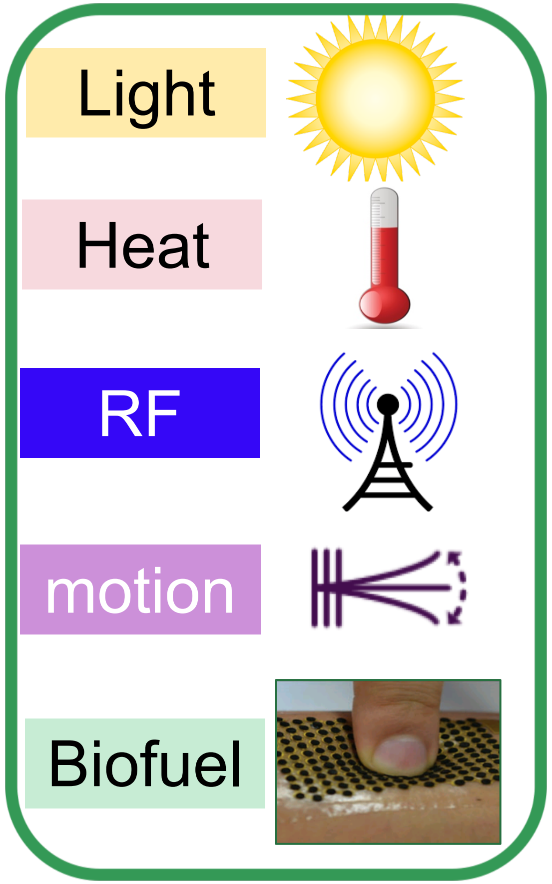
MISIMO:
A Multi-Input Single-Inductor Multi-Output Energy Harvester Employing Event-Driven MPPT Control to Achieve 89% Peak Efficiency and a 60,000x Dynamic Range in 28nm FDSOI

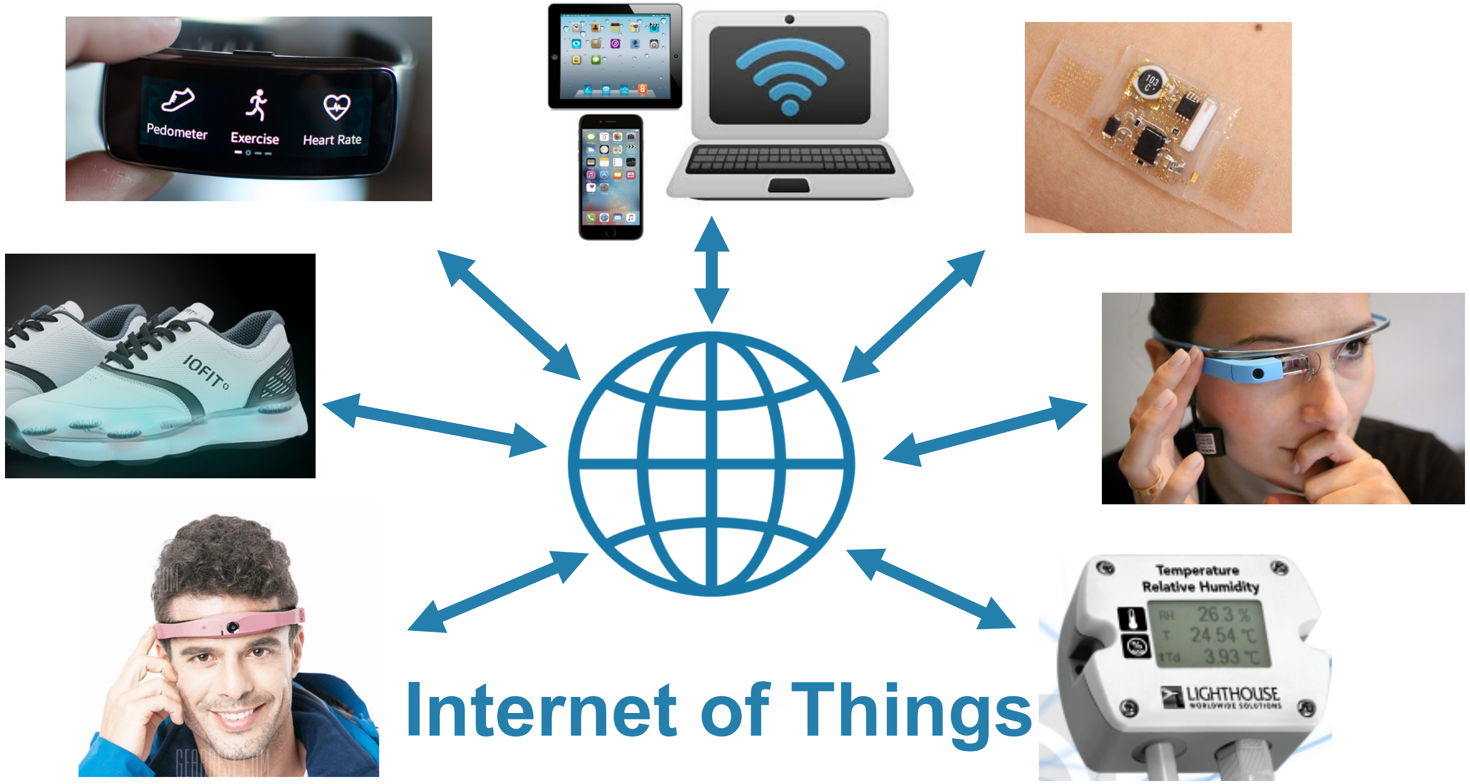
Sally Safwat Amin and Patrick P. Mercier
University of California, San Diego, La Jolla, CA, USA

UC San Diego

ISSCC 2018

Energy Harvesting for Powering Wearable and IoT Devices

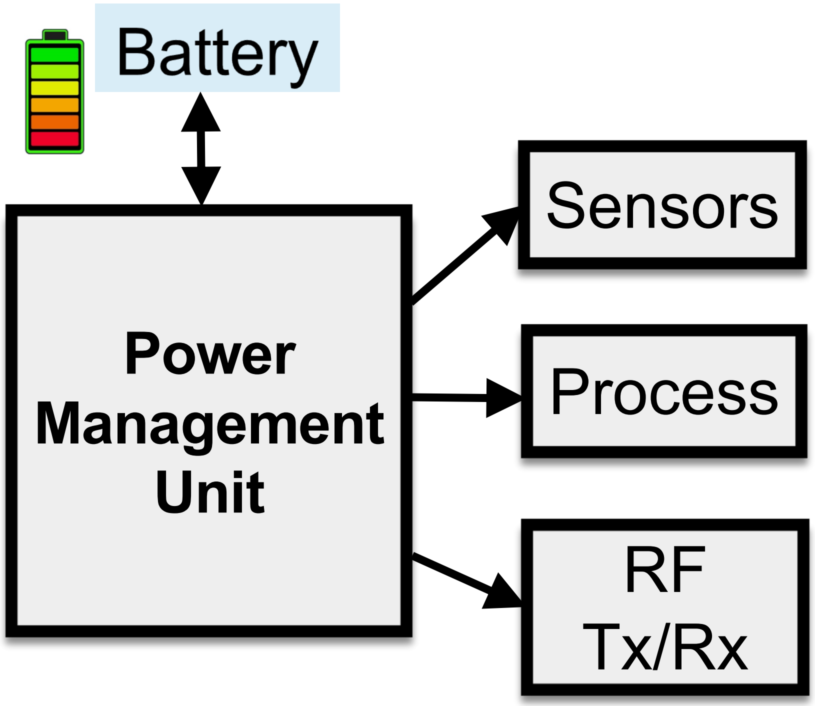




Enable small wearable/IoT devices from ambient energy
– No battery re-charging/replacement

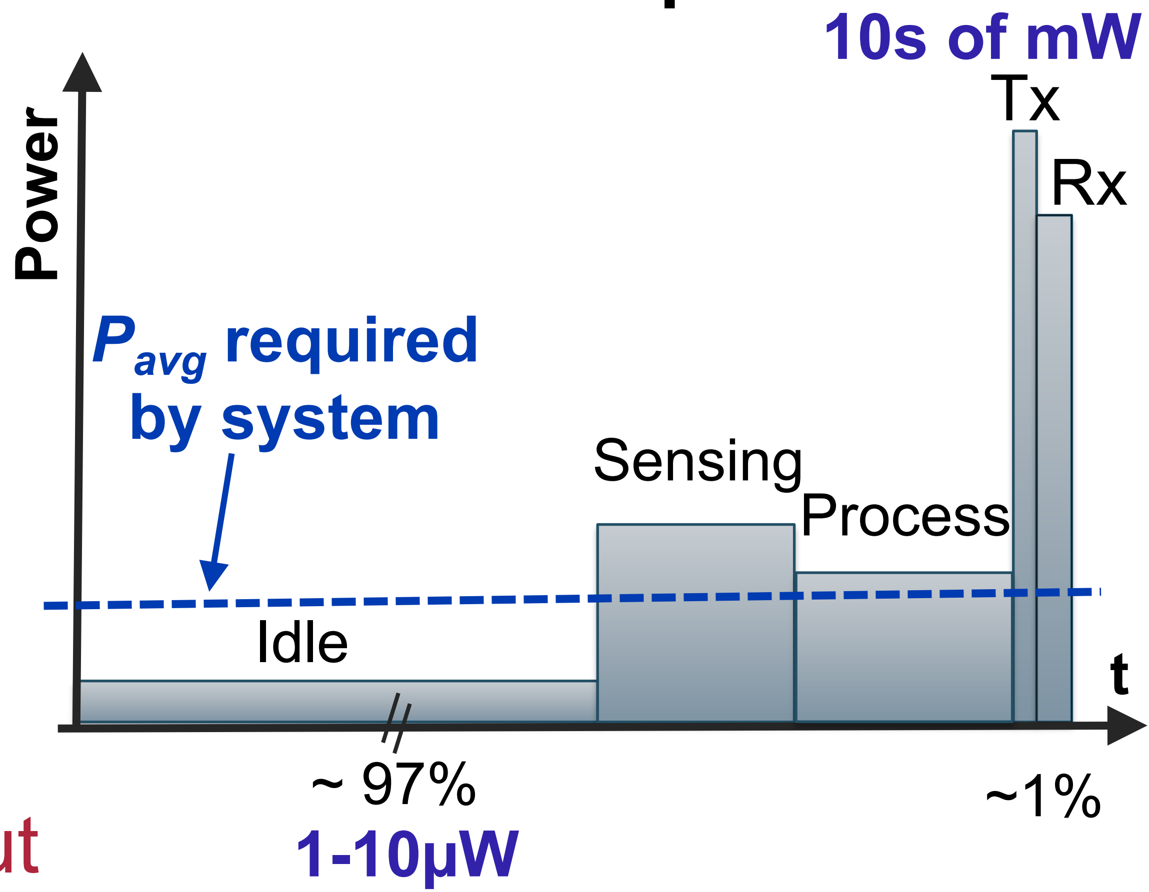
Wireless Sensor Device Power Demand Pattern

