System-Level Power Management Strategies for Integrated Platforms

Vivek De
Intel Fellow & Director of Circuit Technology Research
Intel Labs
Hillsboro, Oregon, USA

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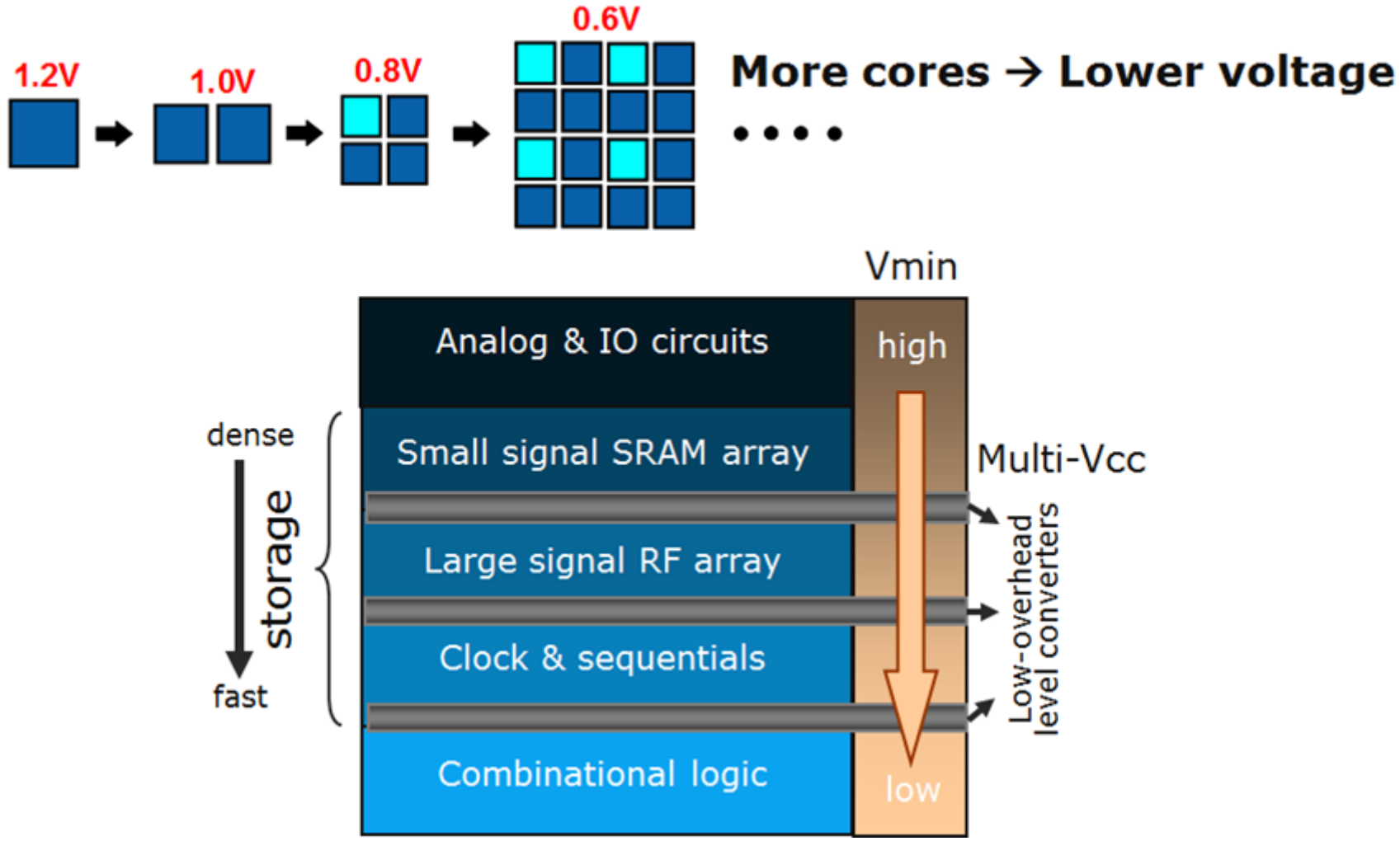
Internet of Everything

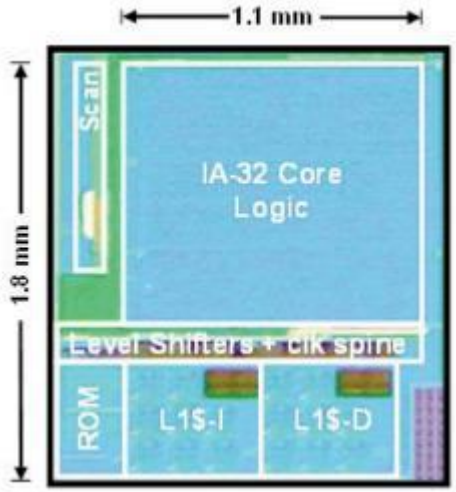
Cyberphysical systems with end-to-end energy efficiency

SoC Power Delivery & Management

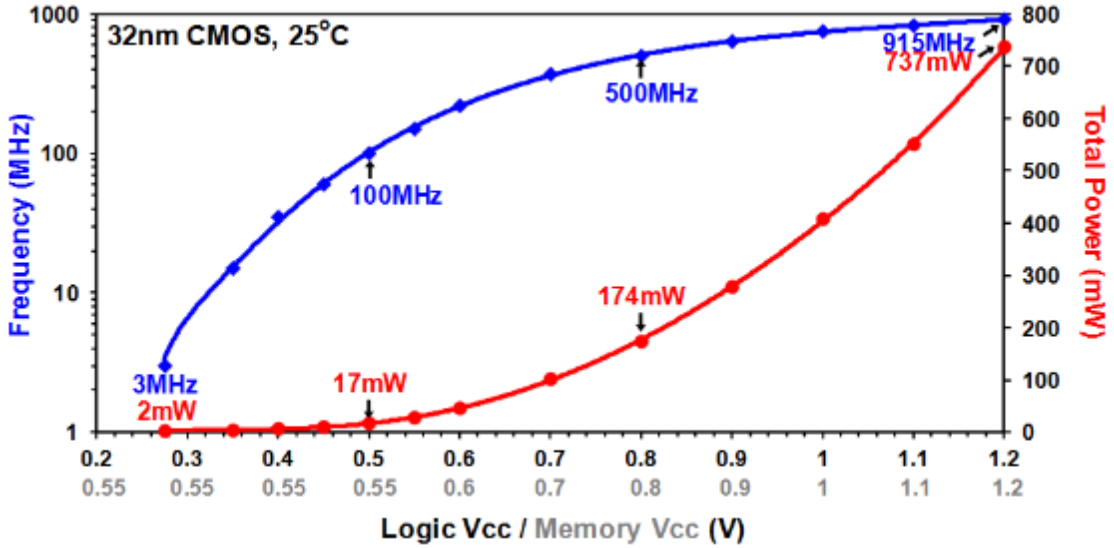
Fine-Grain Multi-Voltage SoC Design

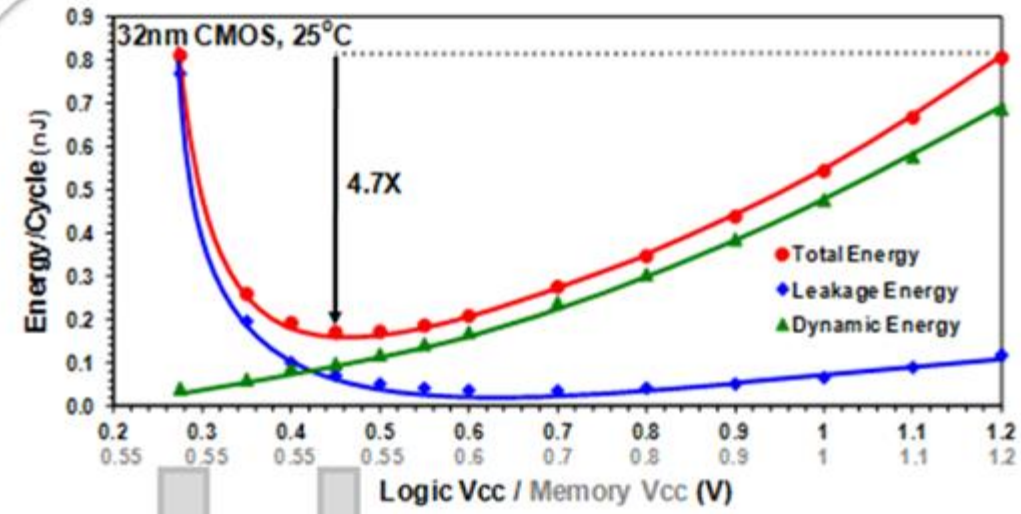


Wide Range DVFS



Technology	32nm High-K Metal Gate
Interconnect	1 Poly, 9 Metal (Cu)
Transistors	Core:6M
Core Area	2mm²
Package	951 Pins FCBGA11



