%	Stable	1.54%	Not stable

Table 3: Transient step response at the load under line and temperature variations.

Type of variations		V_{OUT} (mV)		Voltage droop (mV)
V_{IN} (V)	Temperature (°C)	Max	Min	
1.0	25	700.8	698.9	64.9
1.1	25	701.1	699.0	61.4
0.9	25	698.3	696.0	71.1
1.0	125	692.3	690.0	55.0
1.0	-25	704.3	702.4	63.3

0.1 volts over a wide range of voltage, temperature, and load sharing variations.

5. CONCLUSIONS

IoT have emerged as a powerful technology that creates valuable networked connections among a wide variety of locally intelligent electronic devices. Novel, IoT based market segments, such as intelligent transportation, revolutionary health care, sophisticated security systems, and smart energy applications are emerging that fundamentally change our daily experience and reshape world economy. Many of the IoT edge devices will be powered from non-conventional energy sources (e.g., harvested piezo/thermoelectric, wind flow, solar, photovoltaic energy and/or wireless power transfer). While quality of power in the future IoT edge devices can be addressed with distributed point-of-load power supplies, the stability of the distributed power delivery systems fed by these inherently less reliable, non-traditional power sources, is becoming a primary limiting factor for scalability of future IoT systems. A passivity-based stability criterion has recently been proposed for evaluating the stability of parallel voltage regulators, driving a single power grid. Based on this criterion, a distributed power delivery system is stable if the total output impedance of the parallel connected LDOs is passive.

A design automation flow for stable power delivery in IoT edge devices is proposed in this work based on passivity-based stability criterion. The proposed design flow is demonstrated on a set of ISPD benchmark circuits with different number of parallel connected voltage regulators. A system with few LDO regulators is shown to violate quality of power requirements. Alternatively, a system with large number of distributed LDO regulators designed for maximum quality of power is shown to be unstable under step load response. A tradeoff therefore exists between the stability and quality of power in distributed power delivery systems. A preferred number of power supplies should be determined based on both the PBSC and voltage drop characteristics to simultaneously address the quality of power and stability requirements complex IoT systems.

A distributed power delivery system with six LDO regulators is designed based on the results of the stability analysis. The system is fabricated in 28 nm CMOS technology, and tested under aggressive load ramp transition, exhibiting high performance and stable response over a wide range of voltage, temperature, and load sharing variations. The proposed design automation flow provides an efficient means for designing stable, high quality power delivery system for heterogeneous IoT edge devices.

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