Wireless sensor device



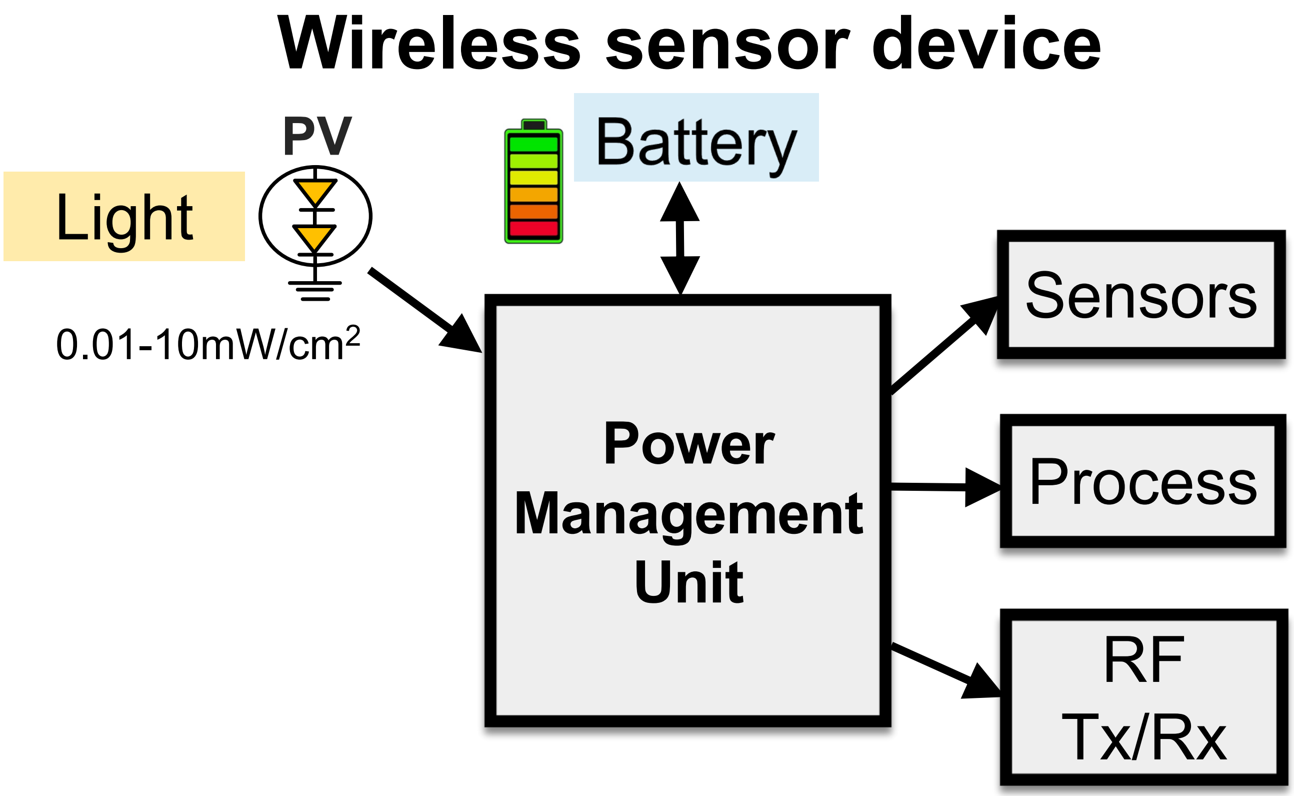
Multi-Output

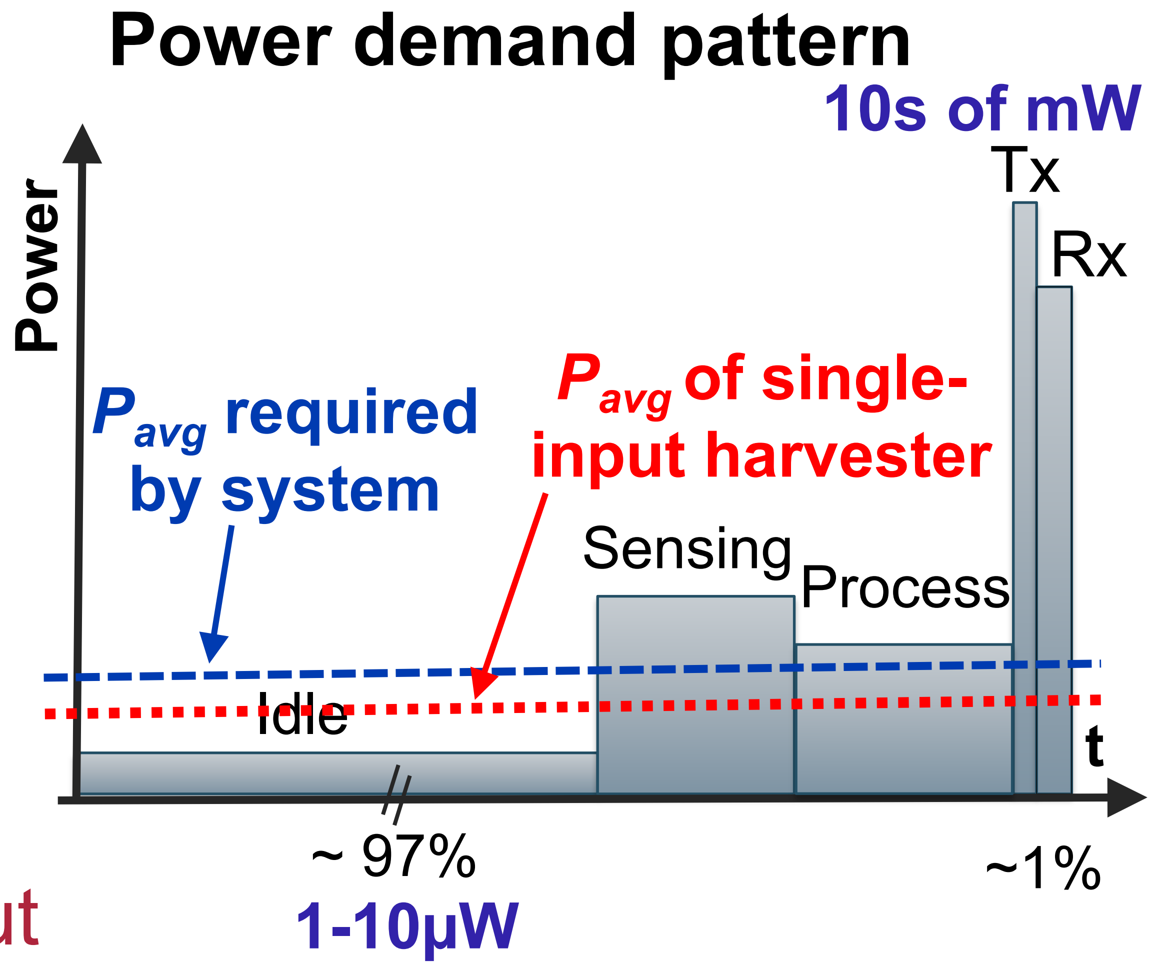
Power demand pattern



≥ 97% idle state, ≤ 3% active state

Energy Harvesting Promise in IoT



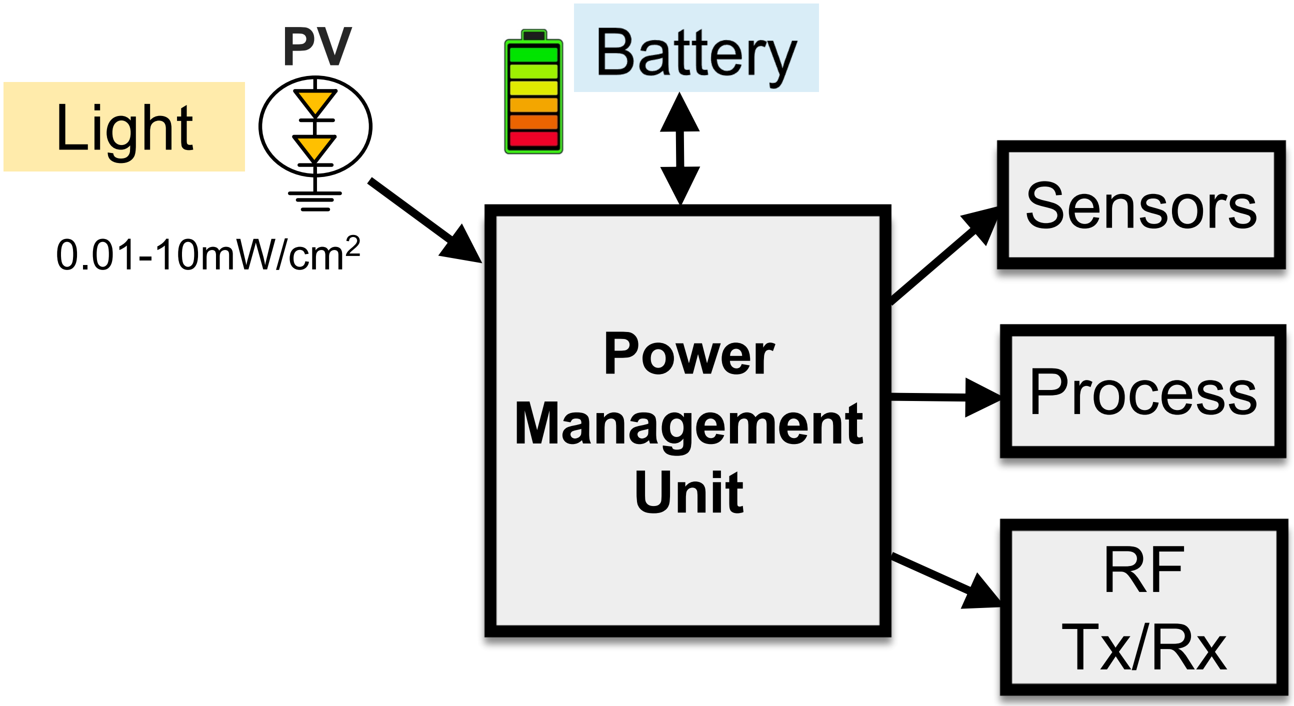


Single-Input **Multi-Output**

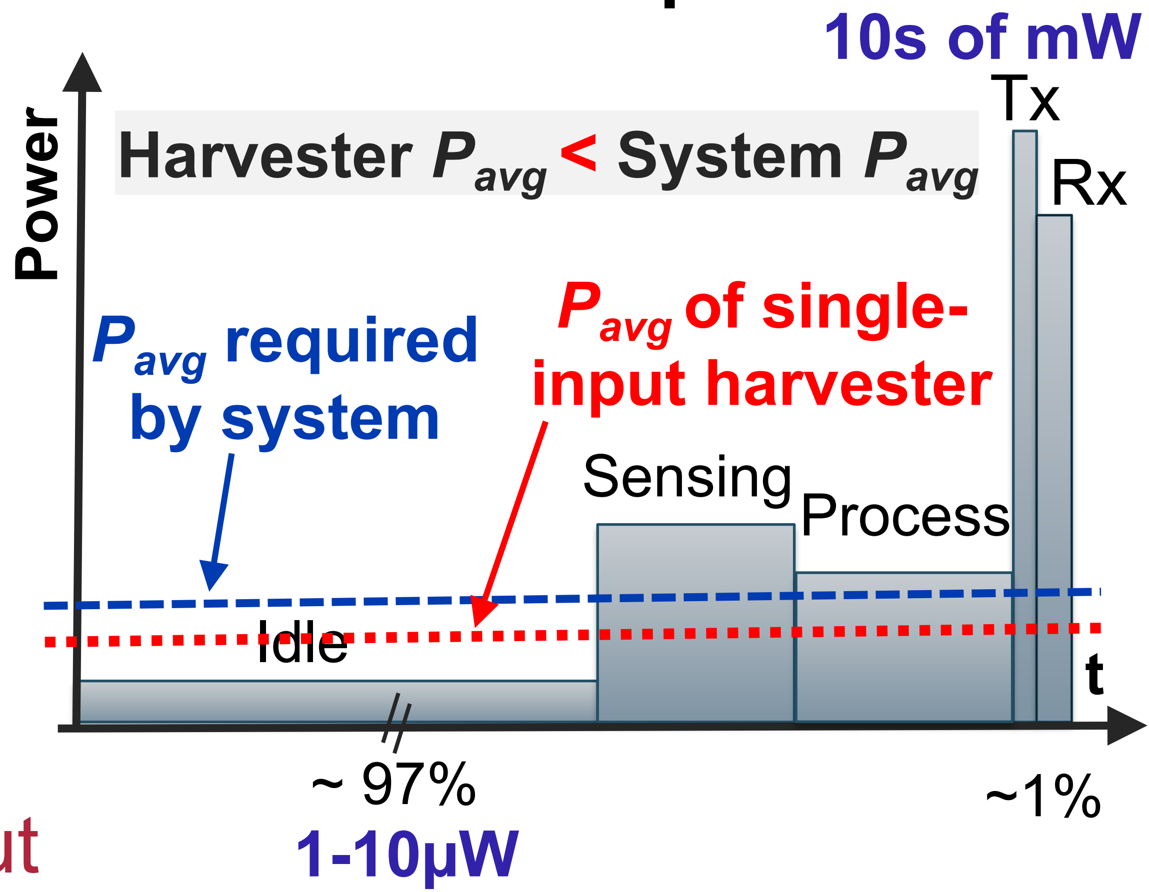
Energy harvesting can extend battery life

Single-Input Harvesting Limitation

Wireless sensor device



Power demand pattern

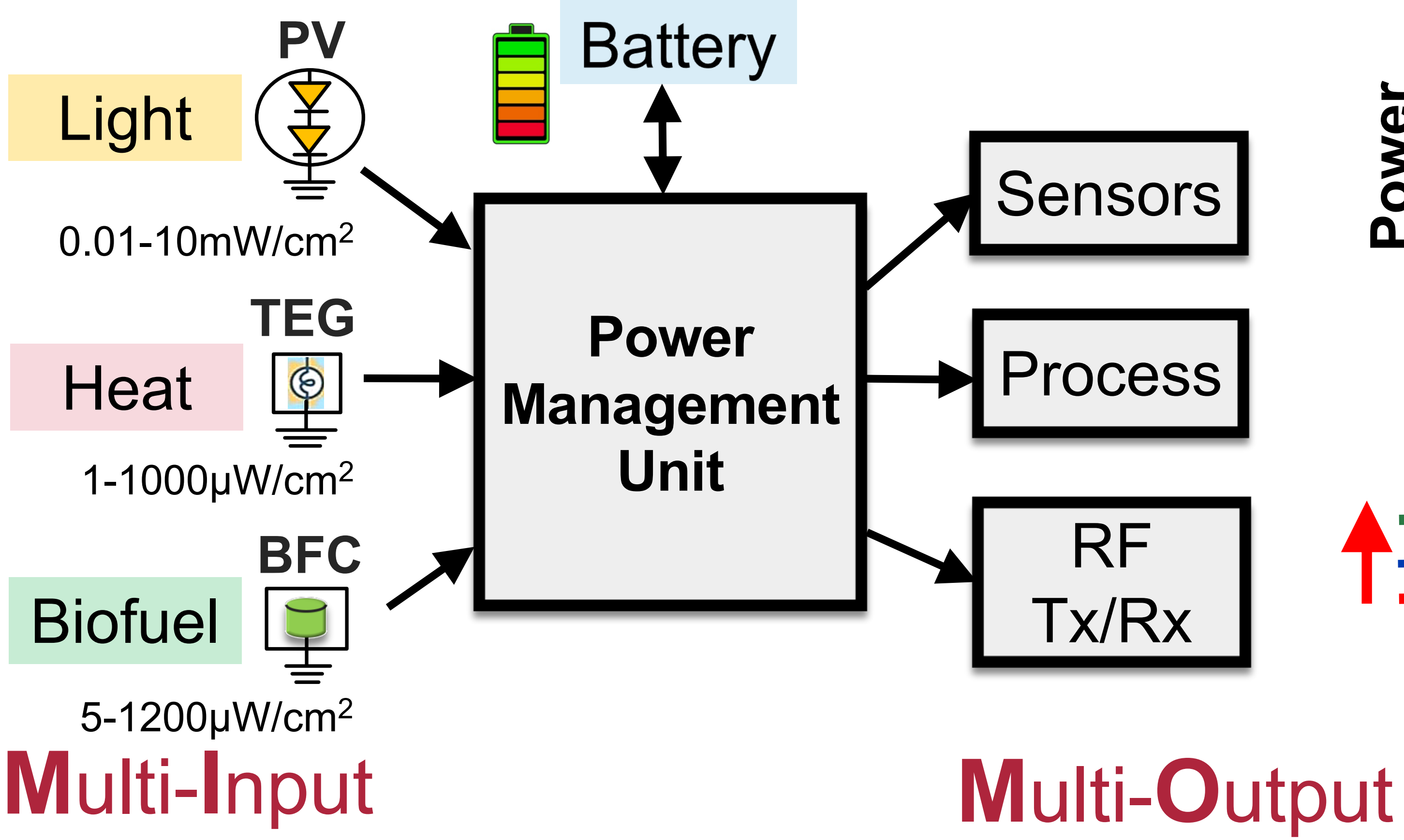


Single-Input **Multi-Output**

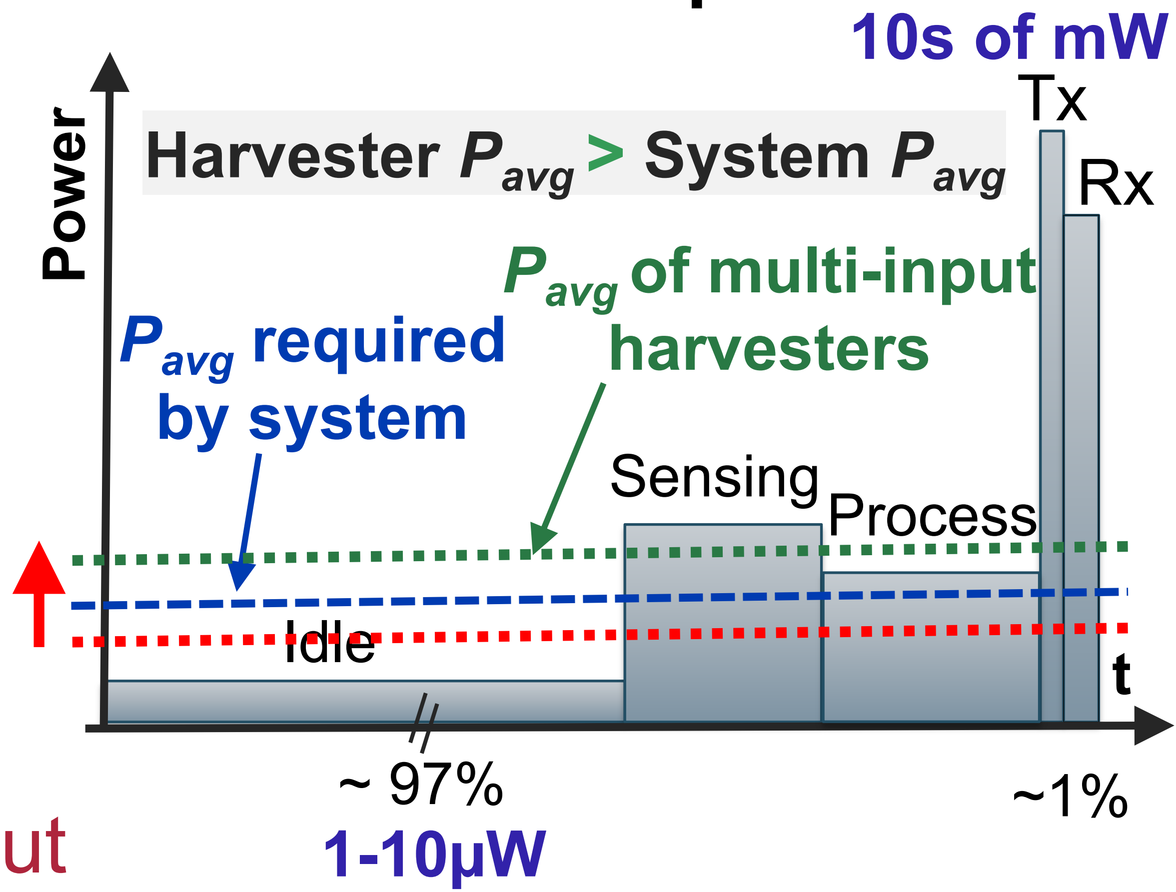
Power available from harvester is low and stochastic

Power Aggregation for Autonomous Operation

Wireless sensor device



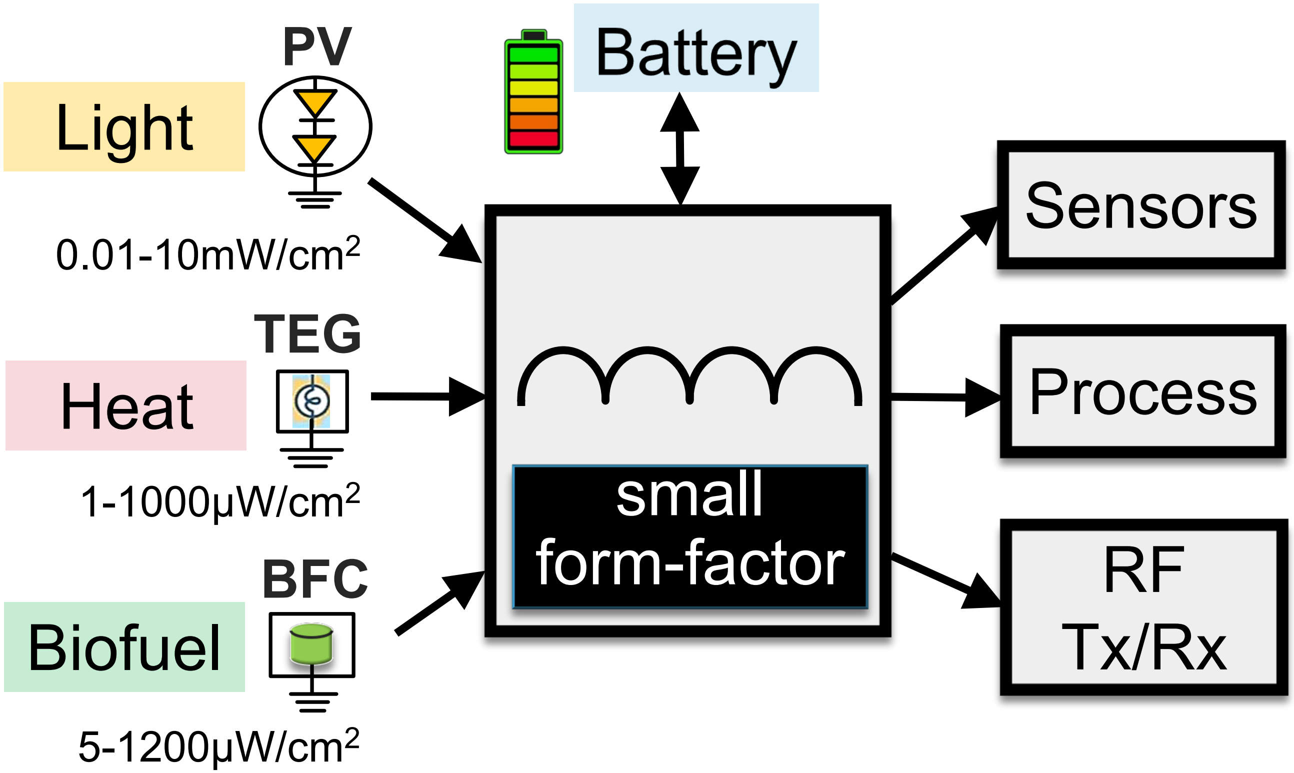
Power demand pattern



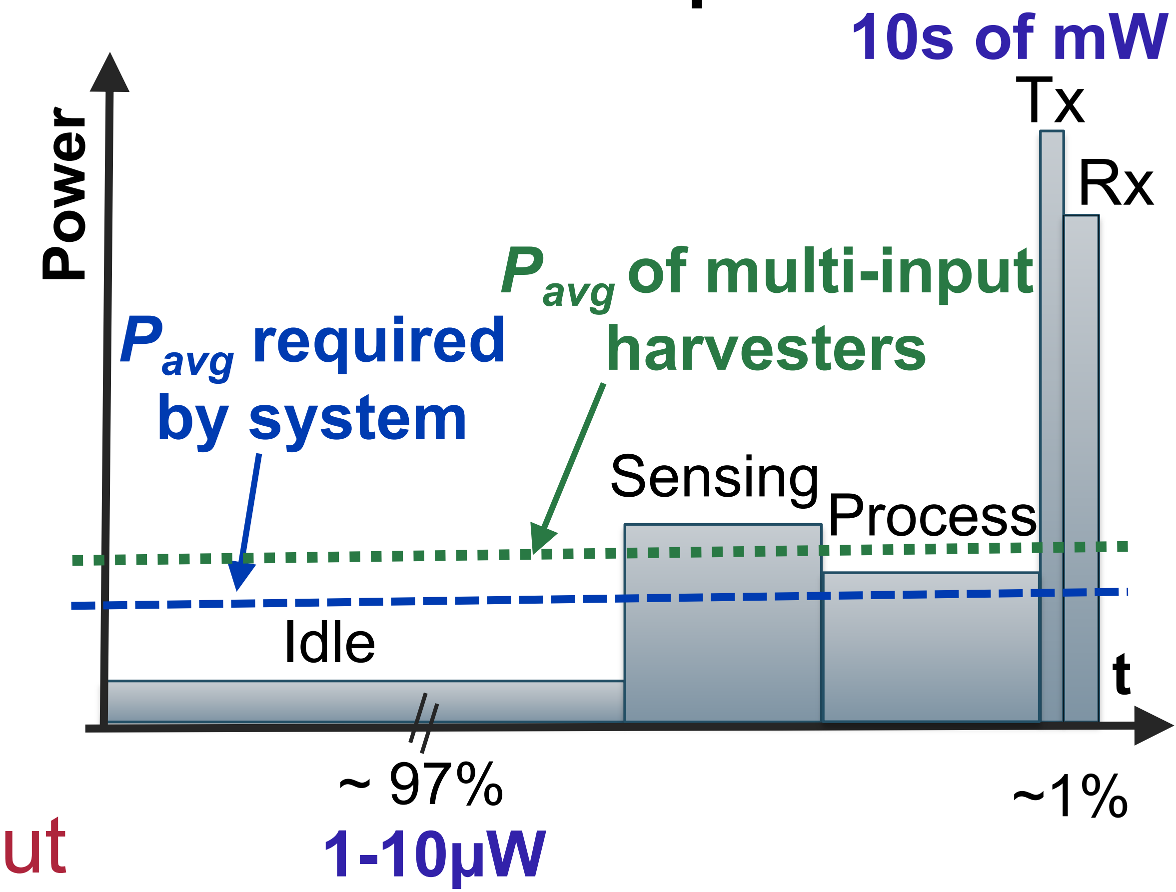
Multi-input harvesting increases harvester P_{avg}