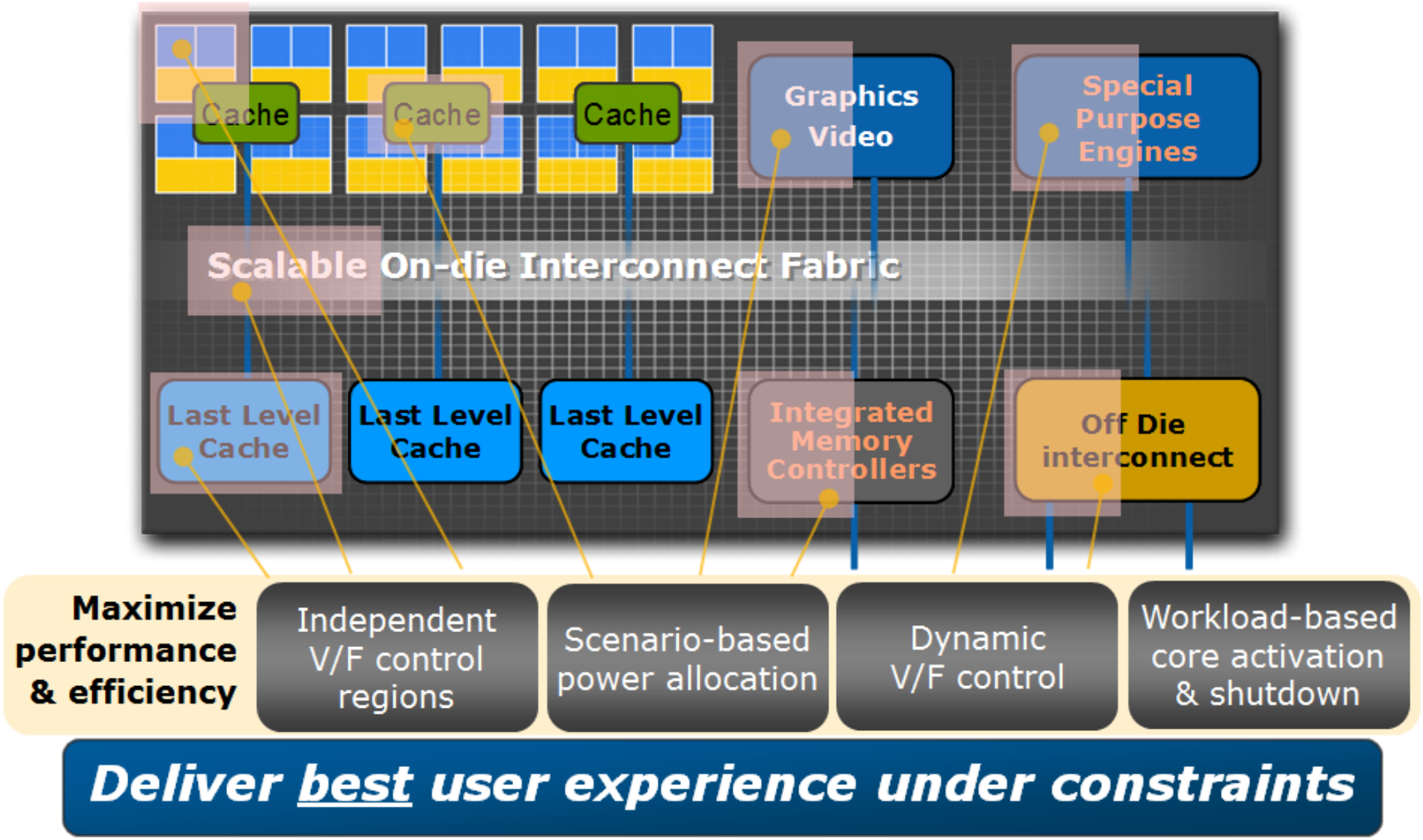


NTV operation for peak energy efficiency

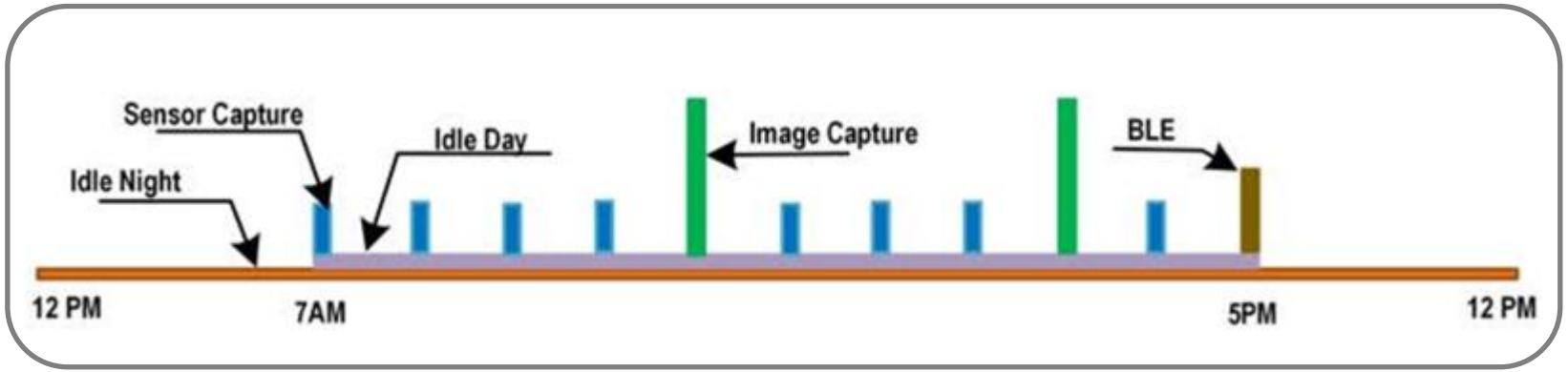
Minimum core voltage limited by circuit functional and timing failures from process variations and noises