Small Form-Factor MISIMO for Powering IoT Devices

Wireless sensor device



Power demand pattern

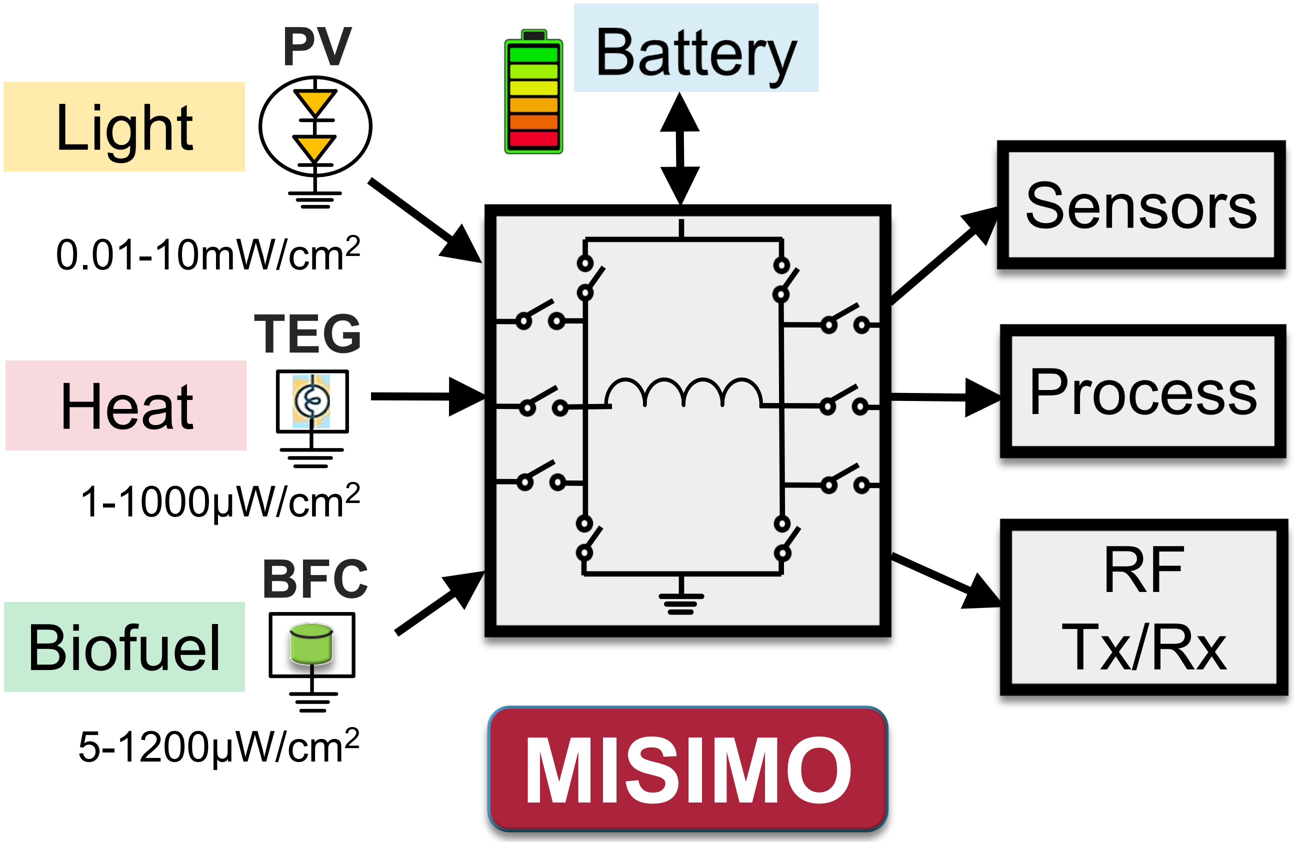


Multi-**I**nput **S**ingle-**I**nductor **M**ulti-**O**utput

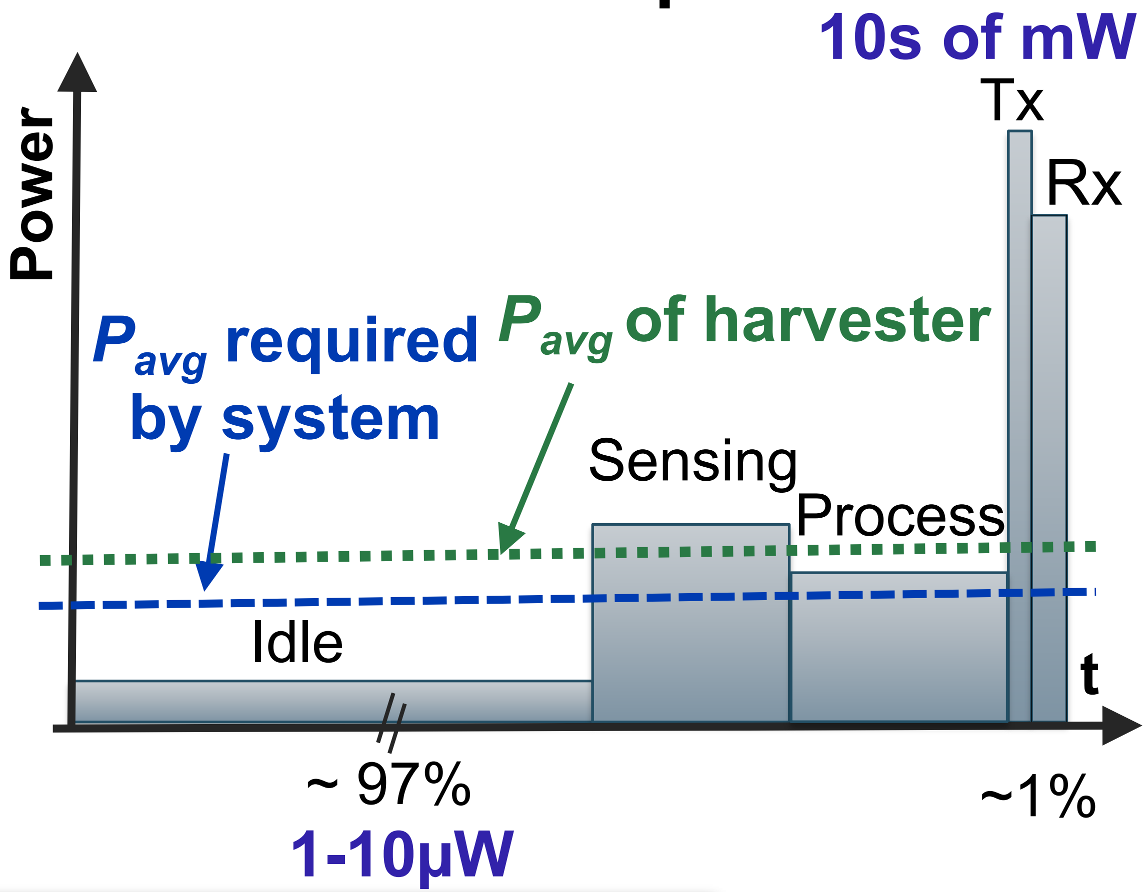
MISIMO

MISIMO Dynamic Switching Capability

Wireless sensor device



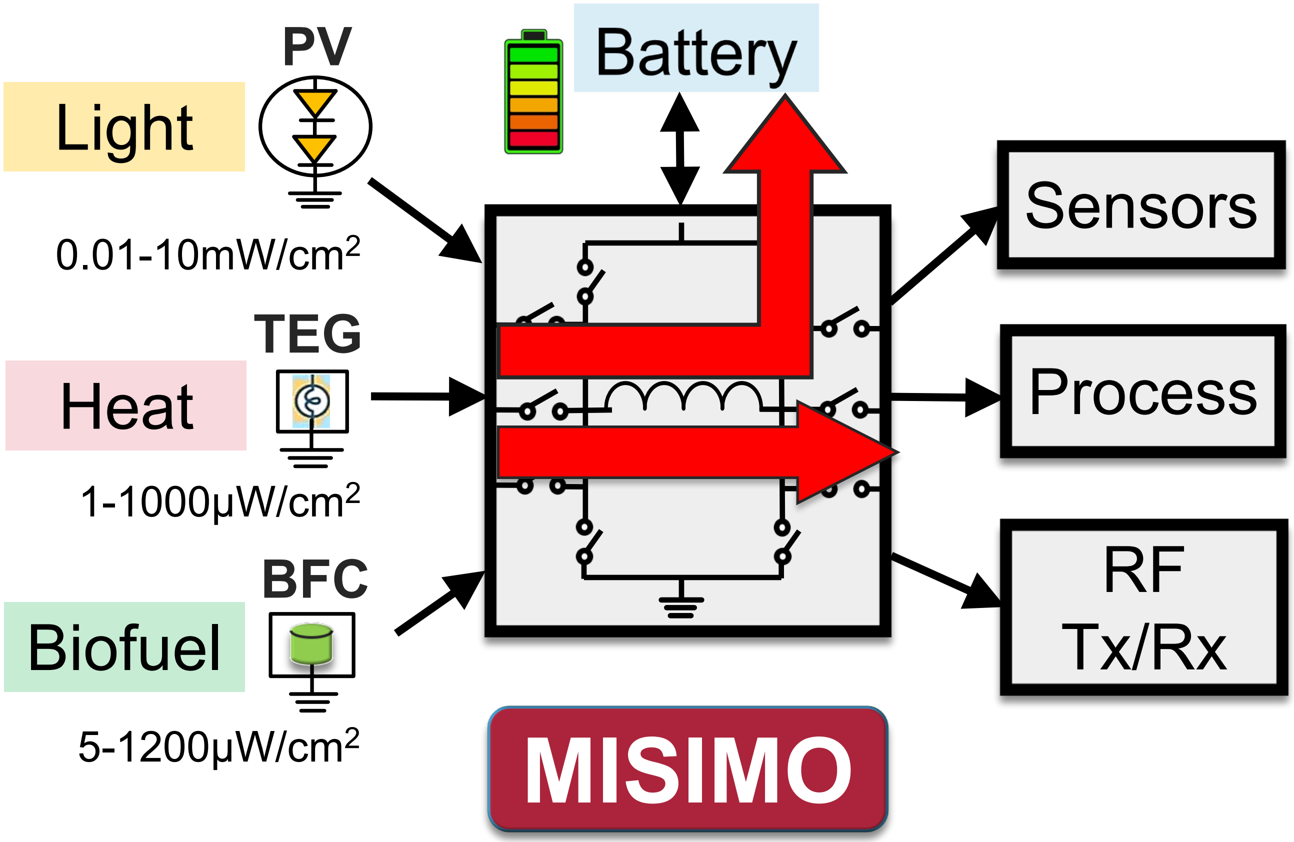
Power demand pattern



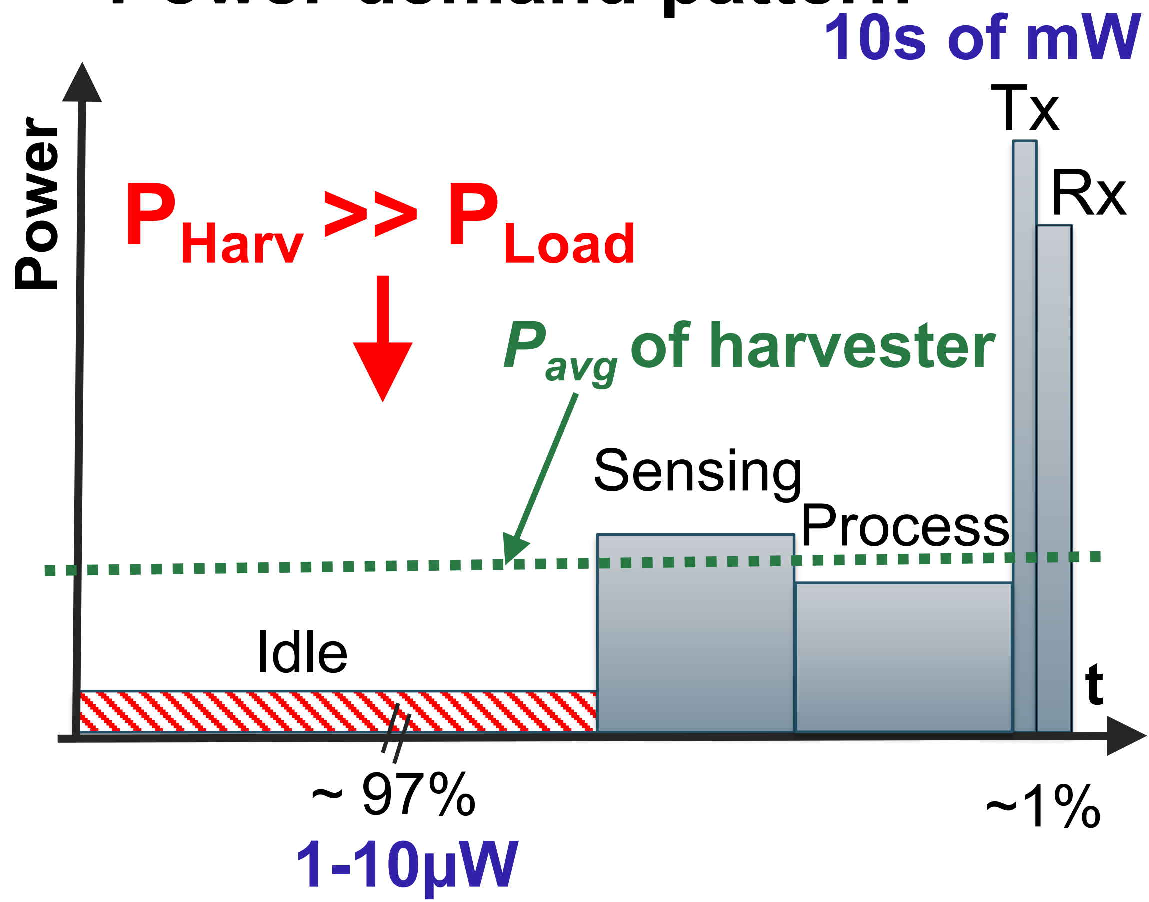
MISIMO dynamically switches between different configurations based on harvester/load conditions

MISIMO Dynamic Switching Capability

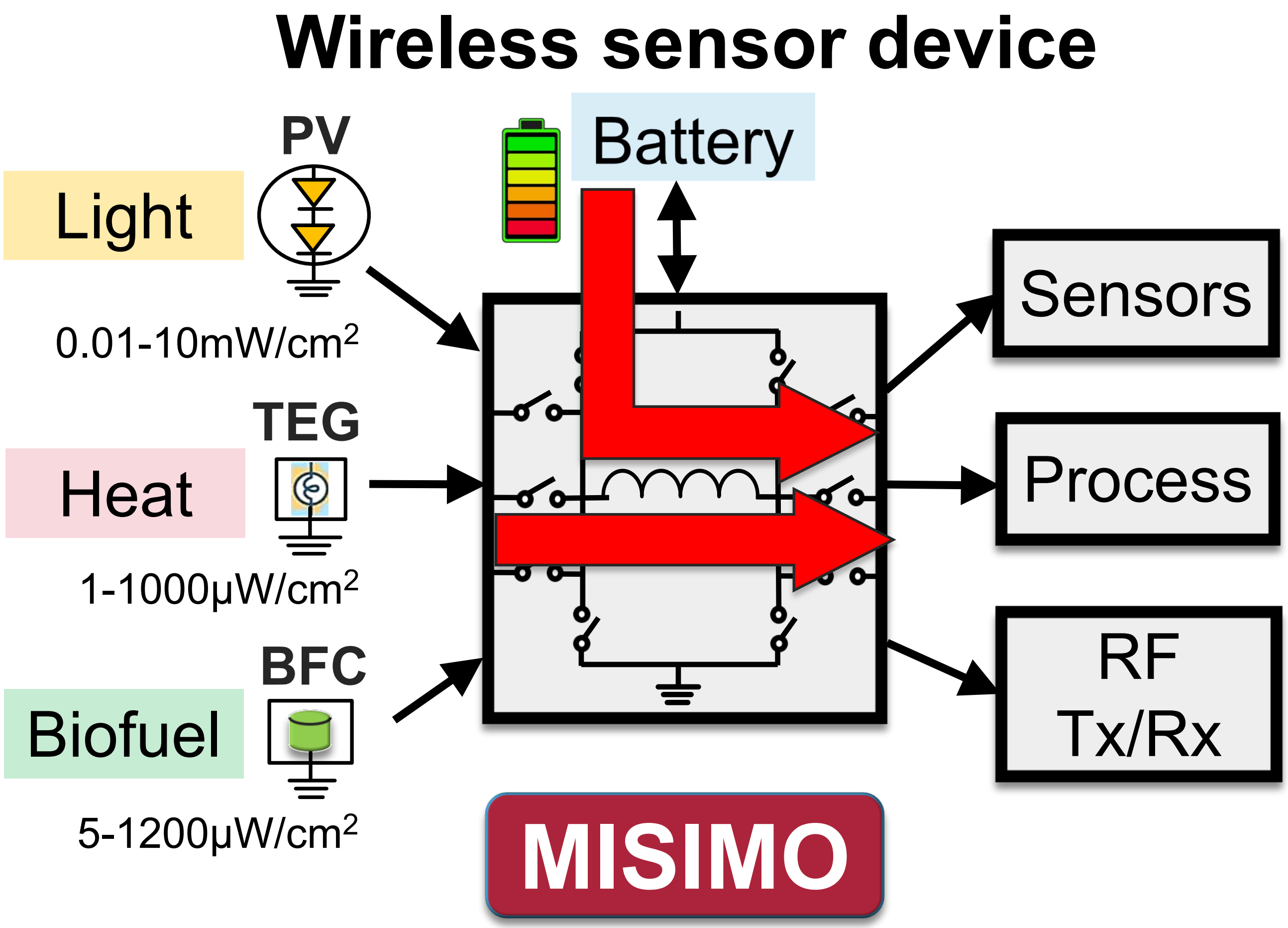
Wireless sensor device

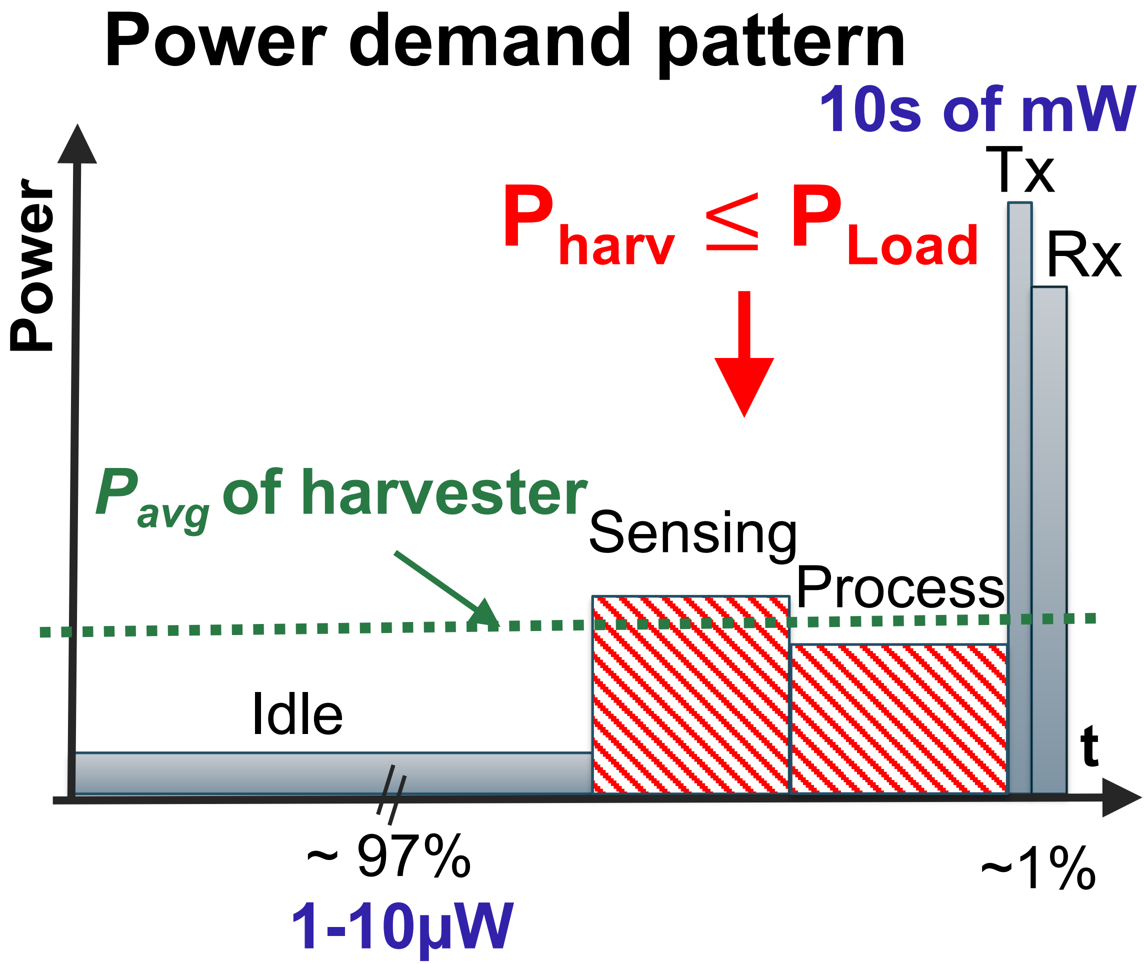


Power demand pattern



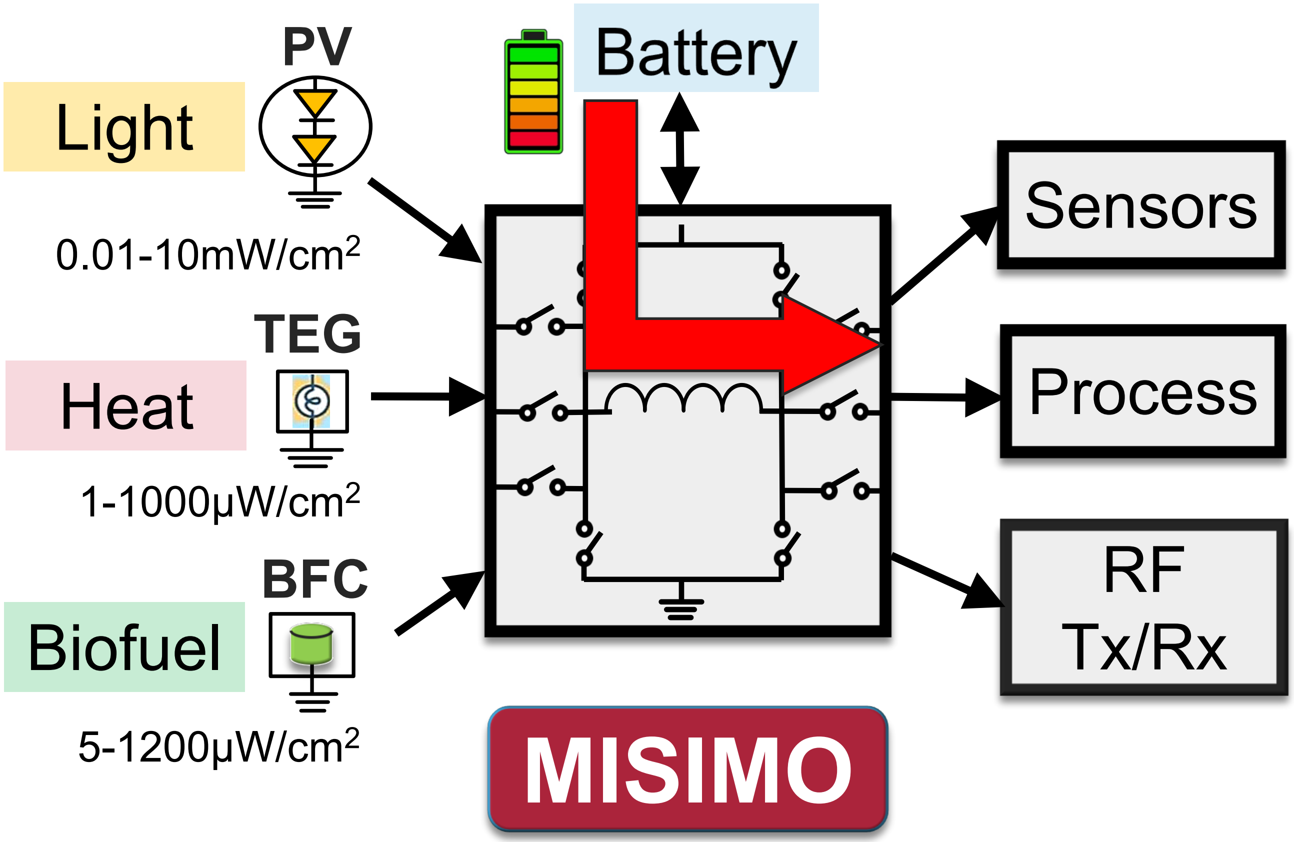
MISIMO Dynamic Switching Capability



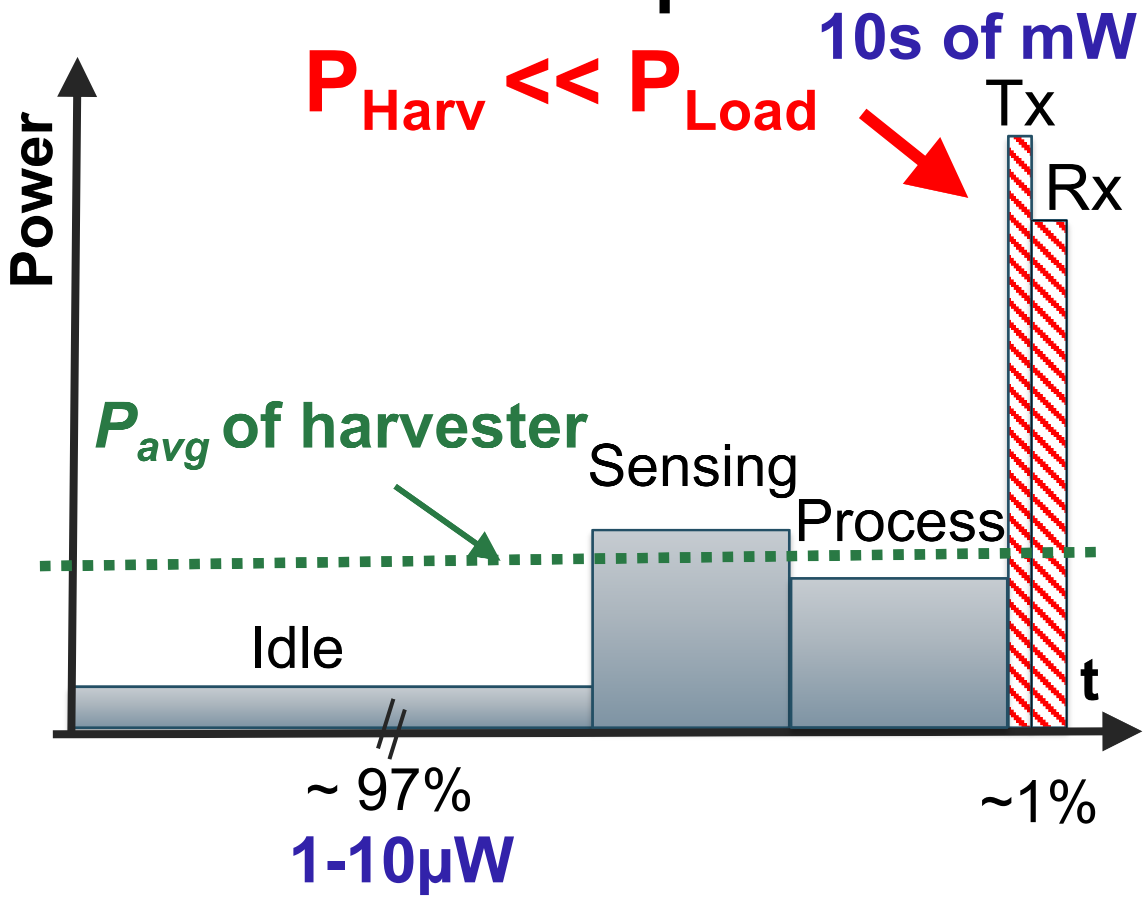


MISIMO Dynamic Switching Capability

Wireless sensor device



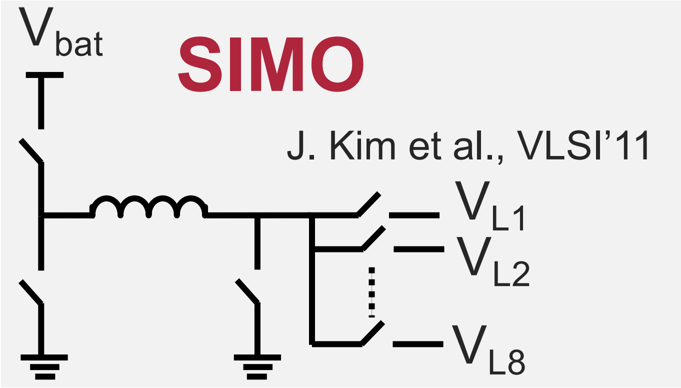
Power demand pattern

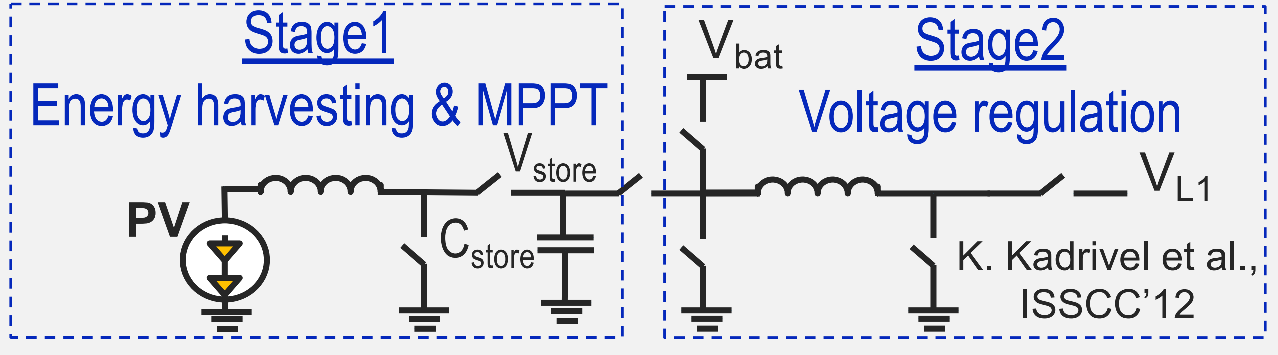


Outline

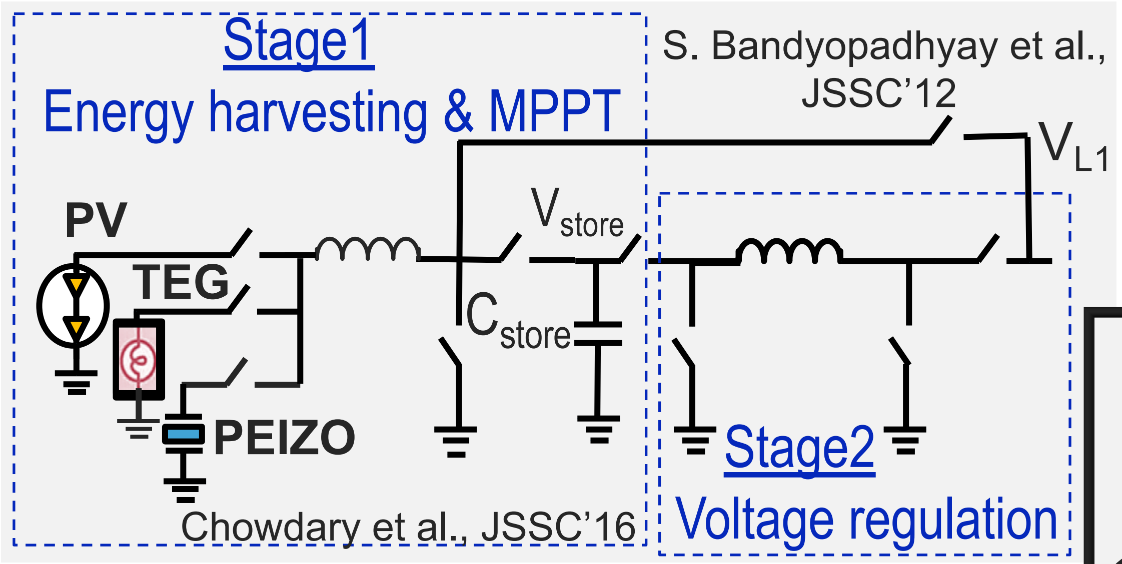
- State-of-the-Art and Single-Inductor Challenges
- Decoupling Source MPPT and Load Regulation
- Circuit Techniques for Wide Dynamic Range
- Measurement Results
- Conclusion

Towards Small Form-Factor MISIMO

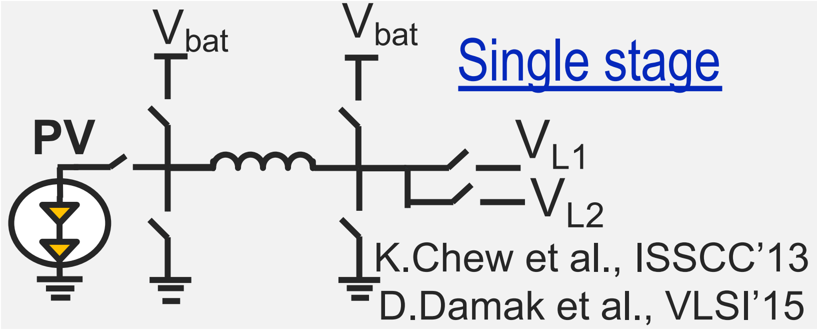




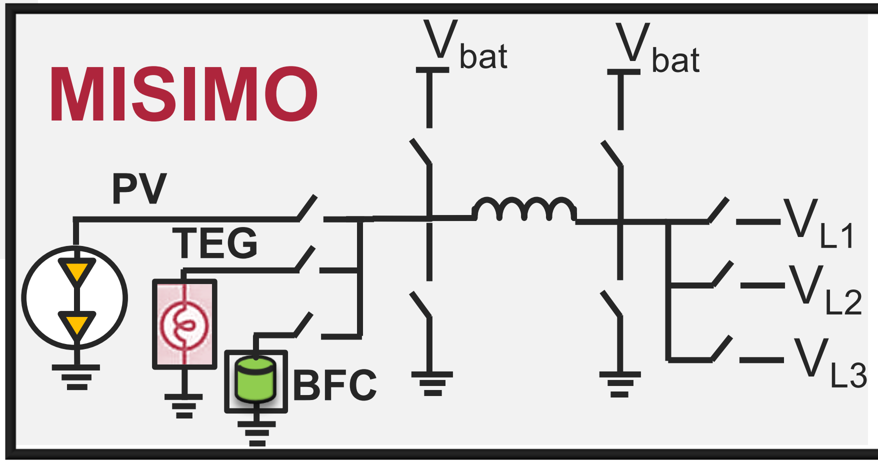
- Single input
- Single output
- Cascaded losses