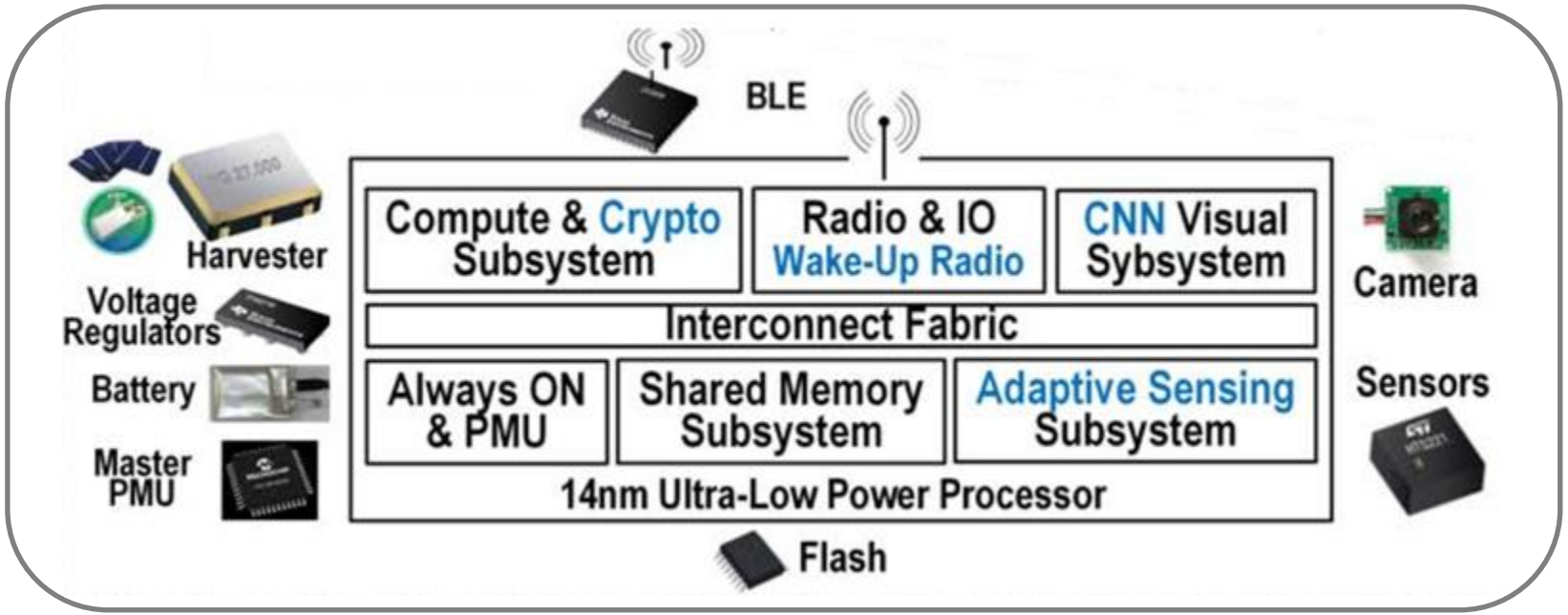
* S. Jain, et al., 2012 ISSCC

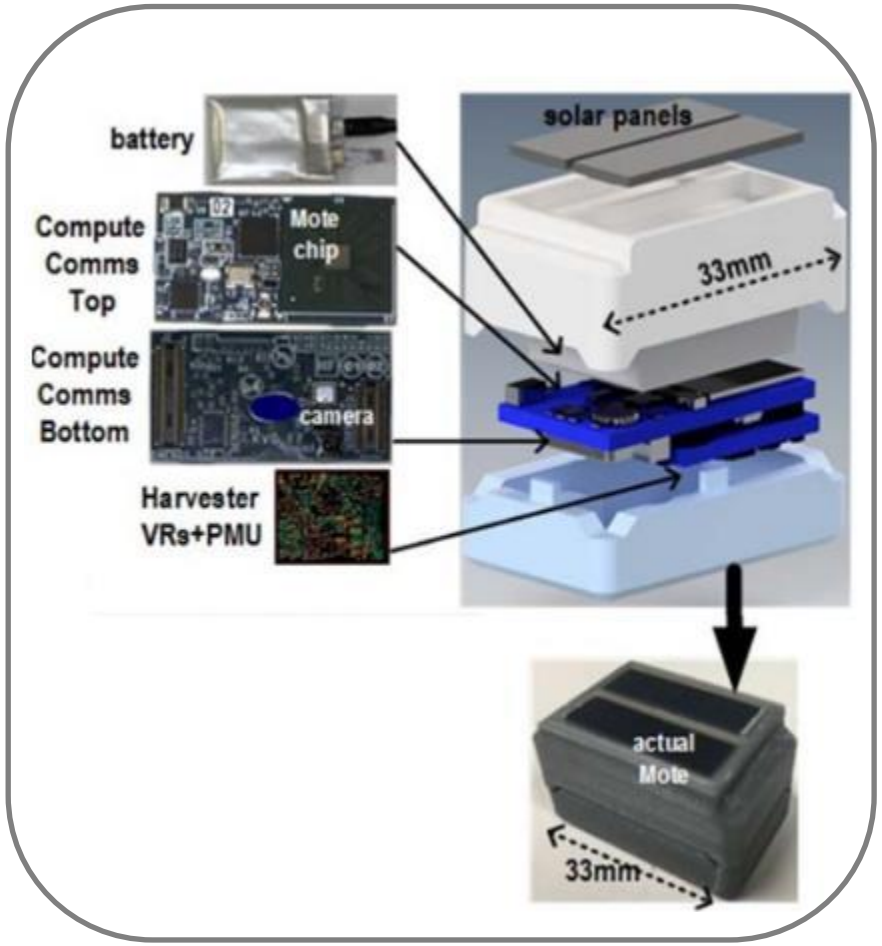
Fast & Efficient SoC Power Management



Self-Powered cm-Scale Integrated Platforms

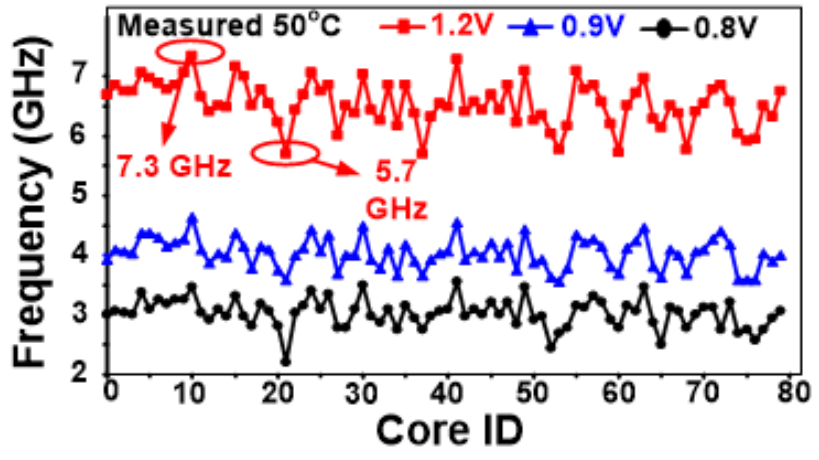


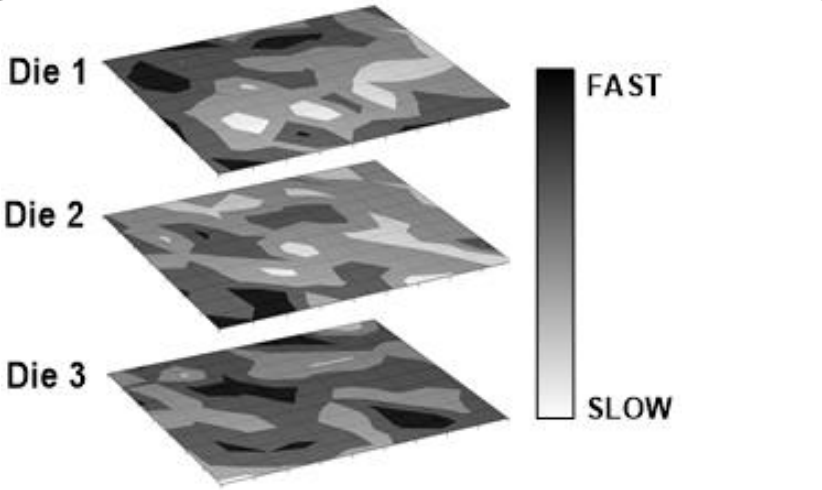


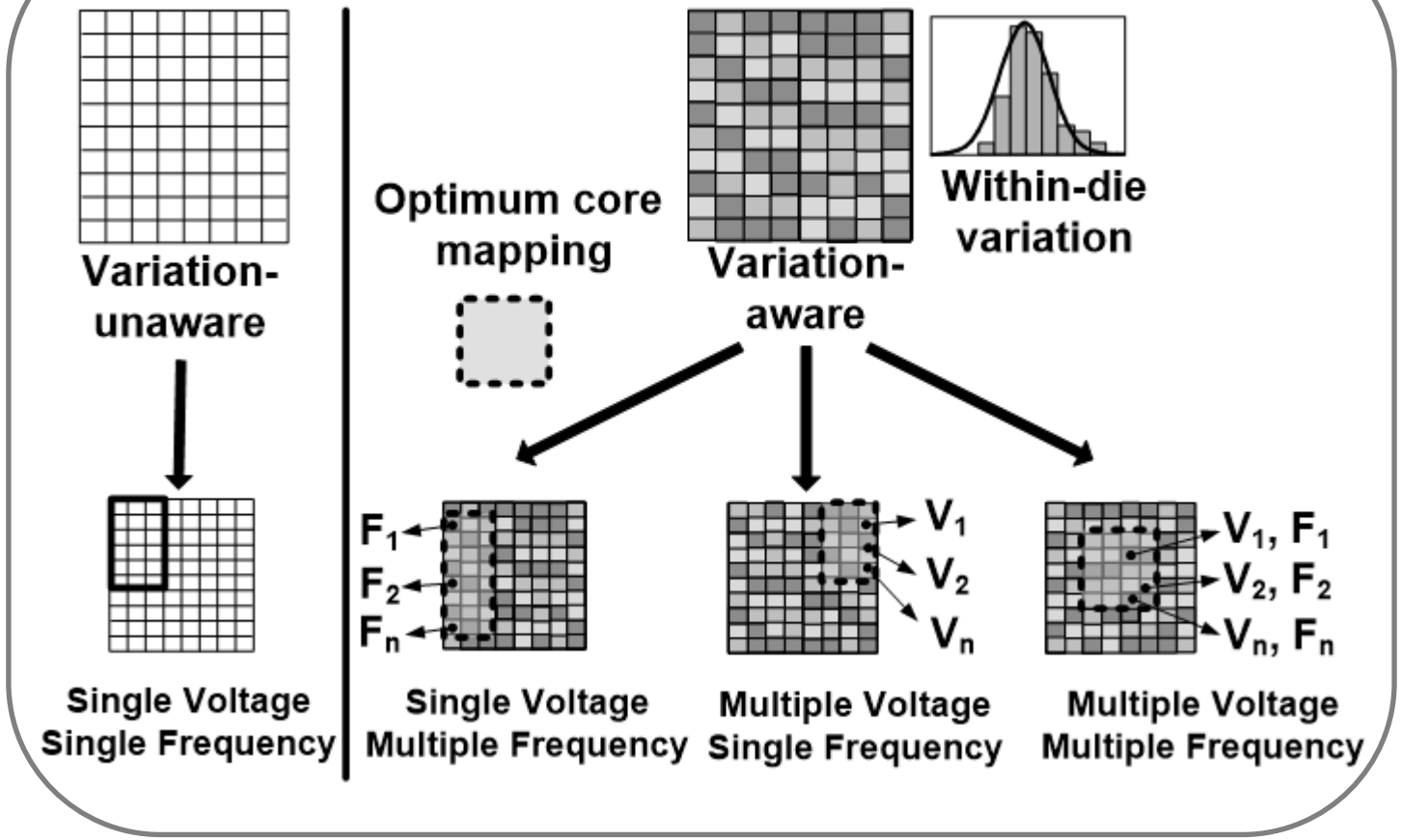


* T. Karnik, et al., 2018 ISSCC

Variation-Aware SoC Design & Operation

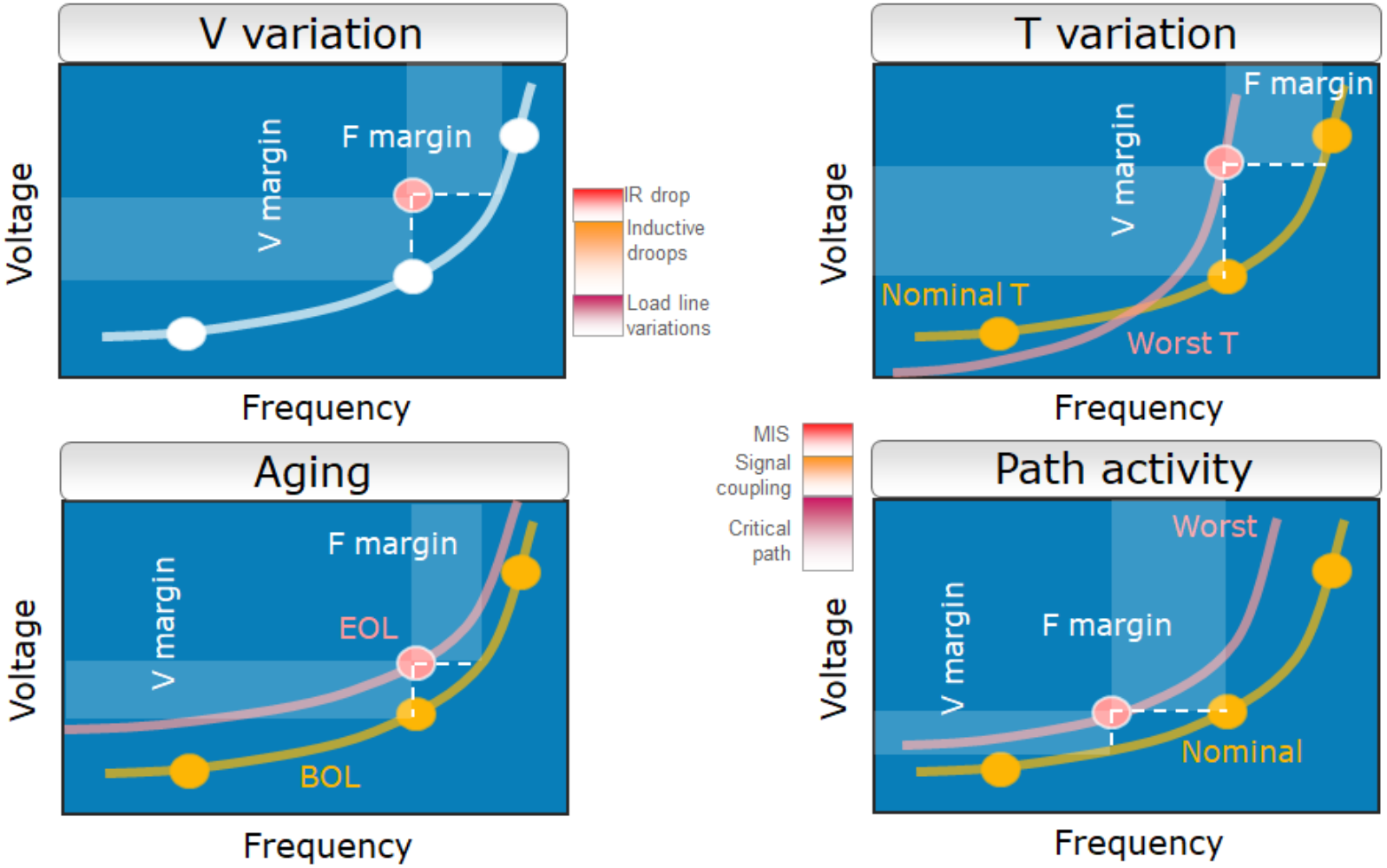




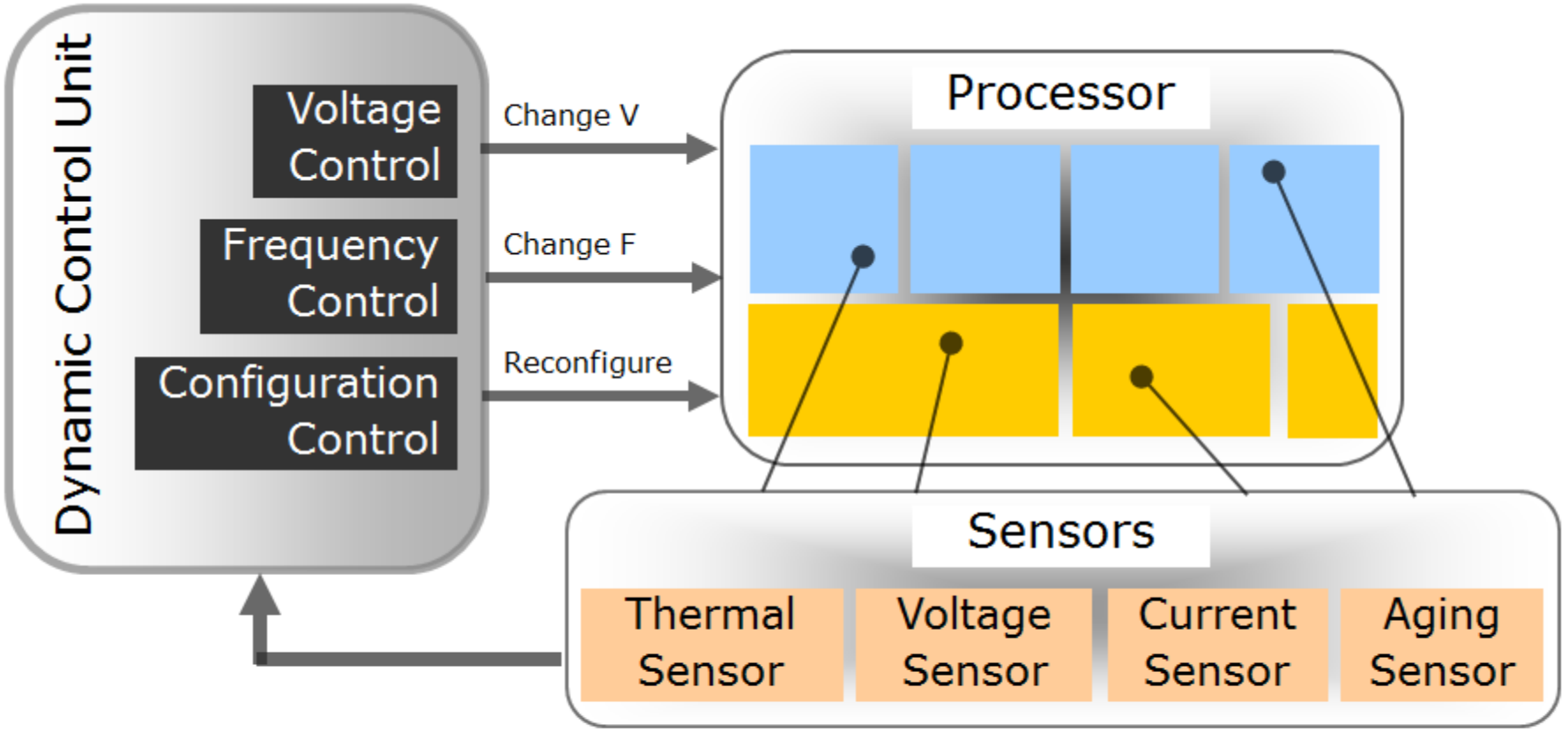


* S. Dighe, et al., JSSC, Jan 2011

Voltage-Frequency Margins



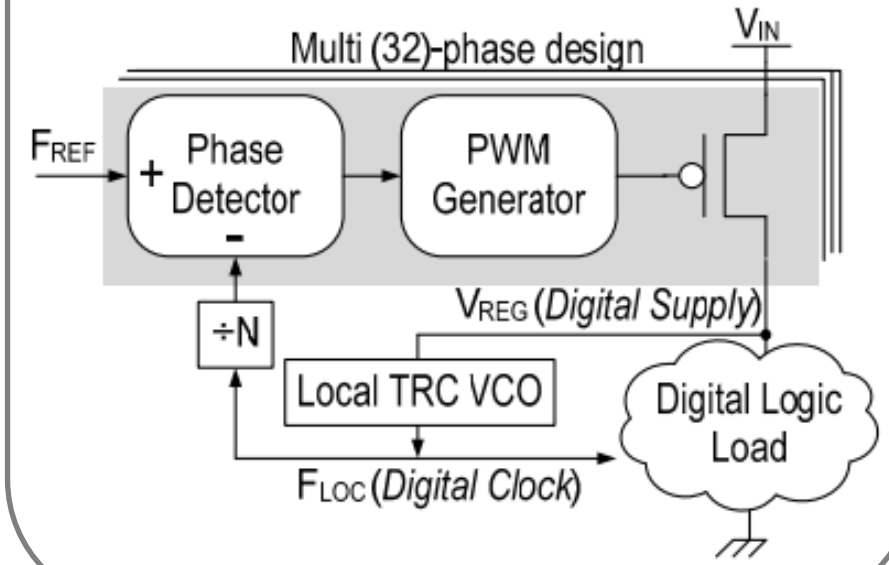
Runtime Self-Adaptation

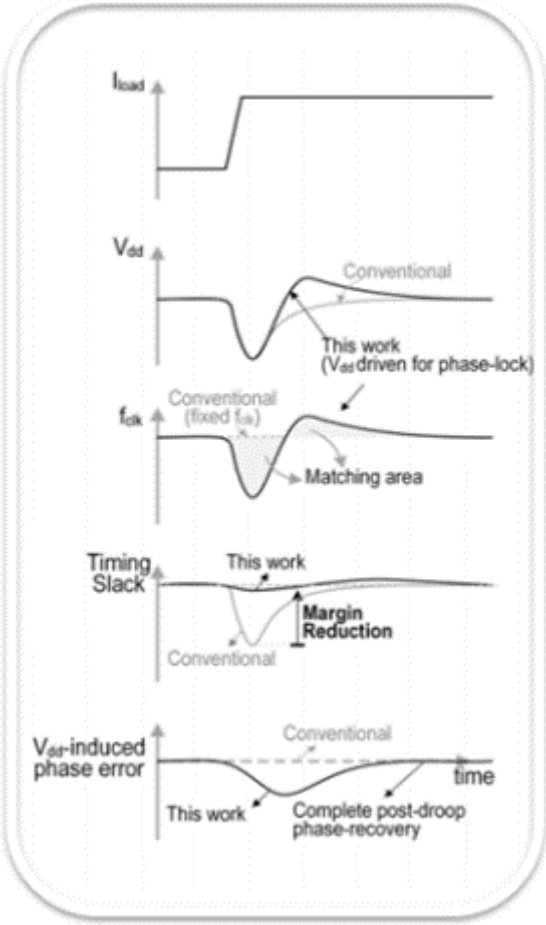


Adapt & reconfigure for best power-performance