+ Multiple inputs
- Cascaded losses
- Single output

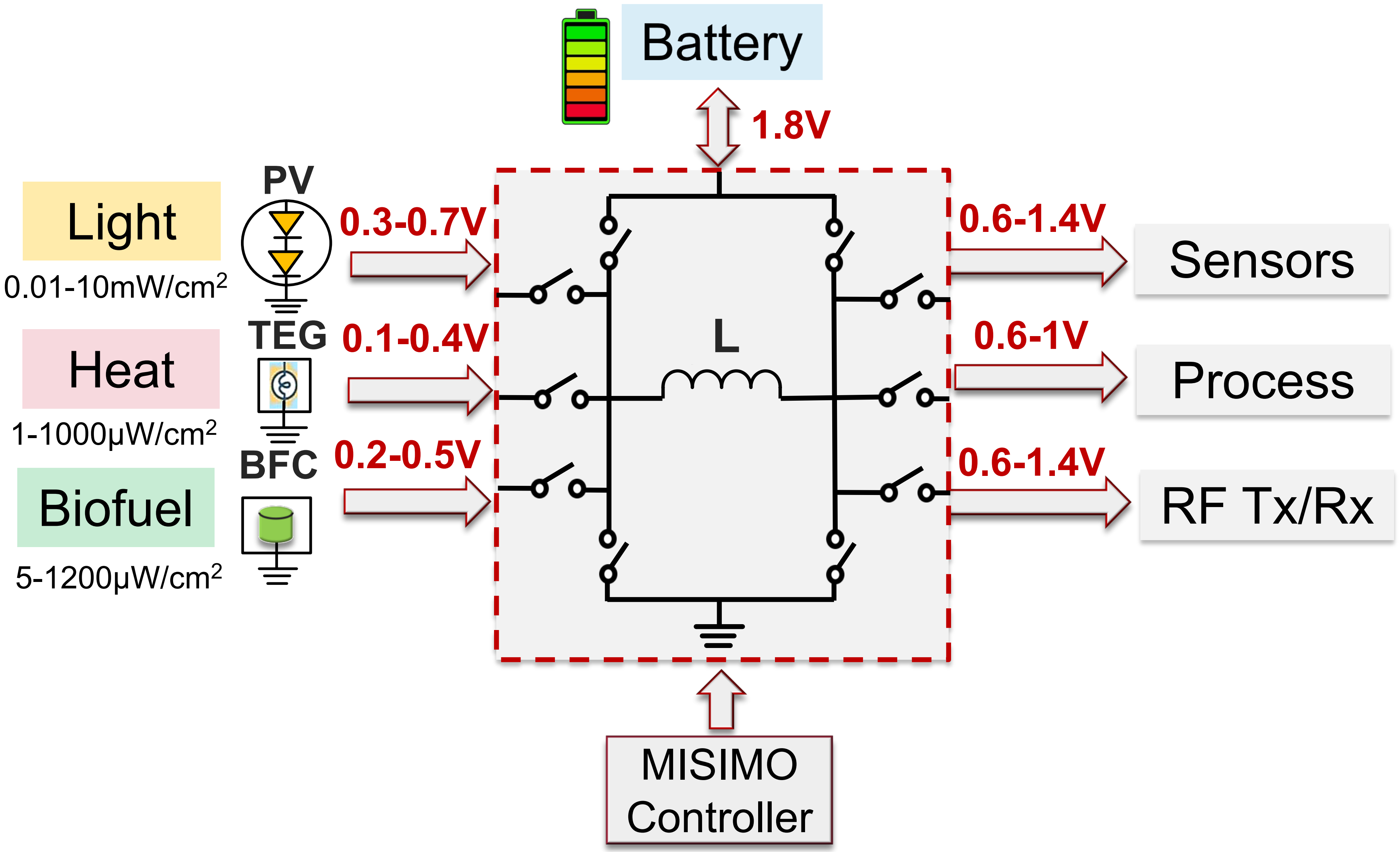


+ No cascaded losses
+ Multiple outputs
- Single input



+ No cascaded losses
+ Multiple inputs
+ Multiple outputs

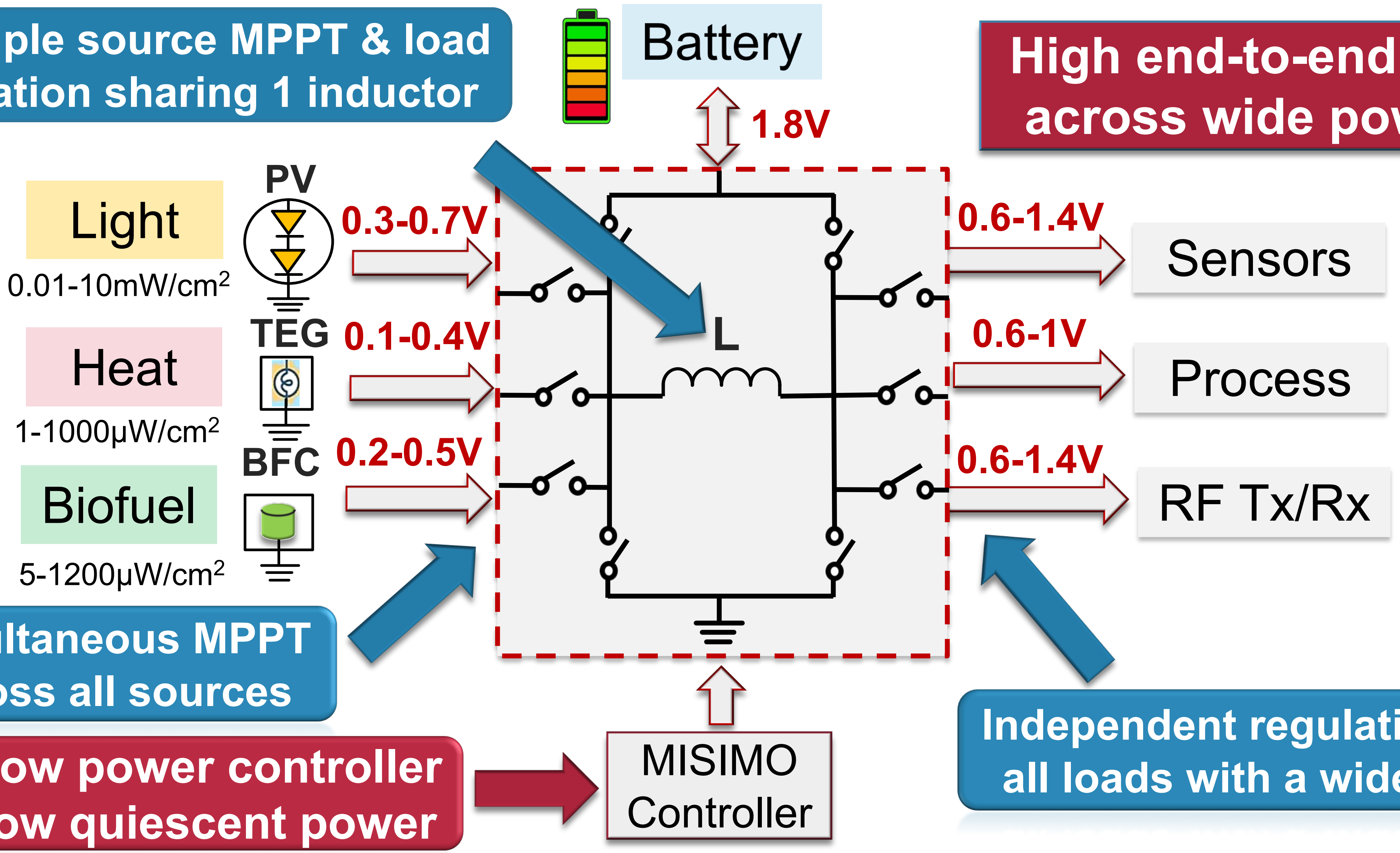
MISIMO Goals and Challenges



MISIMO Goals and Challenges

Decouple source MPPT & load regulation sharing 1 inductor

High end-to-end efficiency across wide power range



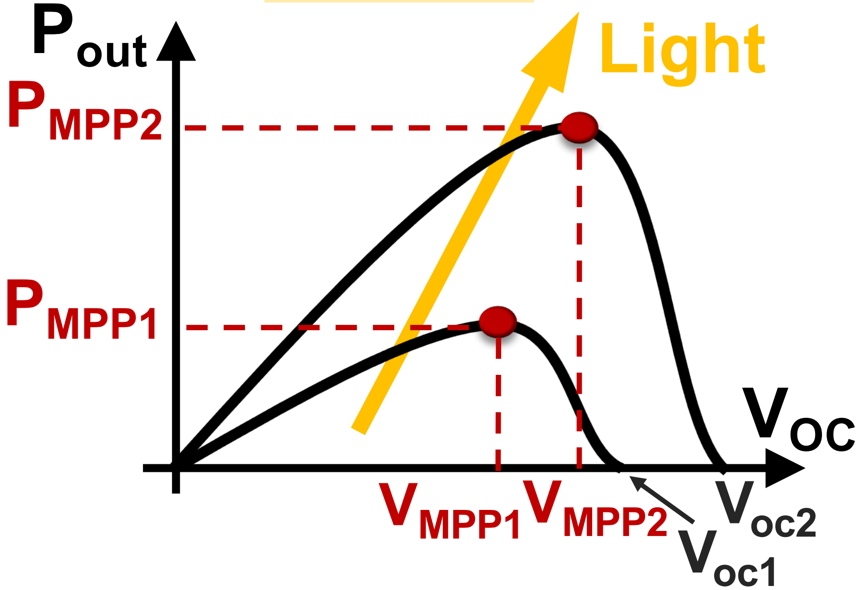
Simultaneous MPPT across all sources

Ultra low power controller with low quiescent power

Independent regulation of all loads with a wide DR

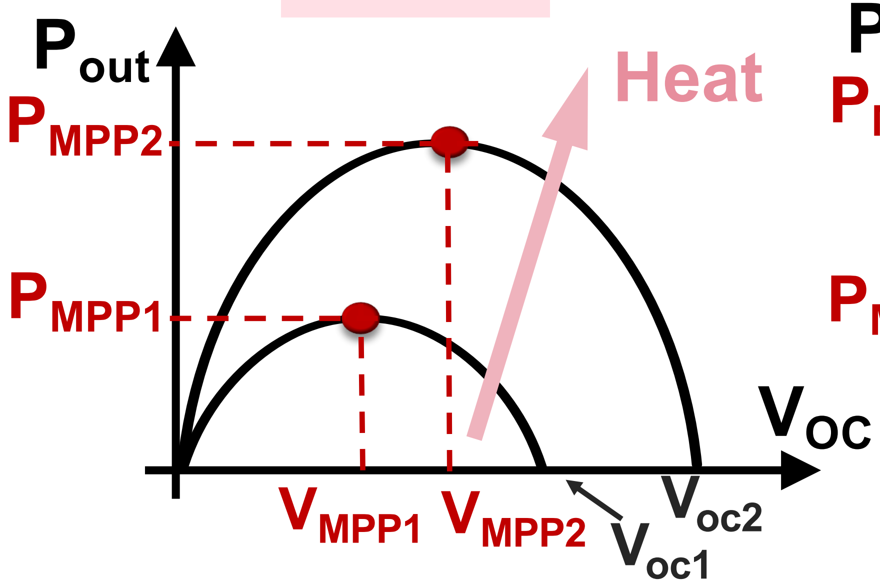
Fractional Open Circuit Voltage (VOC) MPPT

PV



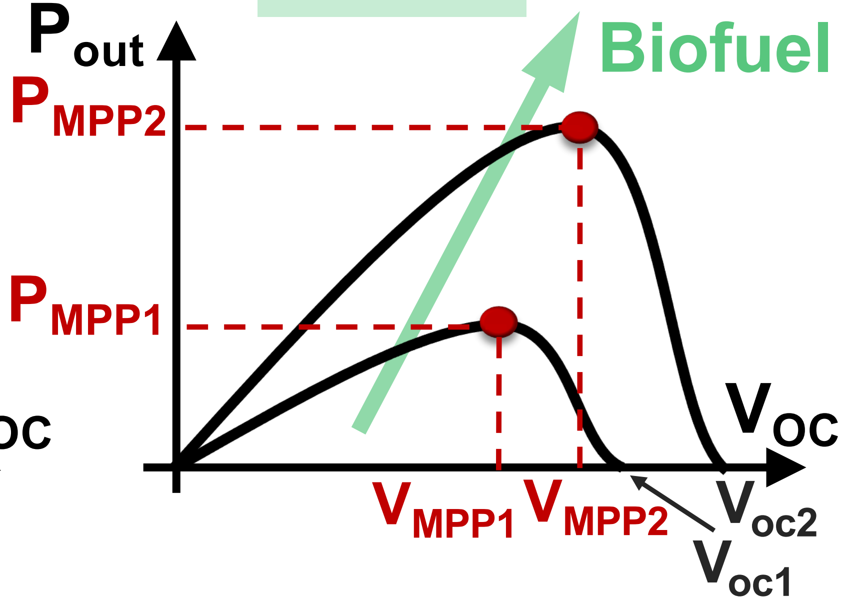
$V_{MPP\text{-}PV} \approx 0.75\ V_{OC}$

TEG



$V_{MPP\text{-}TEG} = 0.5\ V_{OC}$

BFC



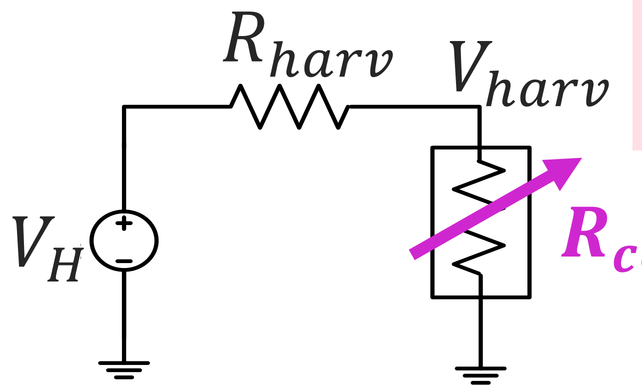
$V_{MPP\text{-}BFC} \approx 0.6\ V_{OC}$

$V_{MPP} = K\ V_{OC}$

Generated by fractional VOC sample and hold circuit

For MPPT: Input voltage is regulated around V_{MPP}

Hysteresis Comparator for 2-D MPPT



Adaptive to the available harvester energy

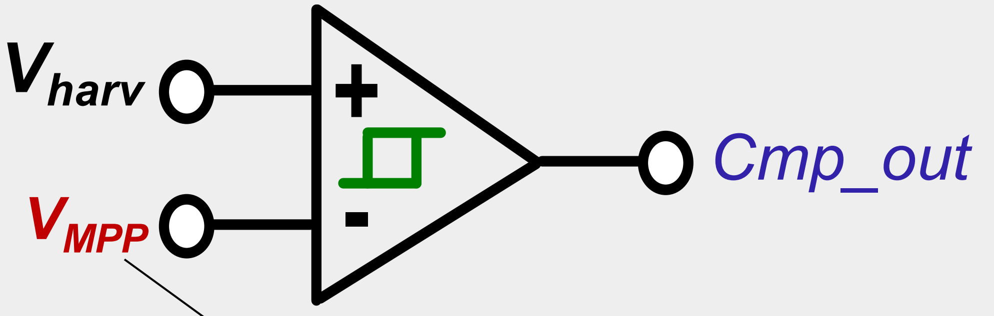
$$R_{conv} = \frac{2LT_{sw}}{T_{\varphi 1}^2}$$