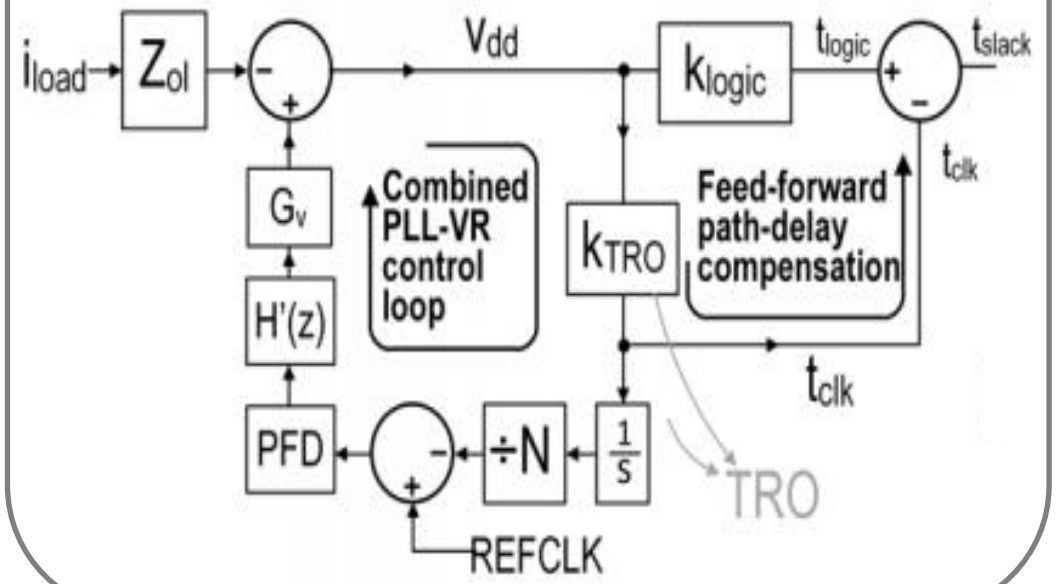
Unified Voltage-Frequency Regulation

Linear Regulator





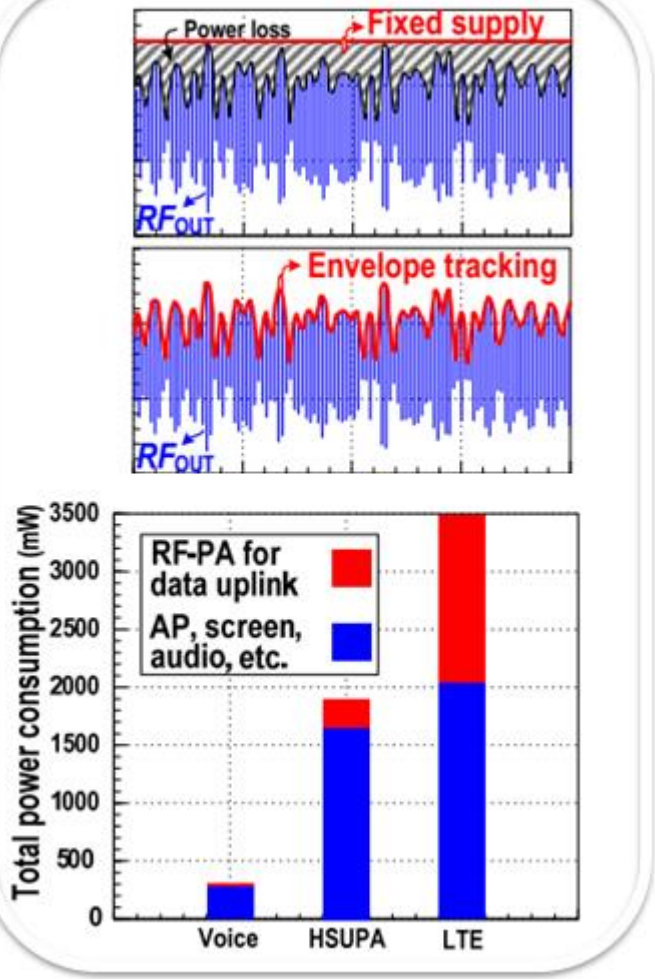
Buck Regulator



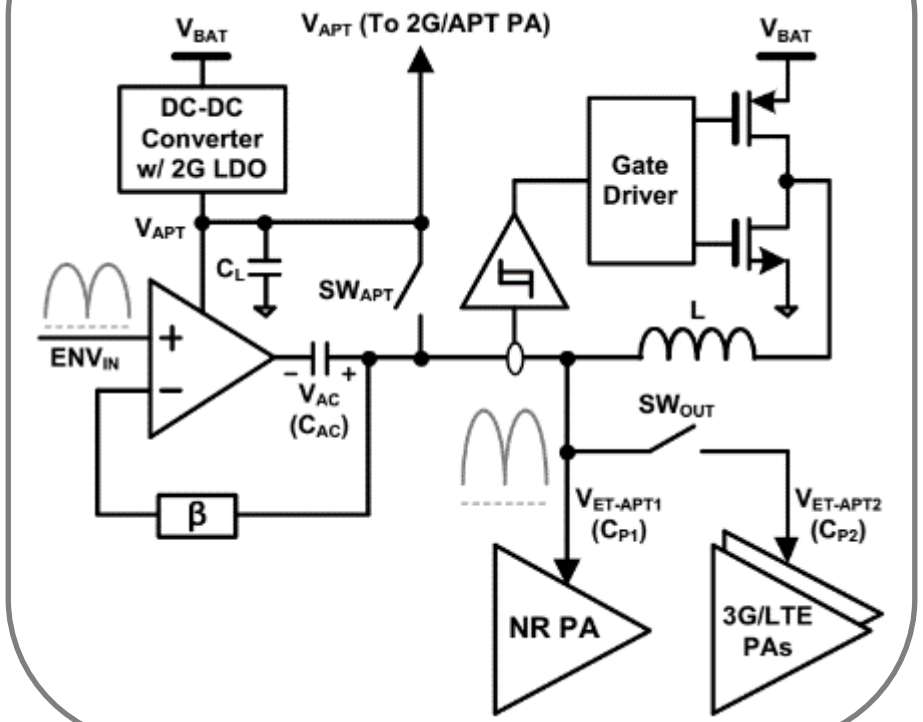
* S. Gangopadhyay, et al., 2016 ESSCIRC

* X. Sun, et al., 2018 ISSCC

Envelop Tracking (ET) RF Power Amplifiers (PA)



ET Supply Modulator (SM)



Communication system		PAPR (dB)	Bandwidth (MHz)
2G	GSM	0	
2.5G	EDGE	3.2	0.2
3G	CDMA2000	3.5 ~ 9	1.25
	WCDMA		5
	TD-SCDMA		1.6
4G	LTE	8.5 ~ 13	2.4 ~ 20

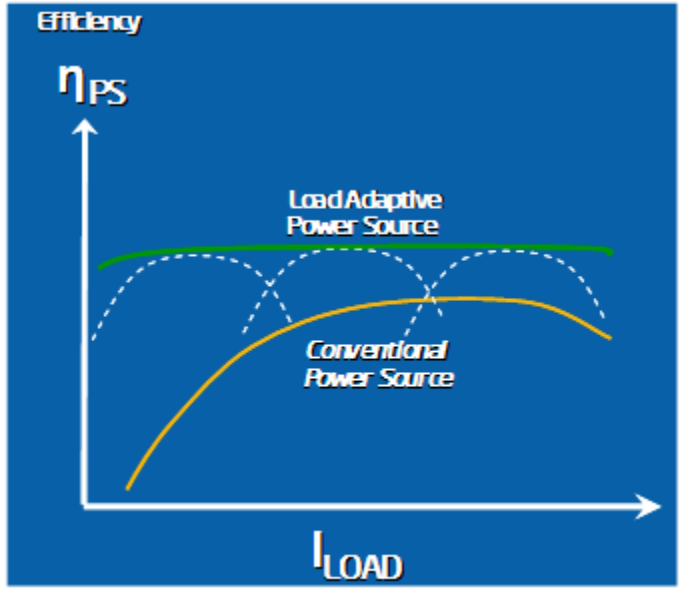
Protocol/ Bandwidth	Avg. ET-SM output power	ET-SM efficiency
LTE 20MHz	1.92W	72-85%
WLAN 10MHz	0.594W	65%
LTE 20MHz	1.53W*	78-83%
LTE 10MHz	0.93W	82% (Peak)
HSUPA 5MHz	0.5W*	60%-80%
LTE 20MHz	0.82W*	83% (Peak)
LTE 10MHz	0.5W*	70% (At least)
LTE 40MHz	0.54W*	64%-83%

100Mhz bandwidth & faster power tracking for 5G

Voltage Regulators for Integrated Platforms

Voltage Regulator (VR) Challenges

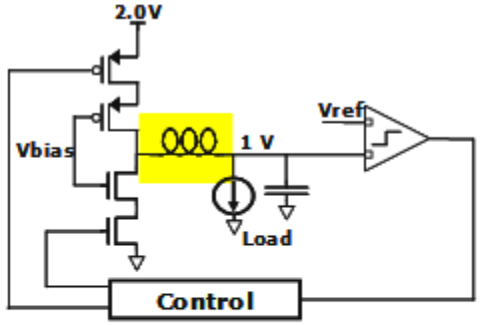
Conversion	Distribution	Control
• Area efficient • Scalable • Persistent rail	• Lower loss • Higher fidelity • Simpler	• Fast & efficient • Load adaptive • Independent rails
Efficient	**Low loss**	**Fine-grain**



Integrated Voltage Regulators (IVR)

LCVR

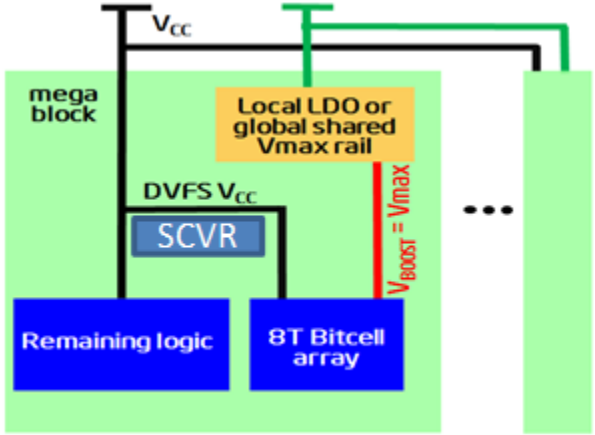
- High efficiency
- Off-die inductor
- Continuous Vout
- Large domains
- Fast response