set for MPPT

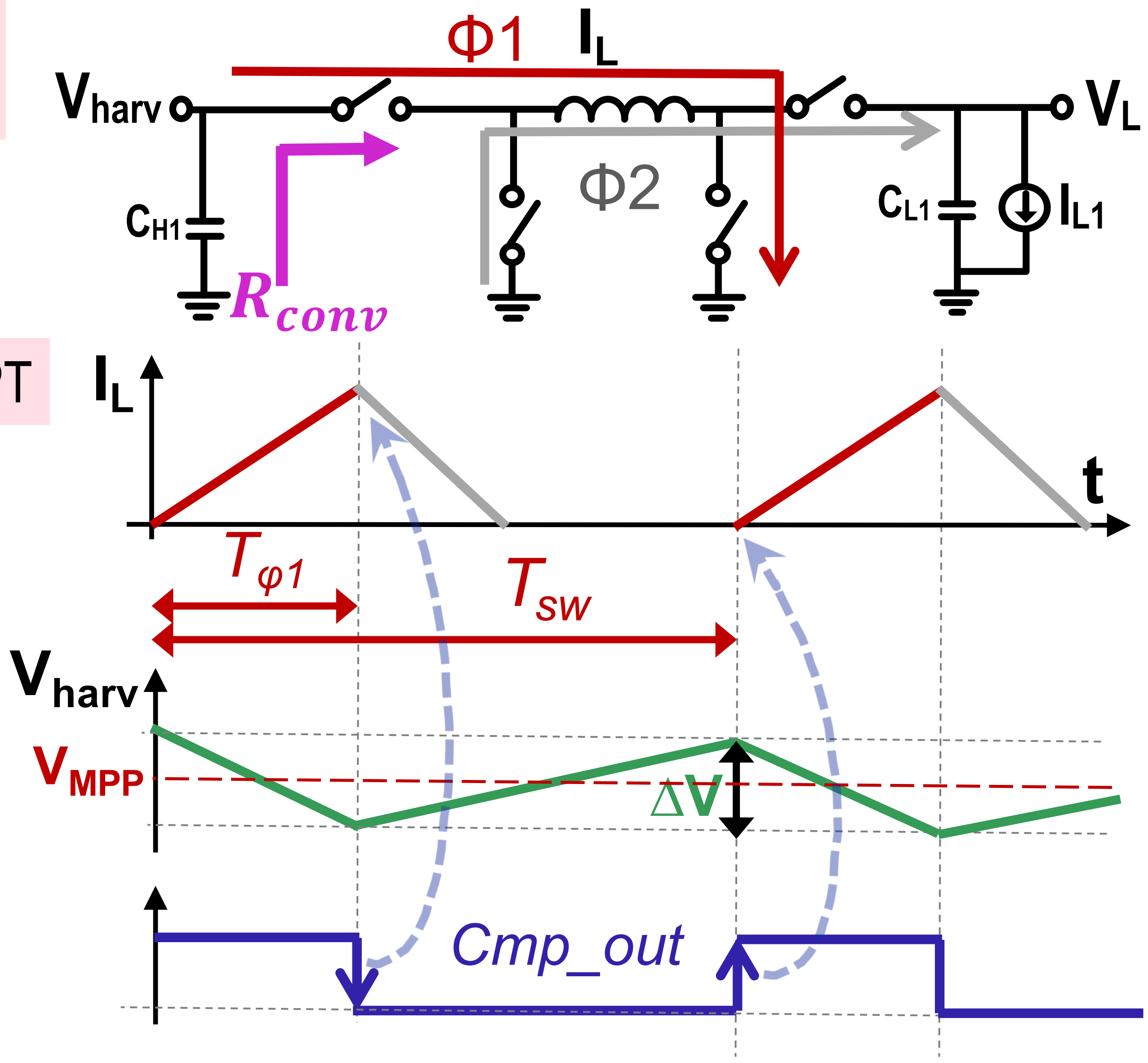
For MPPT

$$R_{conv} = R_{harv}$$
$$V_{harv} = V_{MPP}$$

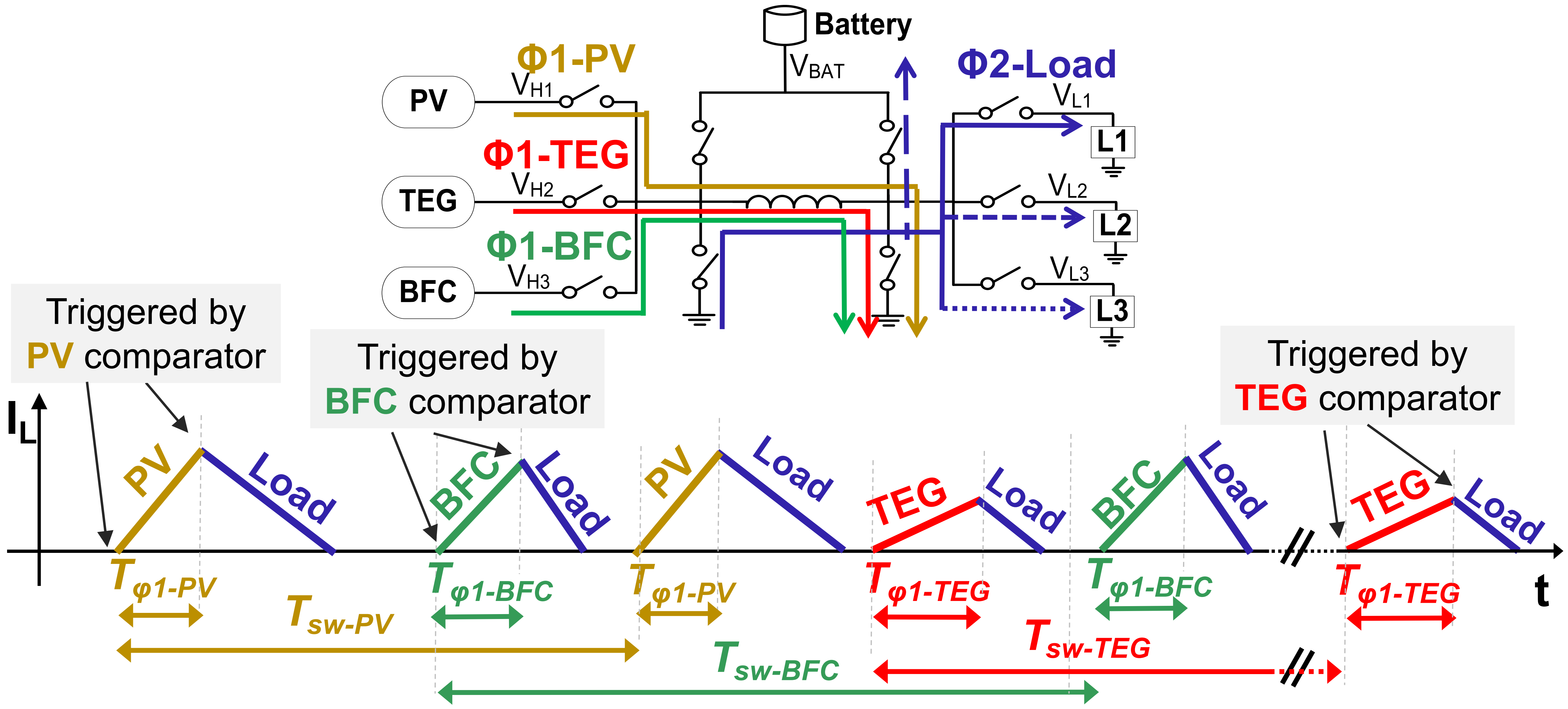
ΔV: hysteresis window



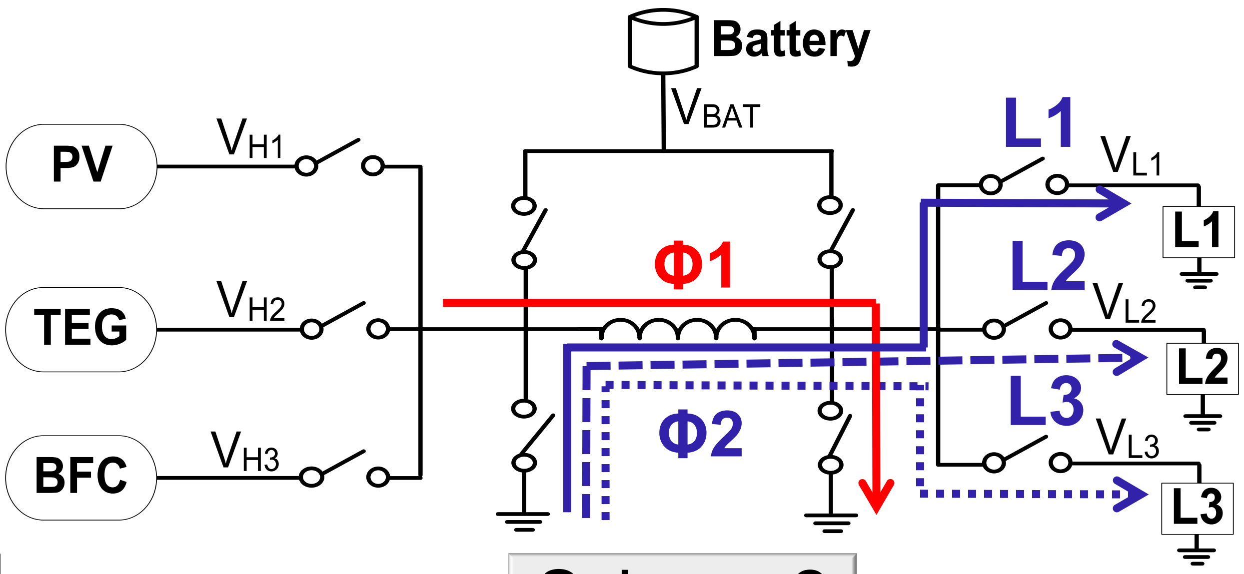
set by FVOC



Time-Shared Inductor for Multi-Input Harvesting

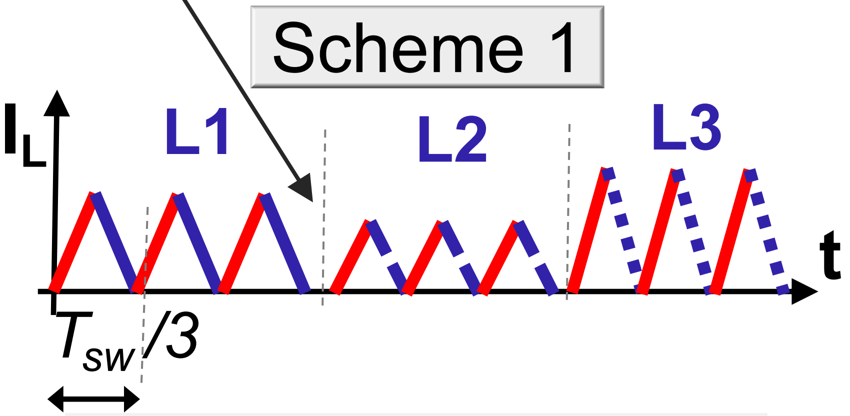


Inductor Switching Schemes for Load Regulation



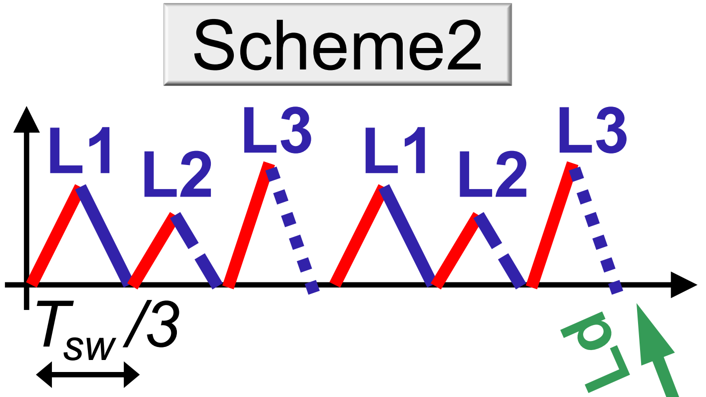
L1 got sufficient energy

Triggered by load Hysteresis comparator



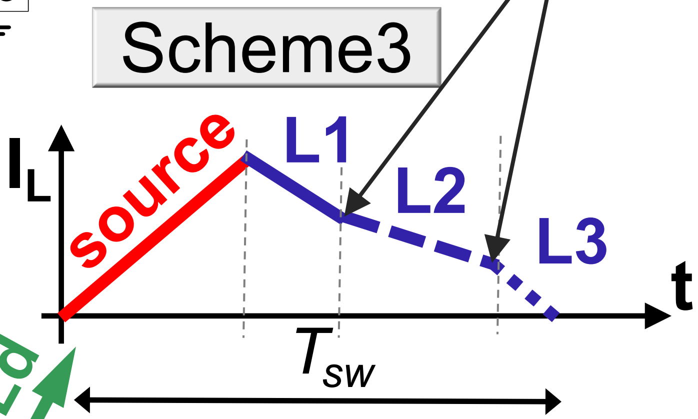
- High switching losses
- High voltage droop

D. Ma et al., JSSC’03



- High switching losses
+ Low voltage droop

J. Kim et al., VLSI’11



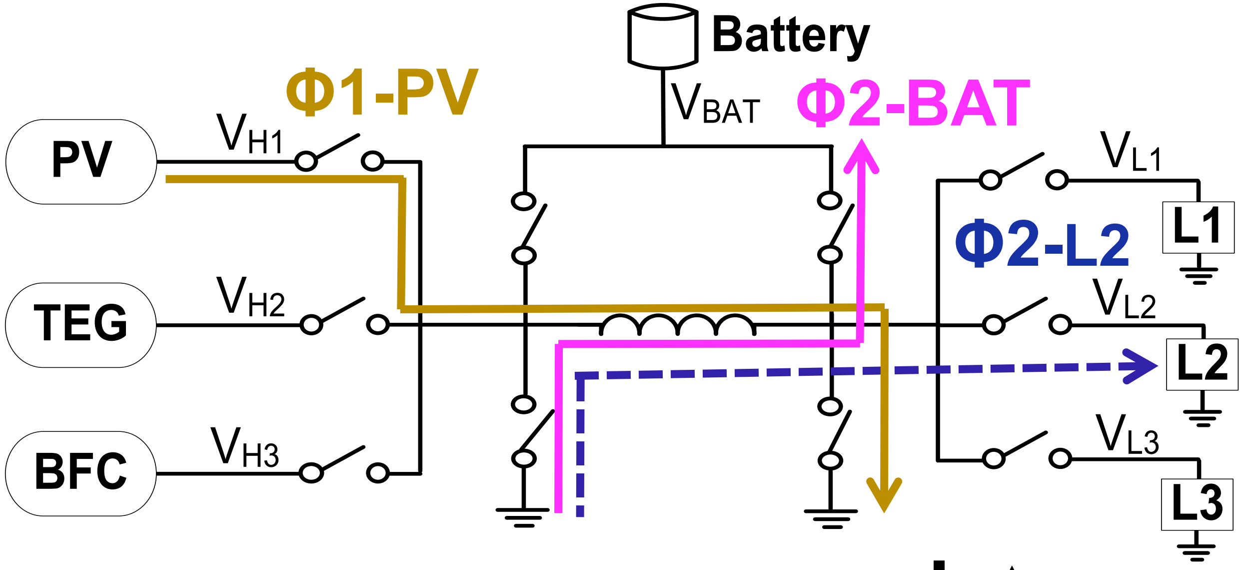
+ Low switching losses

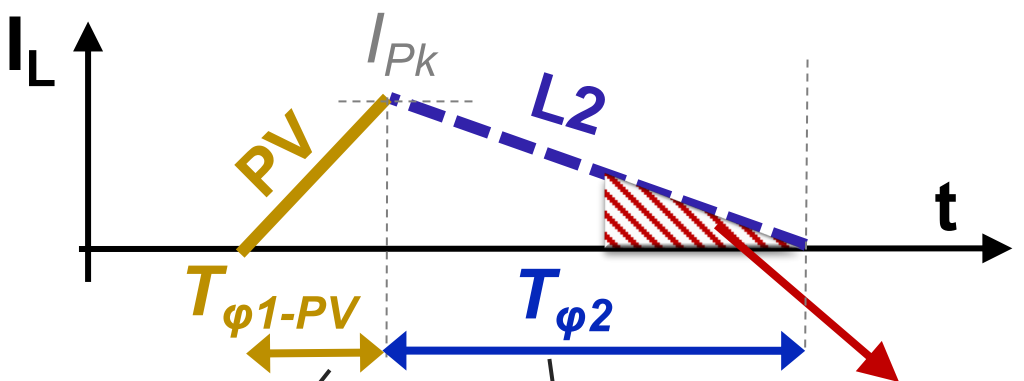
C. Chae et al., ISSCC’07

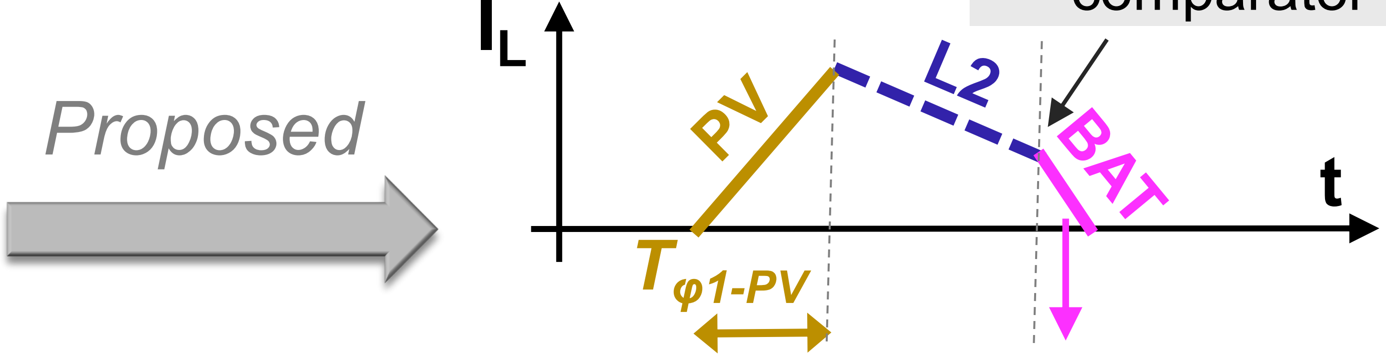
Outline

- State-of-the-Art and Single-Inductor Challenges
- Decoupling Source MPPT and Load Regulation
- Circuit Techniques for Wide Dynamic Range
- Measurement Results
- Conclusion

MPPT and Load Regulation Decoupling







Triggered by load comparator

$T_{\varphi 1}$ set for MPPT

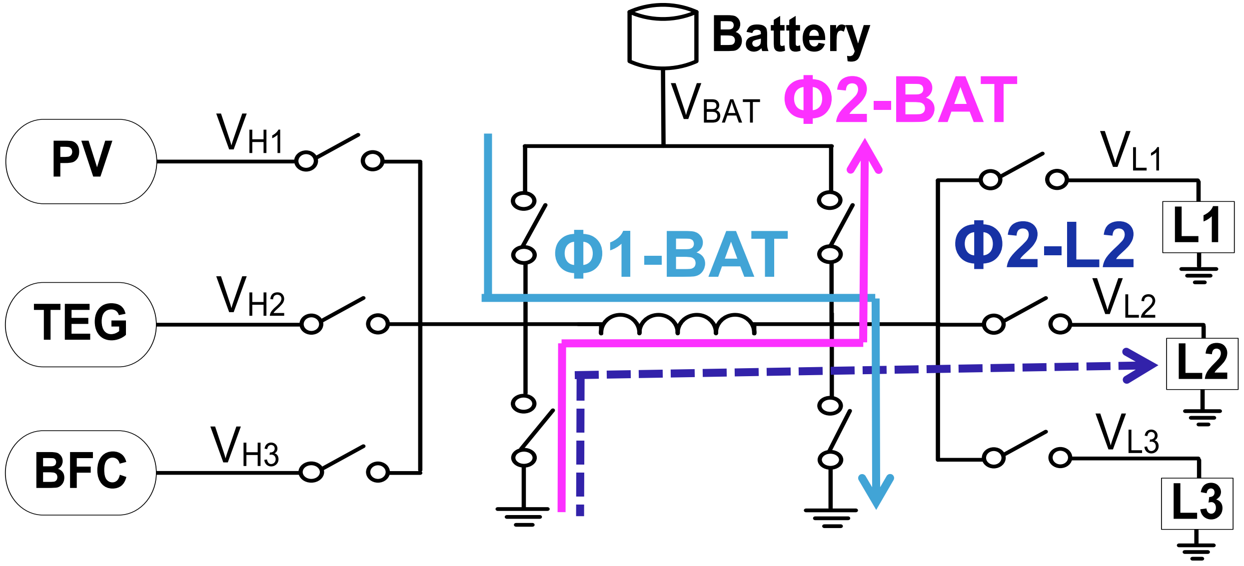
$T_{\varphi 2}$ set by ZCD

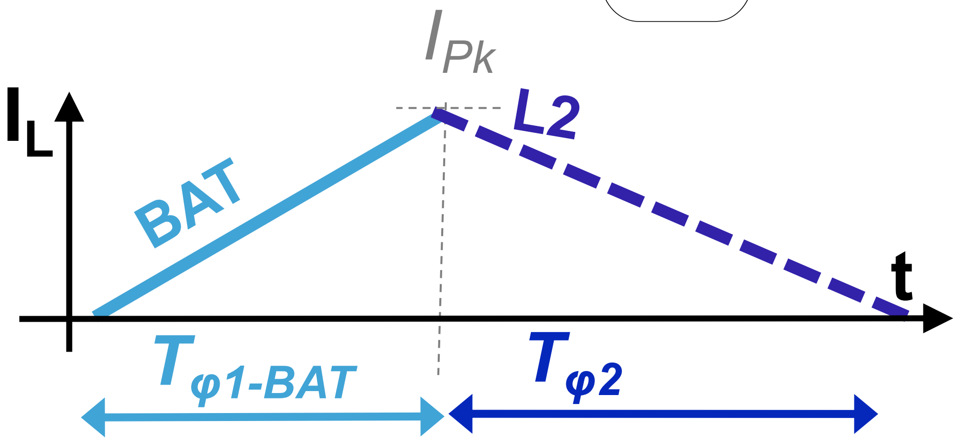
High voltage ripple
Degraded load regulation

Trade off in “K. Chew et al., ISSCC 2013”

Extra charge recycled to battery
MPPT & load regulation decoupled

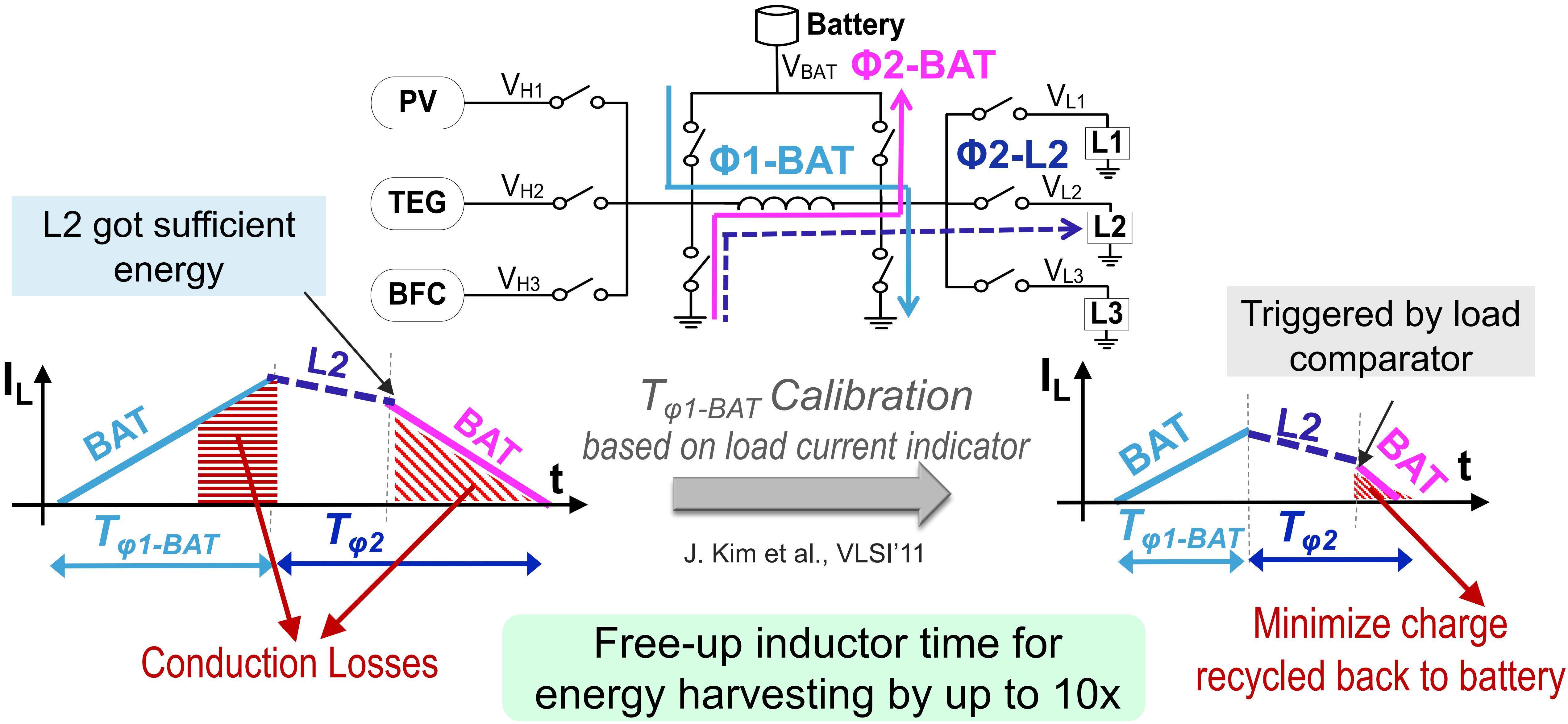
Battery-Inductor Charging Time ($T_{\varphi1\text{-}BAT}$) Calibration





$T_{\varphi1\text{-}BAT}$ should be large enough to support the maximum load power

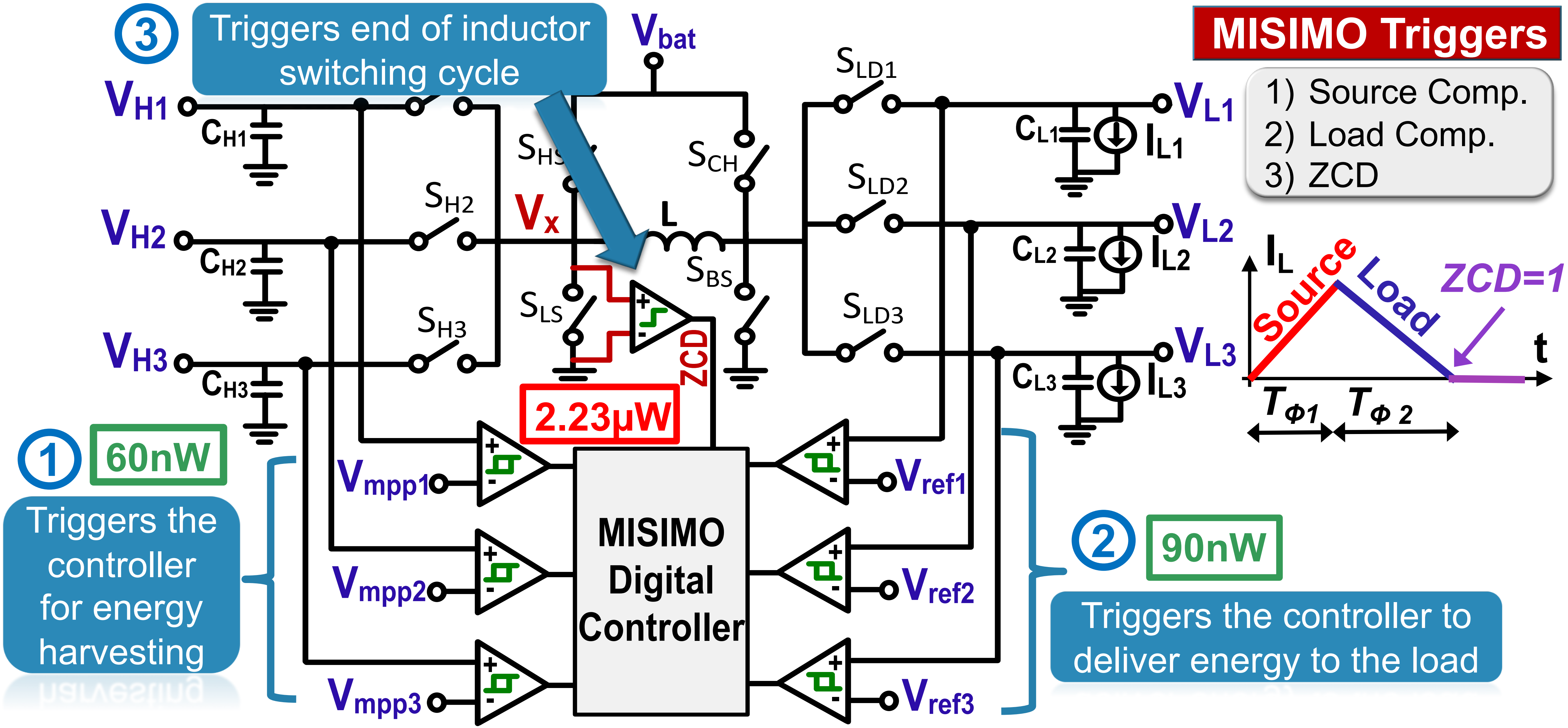
Battery-Inductor Charging Time ($T_{\varphi 1\text{-}BAT}$) Calibration