Off-die inductors
All circuits on die

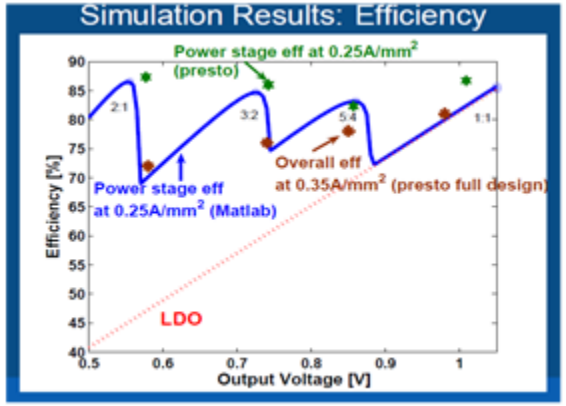
SCVR

- High efficiency
- Die integration
- Discrete Vout
- Finer domains
- Faster response

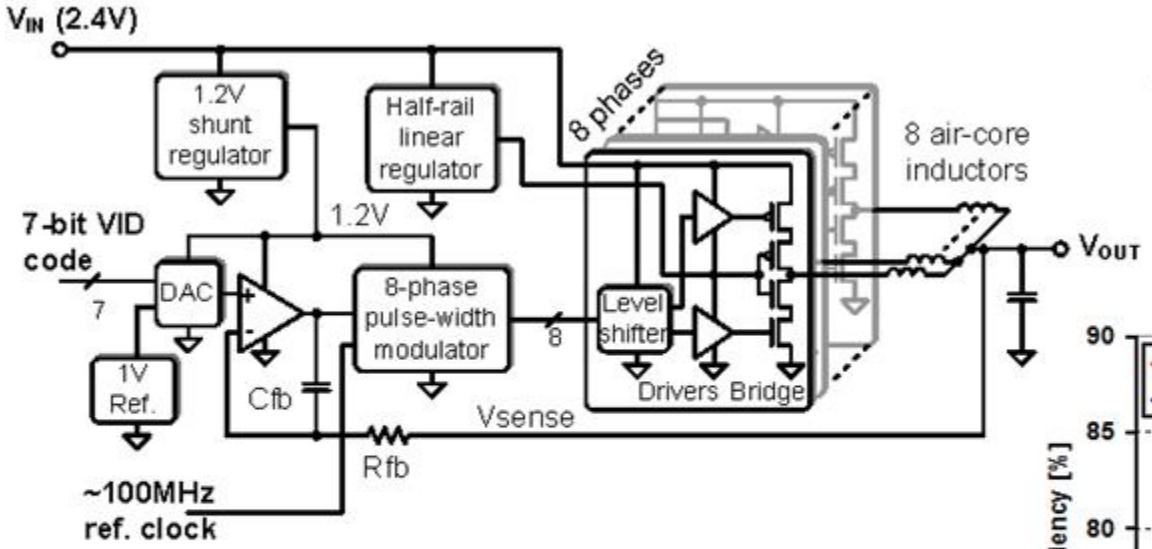


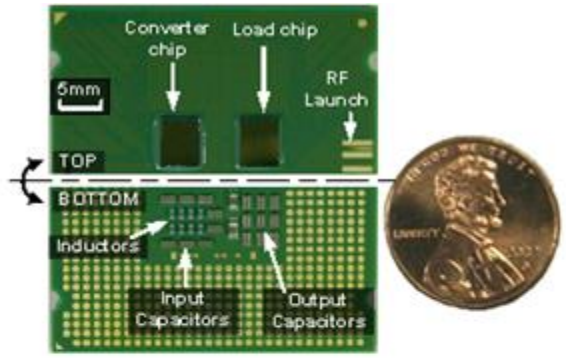
LDO

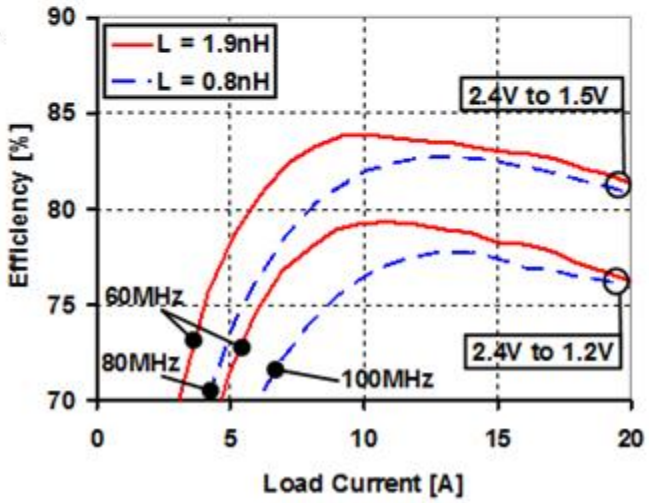
- Low efficiency
- Die integration
- Narrow Vout range
- Finest domains
- Fastest response



Integrated High-Frequency LCVR

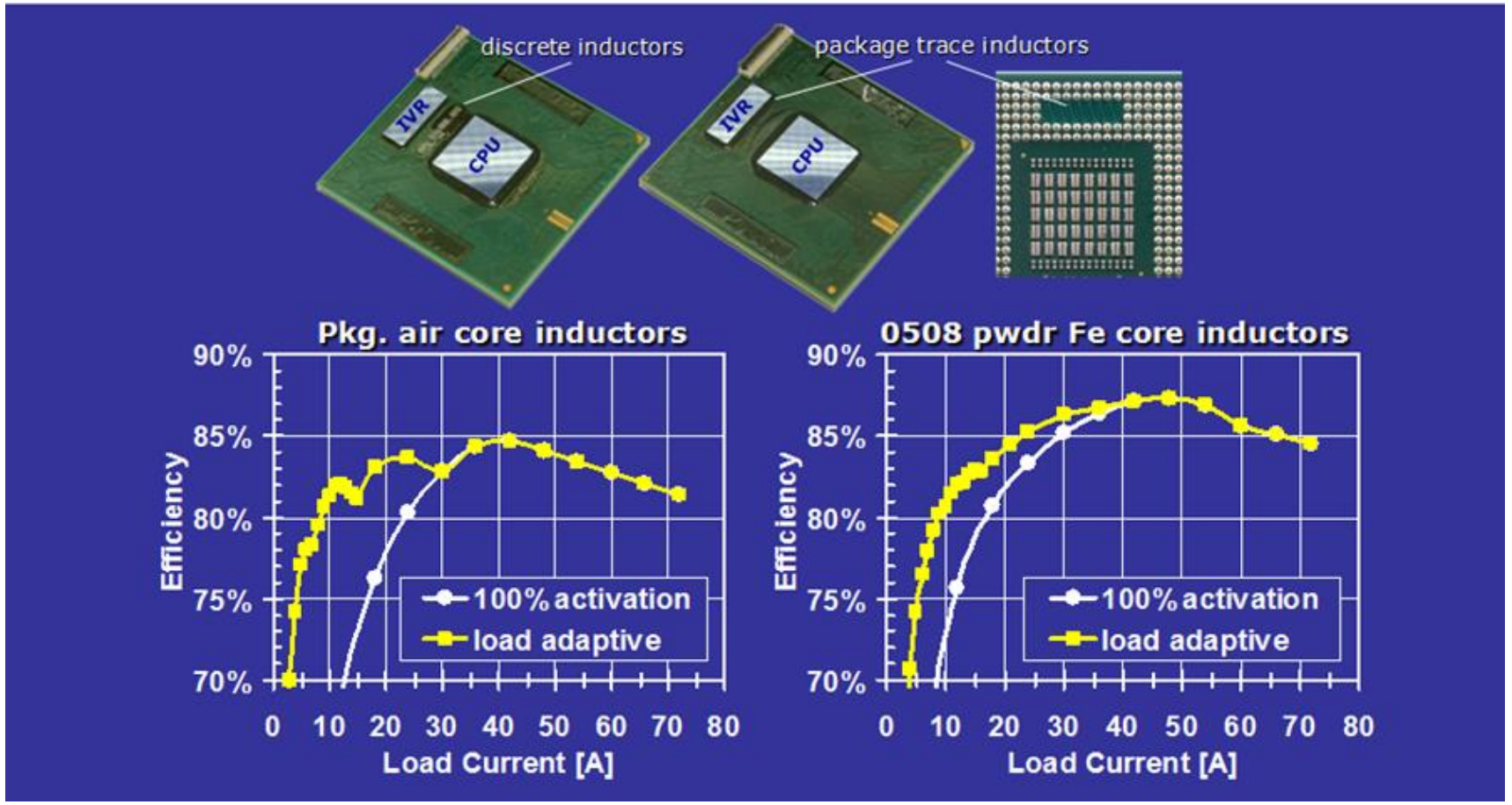






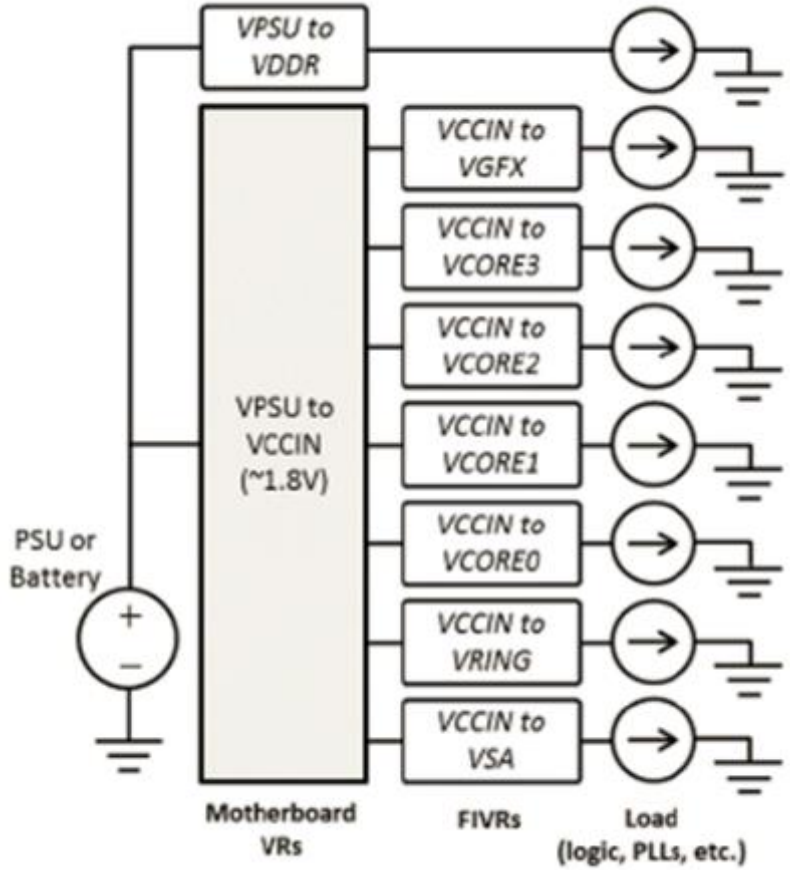
* G. Schrom, et al., 2007 APEC

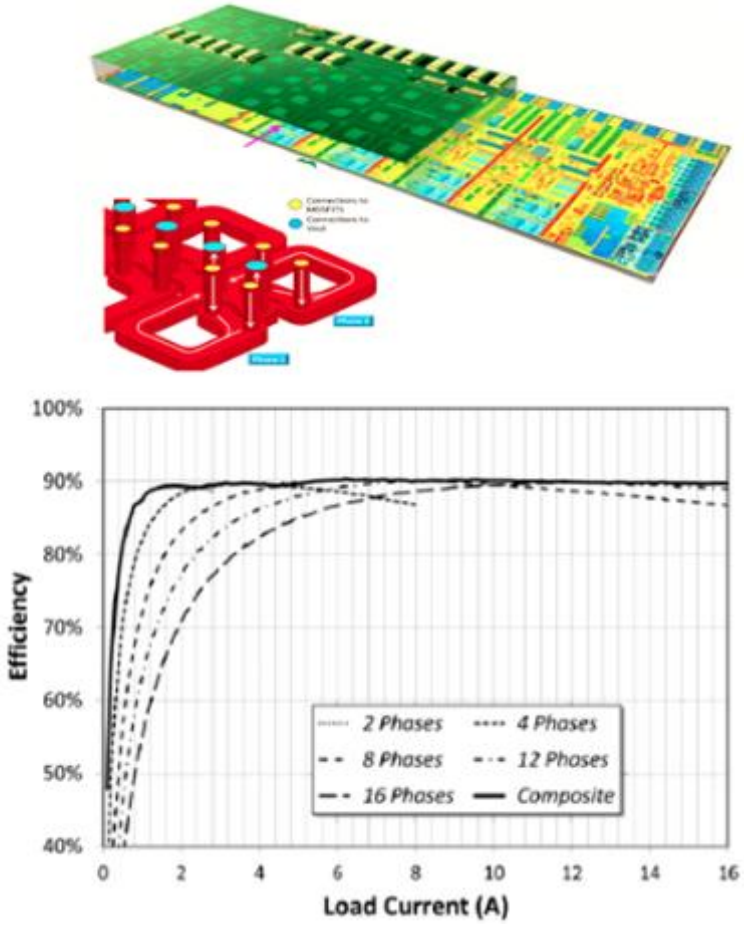
Package-Integrated LCVR



* G. Schrom, et al., 2010 APEC

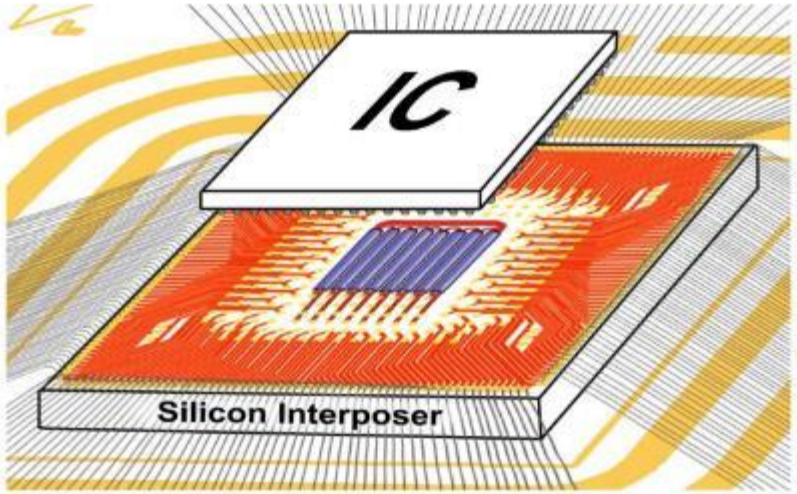
FIVR with In-Package Air-Core Inductors

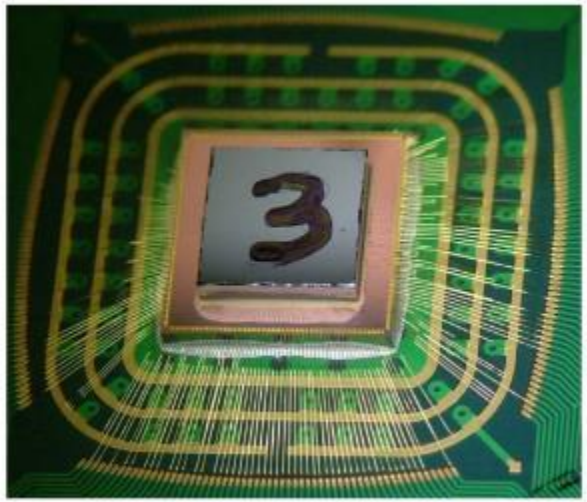


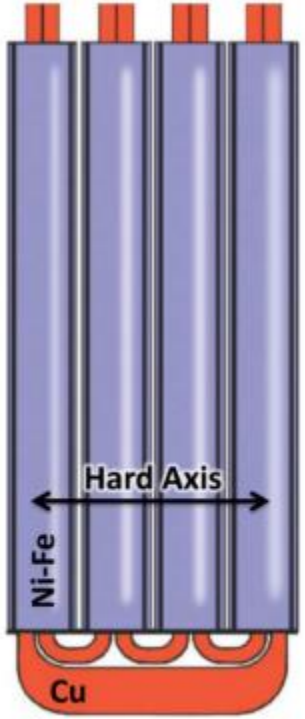


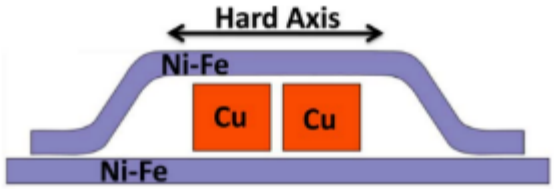
* E. A. Burton, et al., 2014 APEC

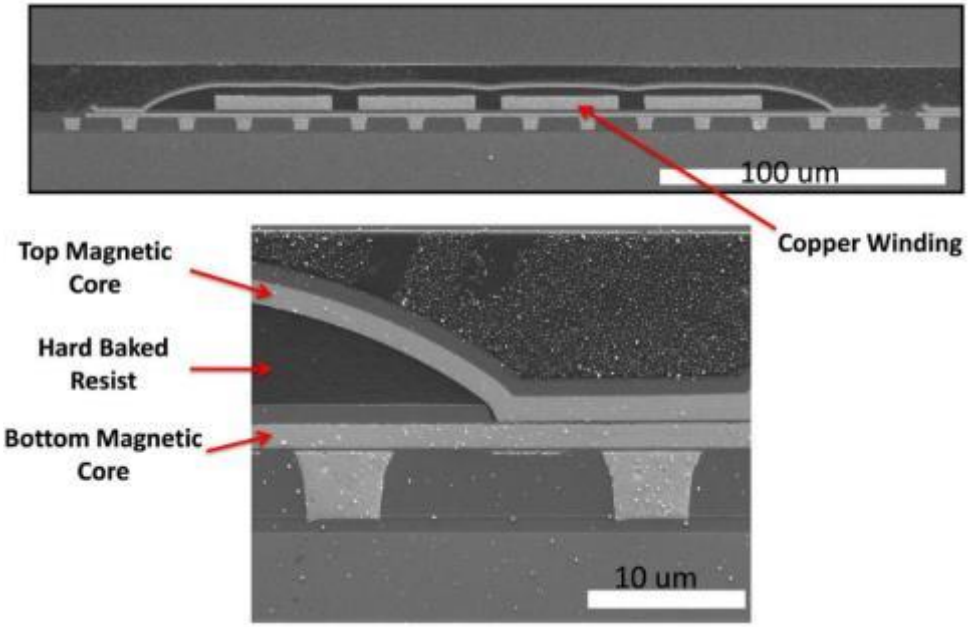
2.5D-IVR with Magnetic-Core Inductors





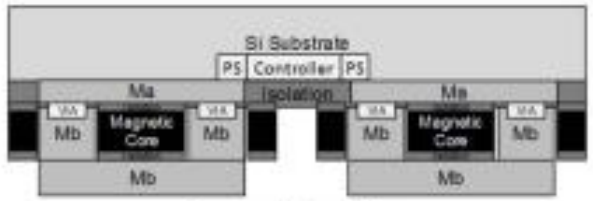


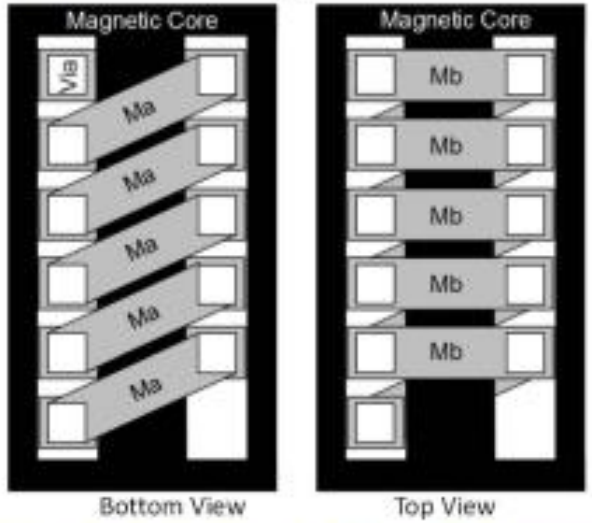




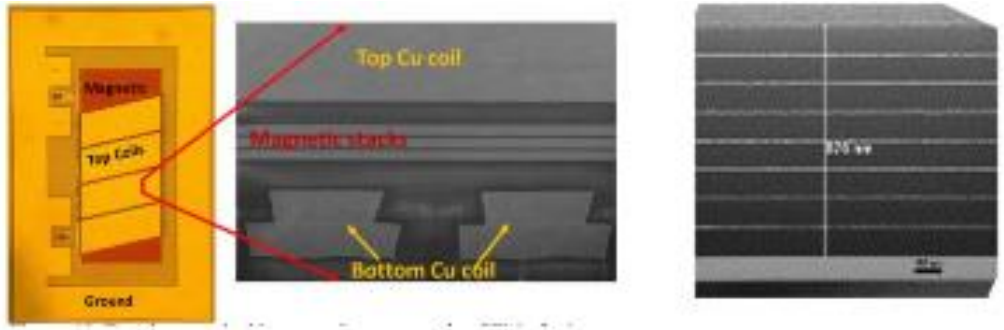
* N. Sturcken, et al., JSSC, Jan 2013

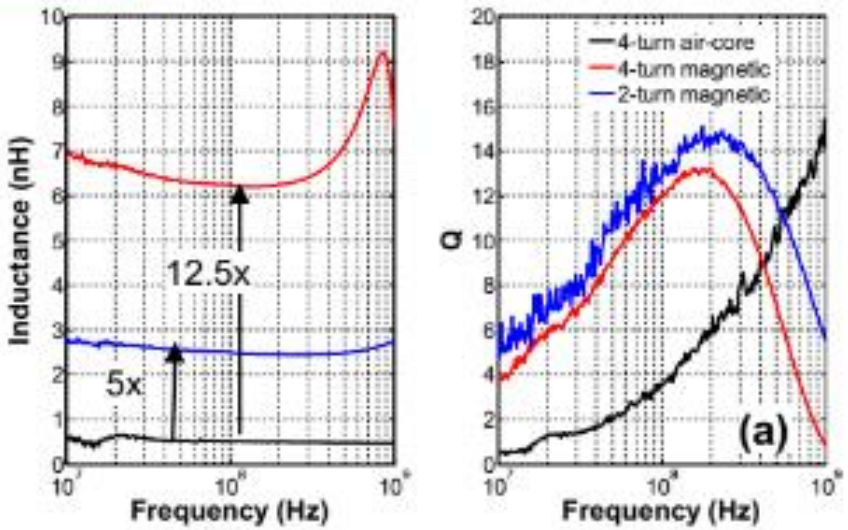
On-Die Solenoid Inductor with Planar Magnetics





1A/mm^2, 1.5nH, 3.5Q @100MHz





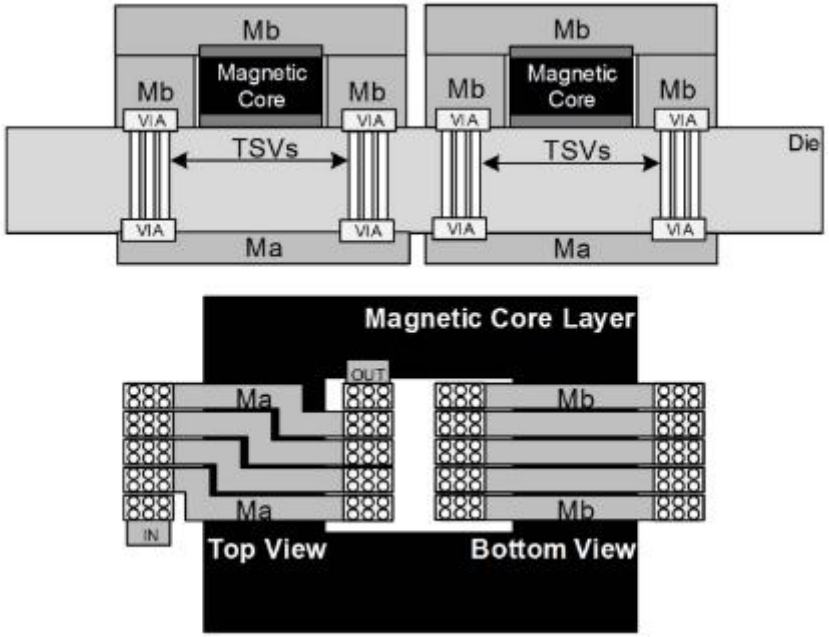
2nH, 17Q @100MHz