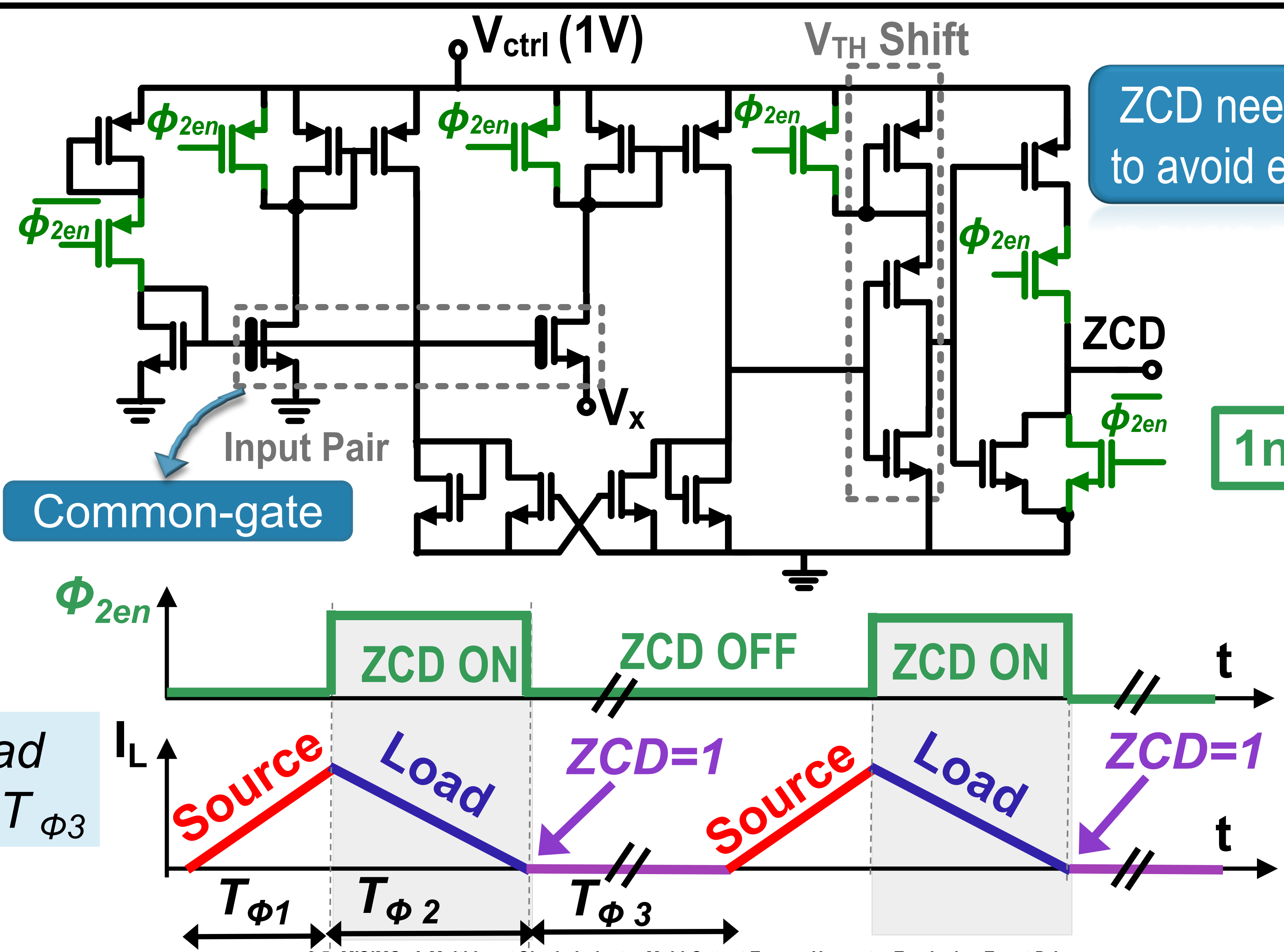
Outline

- State-of-the-Art and Single-Inductor Challenges
- Decoupling Source MPPT and Load Regulation
- Circuit Techniques for Wide Dynamic Range
- Measurement Results
- Conclusion

MISIMO Event Driven Controller



Duty Cycled ZCD for Lowering Quiescent Power



ZCD needs to be fast enough to avoid efficiency degradation

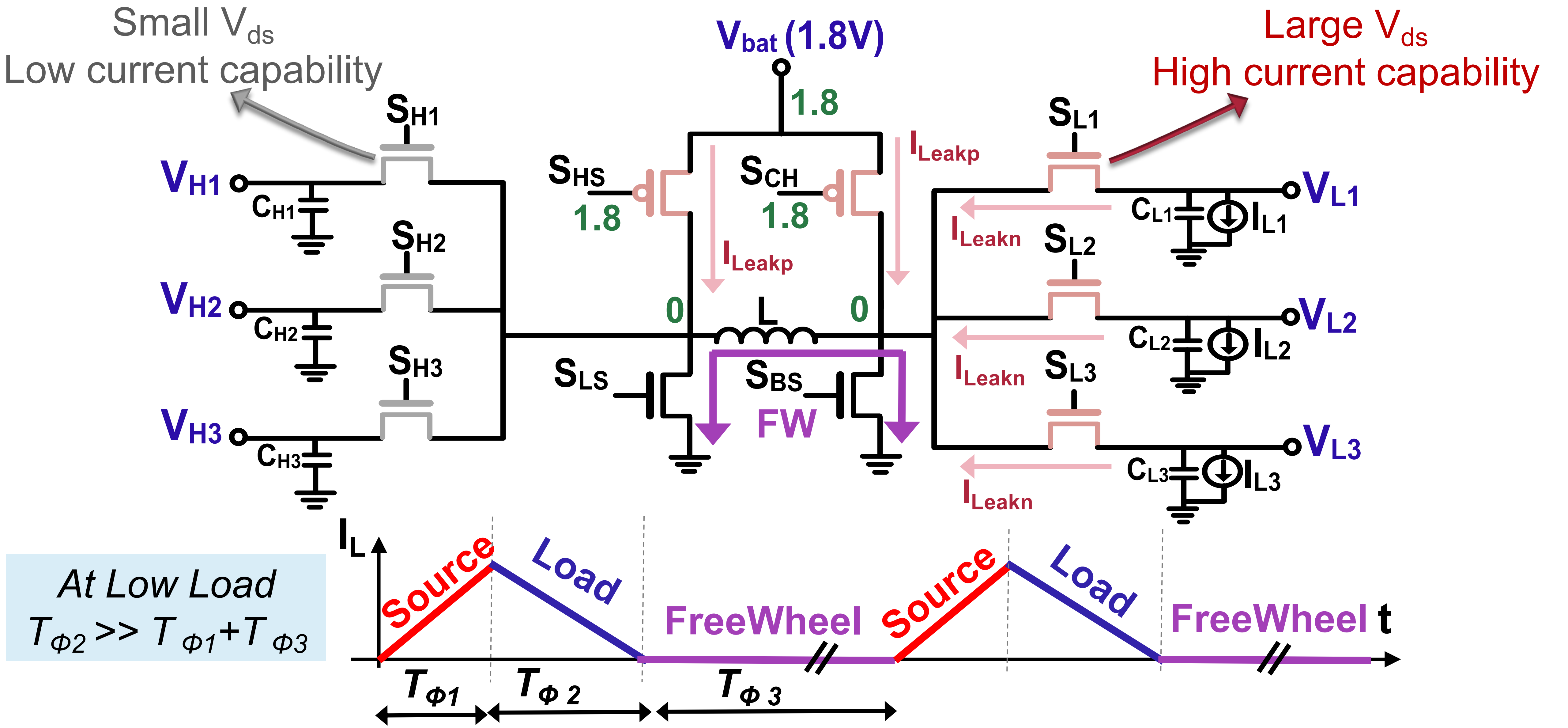
~~2.23μW~~

1nW @ P_{out}=10uW

At Low Load

$T_{\Phi 2} << T_{\Phi 1} + T_{\Phi 3}$

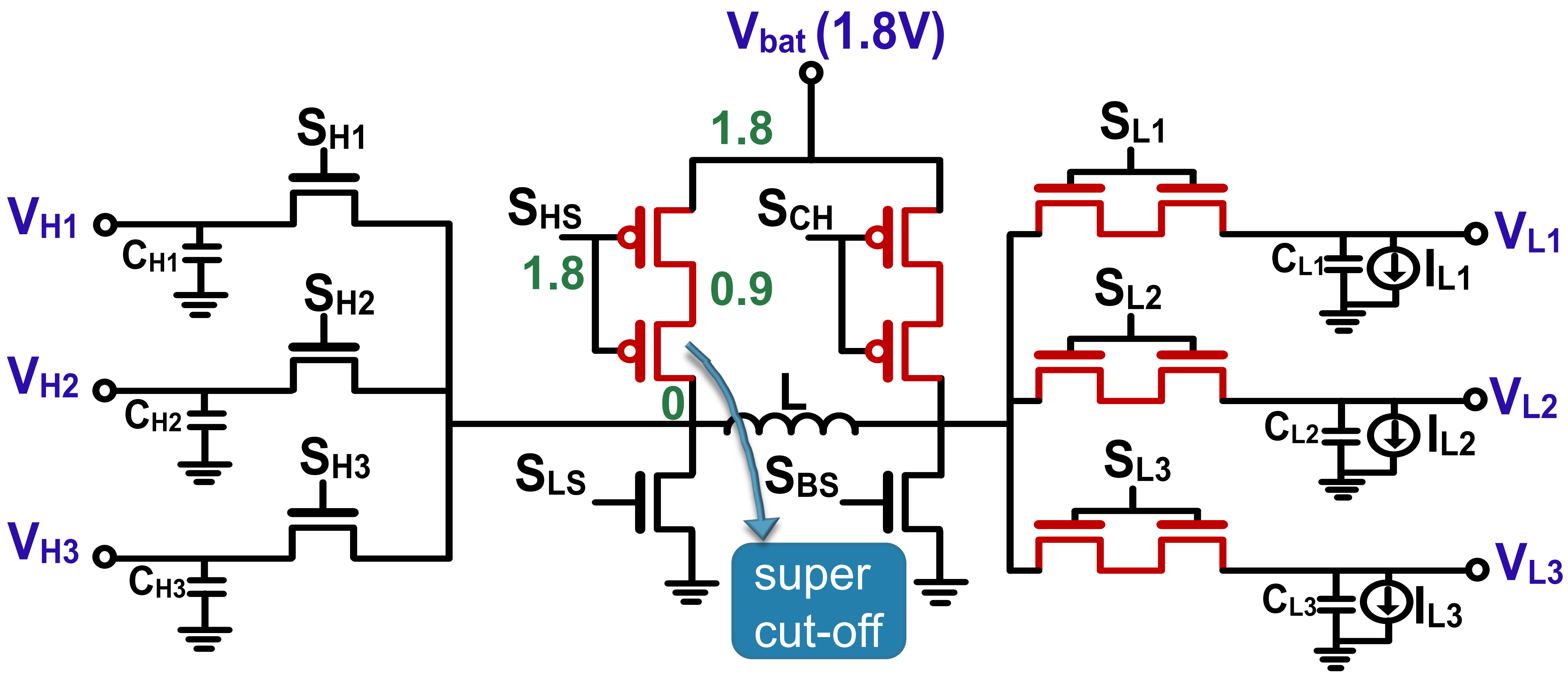
Leakage Dominates Low Load Losses



At Low Load

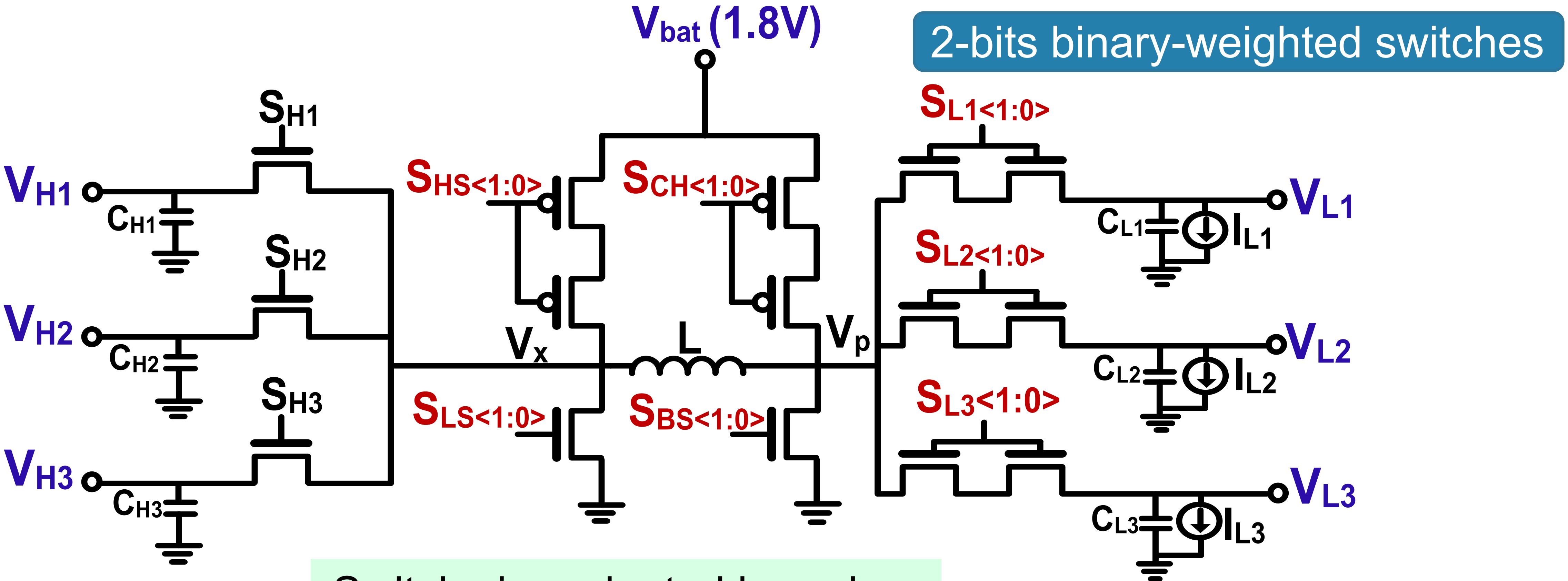
$T_{\Phi 2} >> T_{\Phi 1} + T_{\Phi 3}$

Cascoding Power Switches to Lower Leakage Losses



Cascoding transistors reduces leakage in freewheel phase by 9x

Switch Size Modulation (SSM)



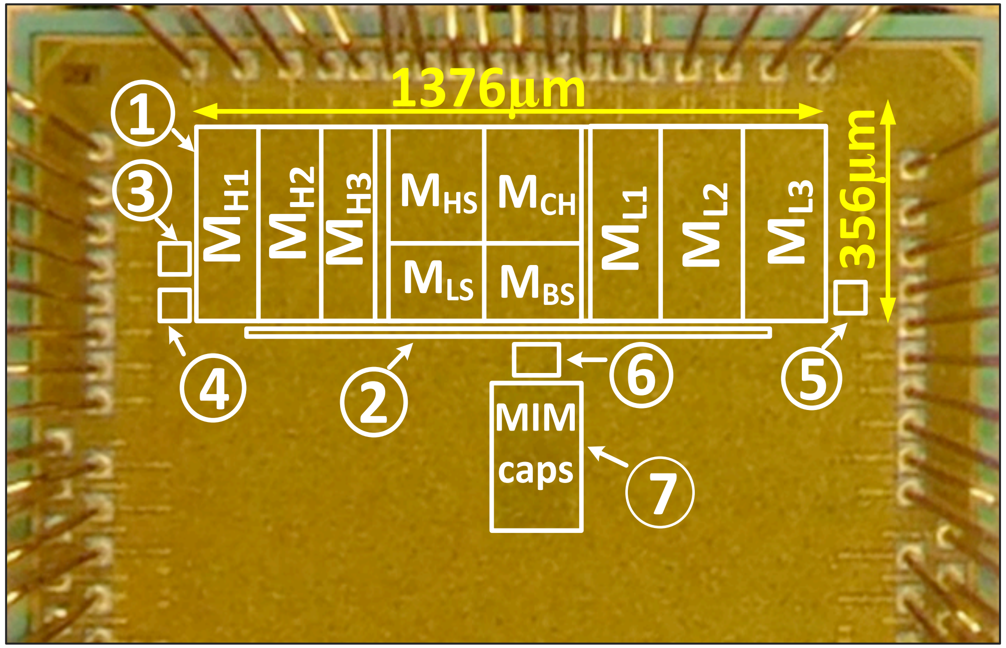
Switch size adapted based on load current indicator output