* H. K. Krishnamurthy, et al., JSSC, Jan 2018

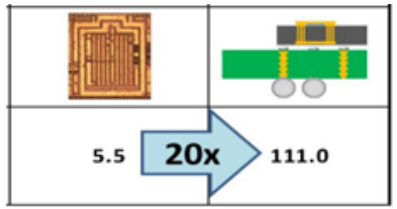
* N. Wang, et al., 2016 IEDM

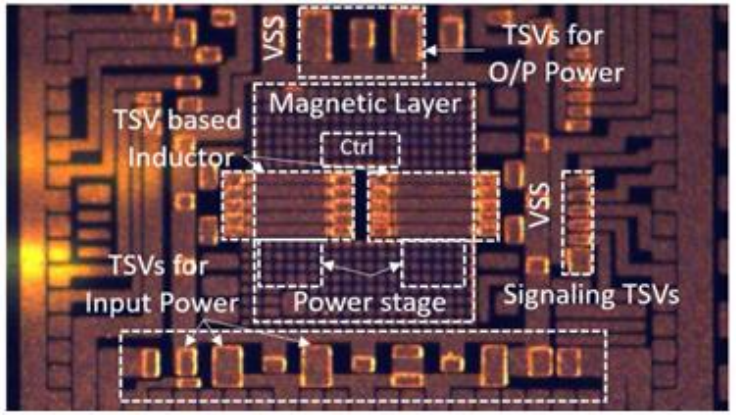
3D-Integrated LCVR

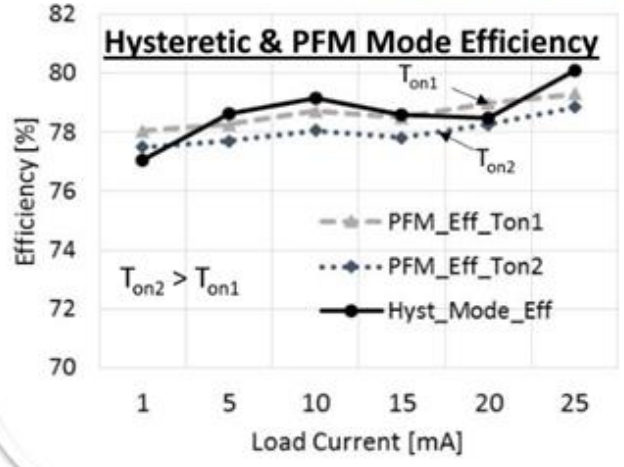
3D-TSV Inductor

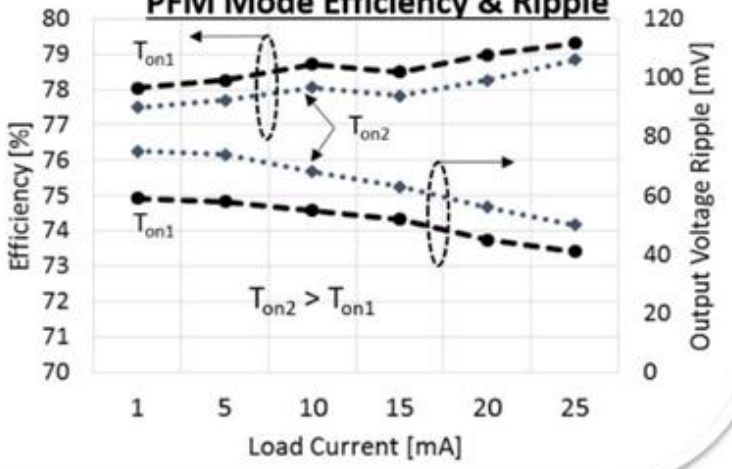


Inductance density (nH/mm²)









* H. K. Krishnamurthy, et al., JSSC, Apr 2018

Summary

- Future "smart & connected" systems demand uncompromising performance with maximum energy efficiency in compact form factors

- Integrated platforms across IoE edge-network-cloud need
  - fine-grain multi-voltage SoC design
  - fast & efficient wide-range DVFS
  - efficient power delivery & energy harvesting
  - self-adaptation to variations

- Monolithic & heterogeneous 2.5D/3D-integrated *efficient, fast & compact* power converters, voltage regulators and supply modulators are essential for smart system-level power management & adaptation