SSM reduces switching losses & improves efficiency by up to 24%

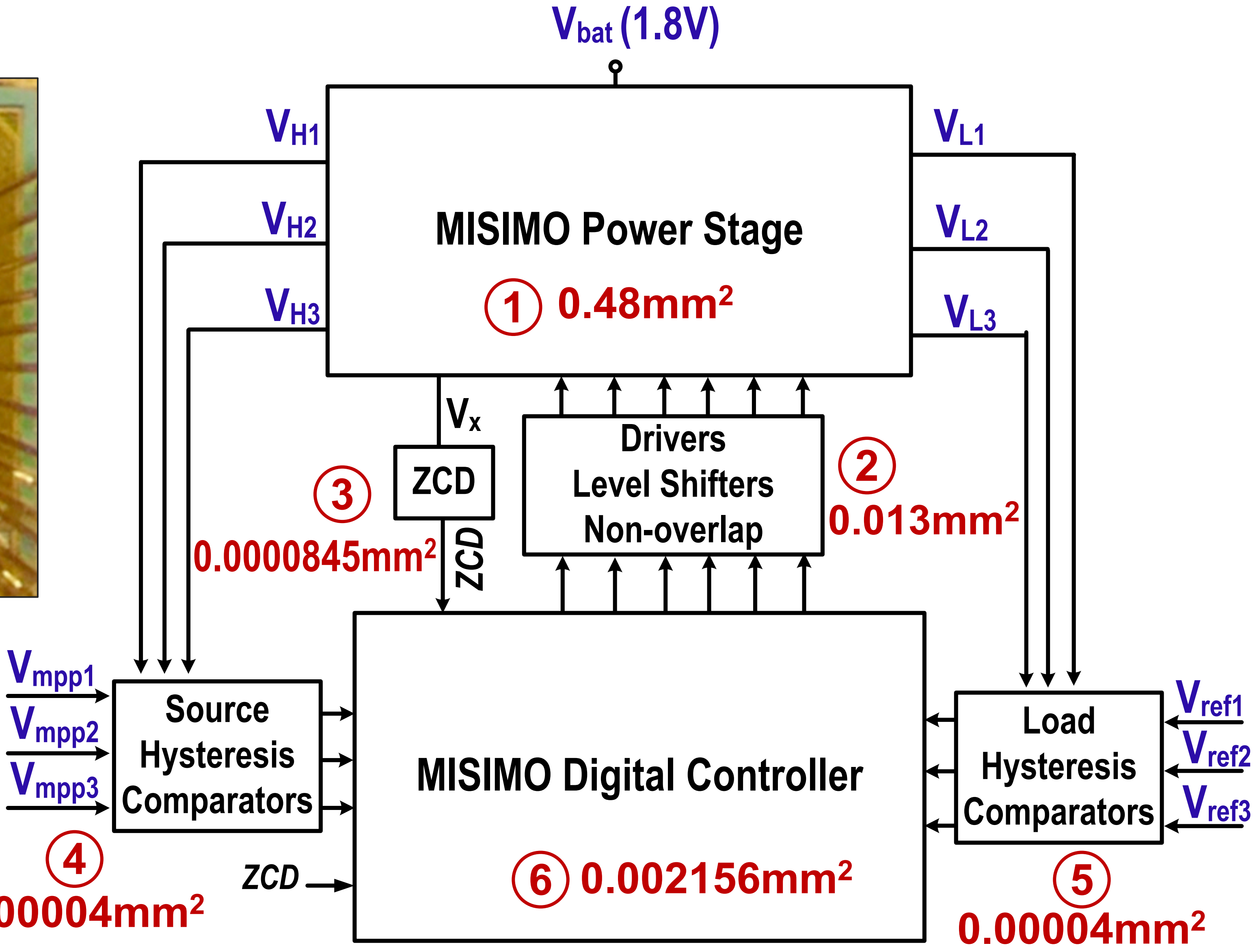
Outline

- State-of-the-Art and Single-Inductor Challenges
- Decoupling Source MPPT and Load Regulation
- Circuit Techniques for Wide Dynamic Range
- Measurement Results
- Conclusion

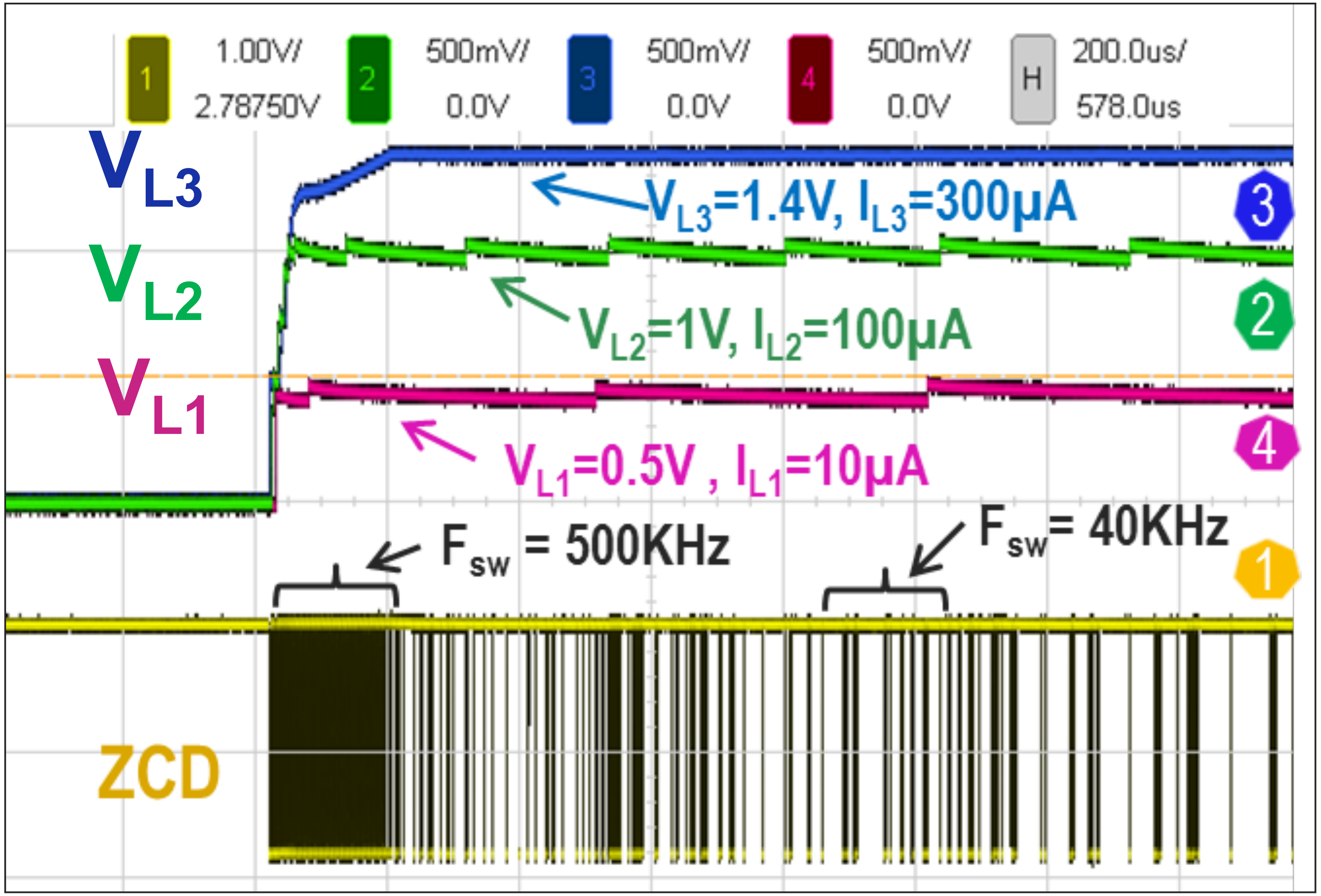
Die Micrograph



Implemented in 28nm FDSOI
Total Area = 0.5mm²

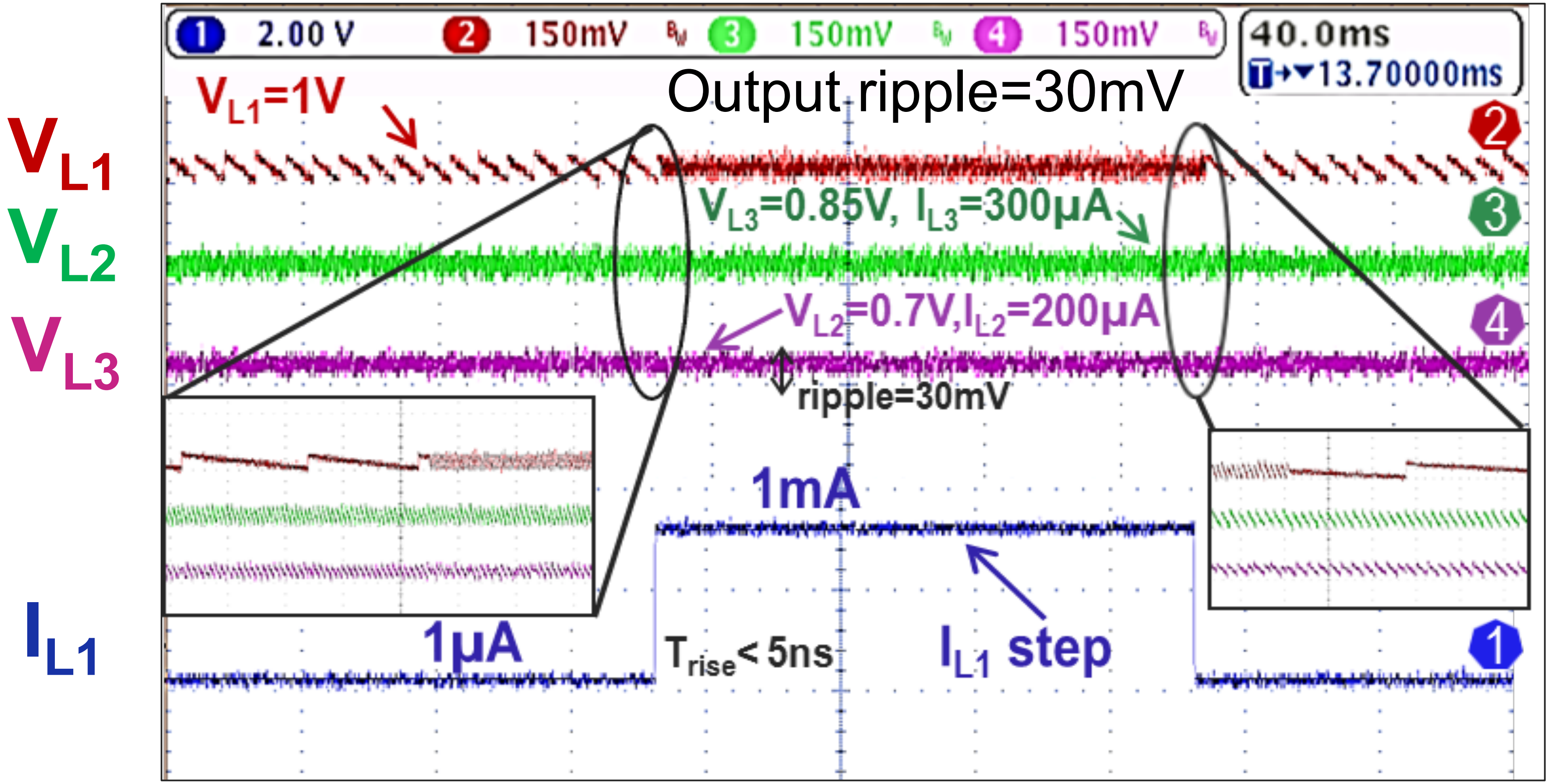


Measured Turn-On Transient Under Battery-Power



Measured turn-on transient demonstrates MISIMO PFM control

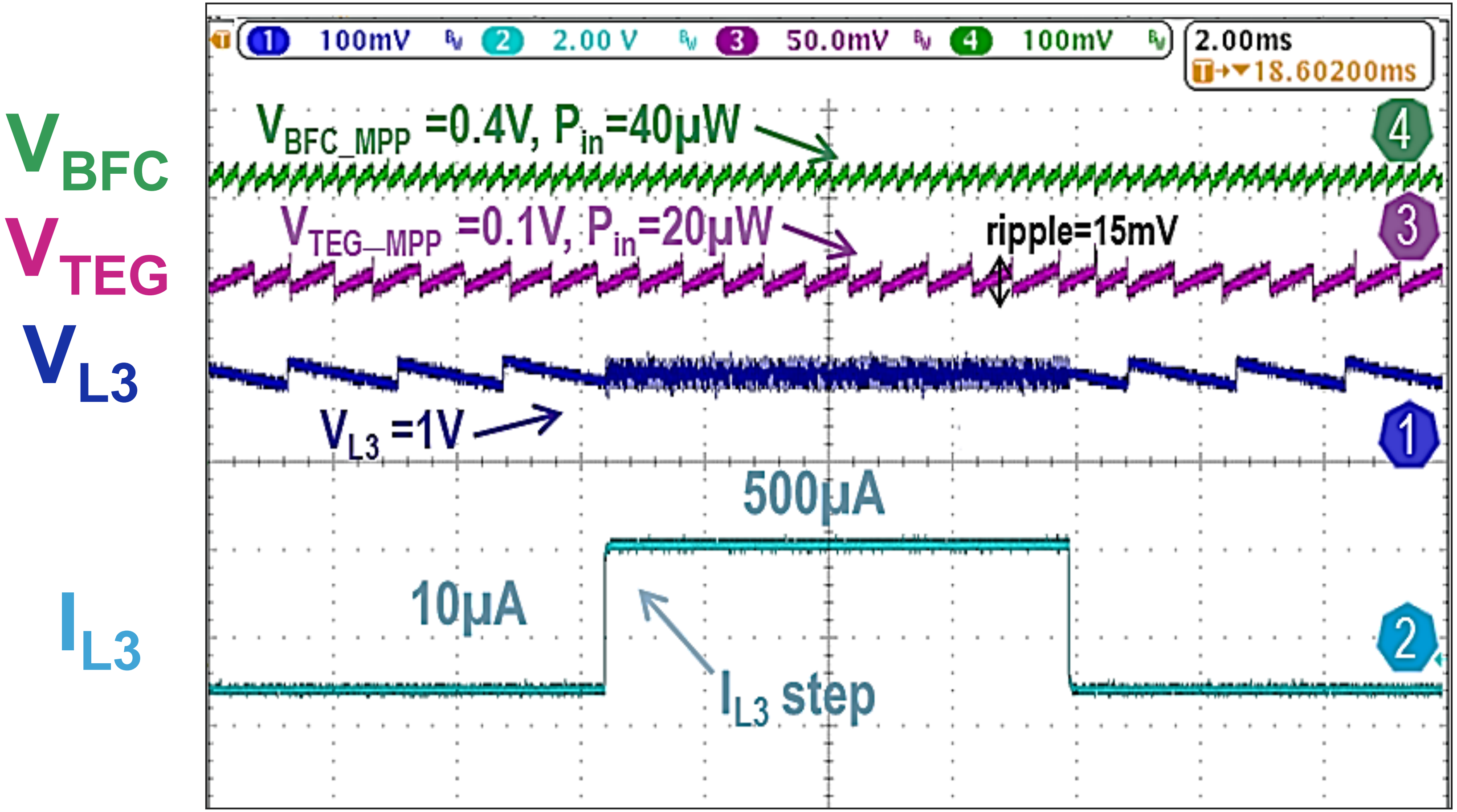
Measured Load1-Step Response



Ripple=30mV

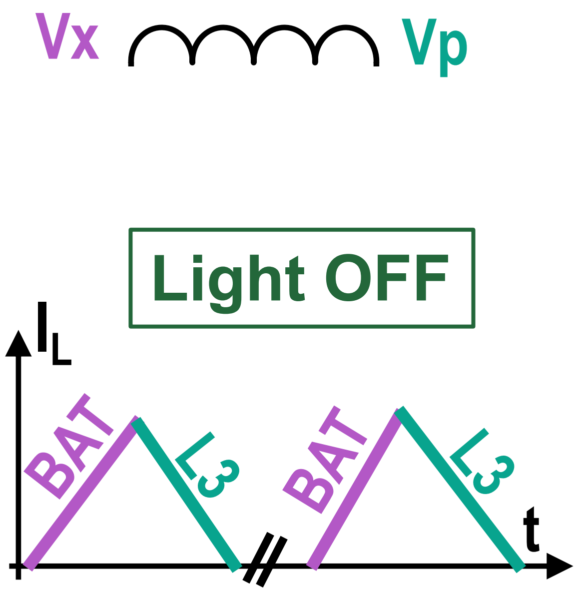
Measured L1 step demonstrates independent voltage regulation across 3 loads and negligible droop

Effect of Load Step on Source Regulation

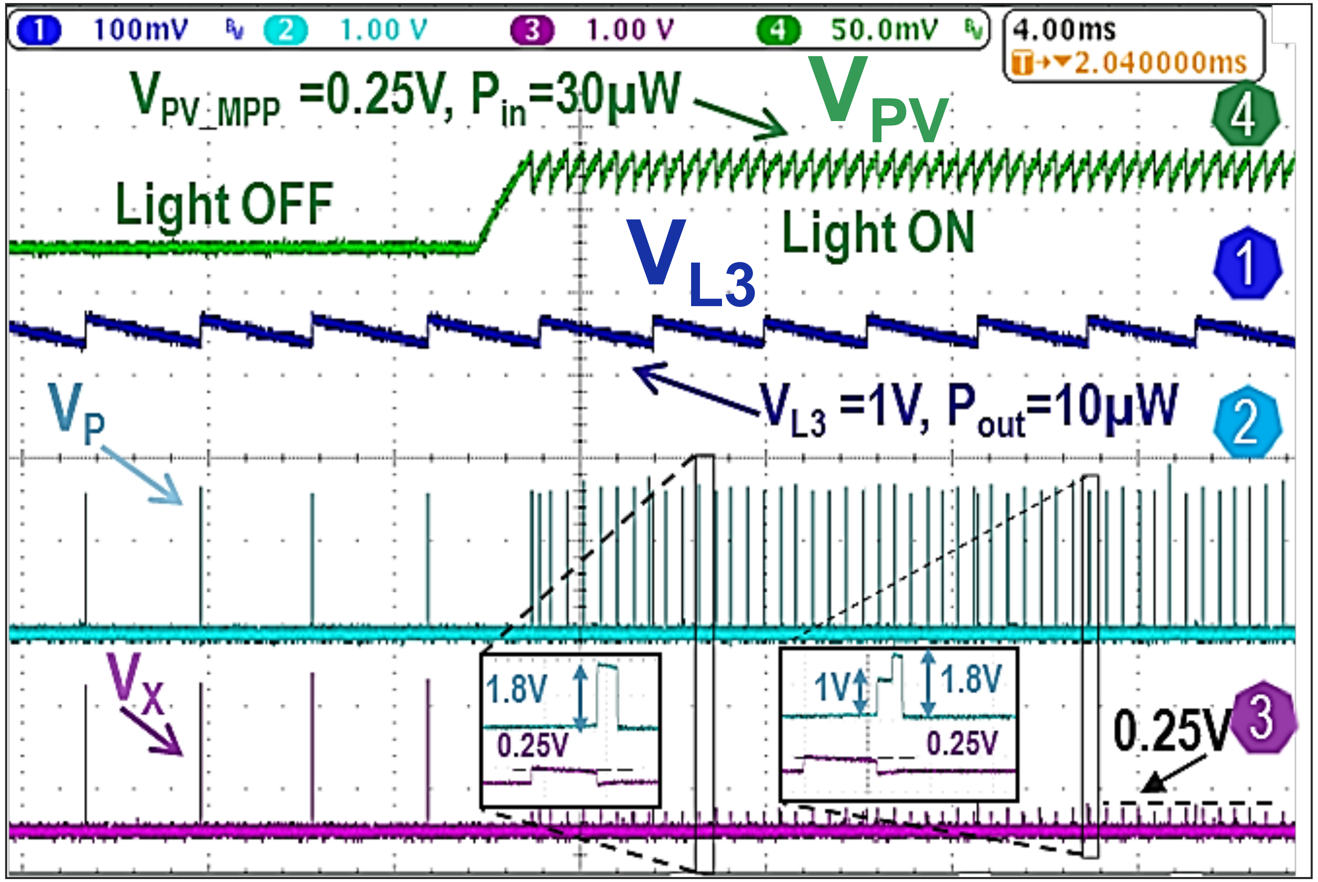


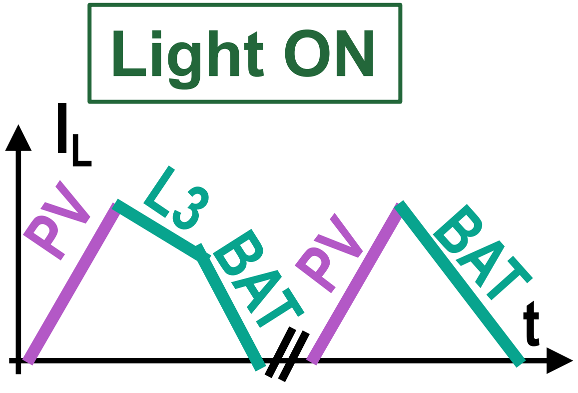
Measured load step shows no effect on the simultaneous source regulation (for MPPT) and load regulation

Measured Light-Step



Battery only deliver power to load

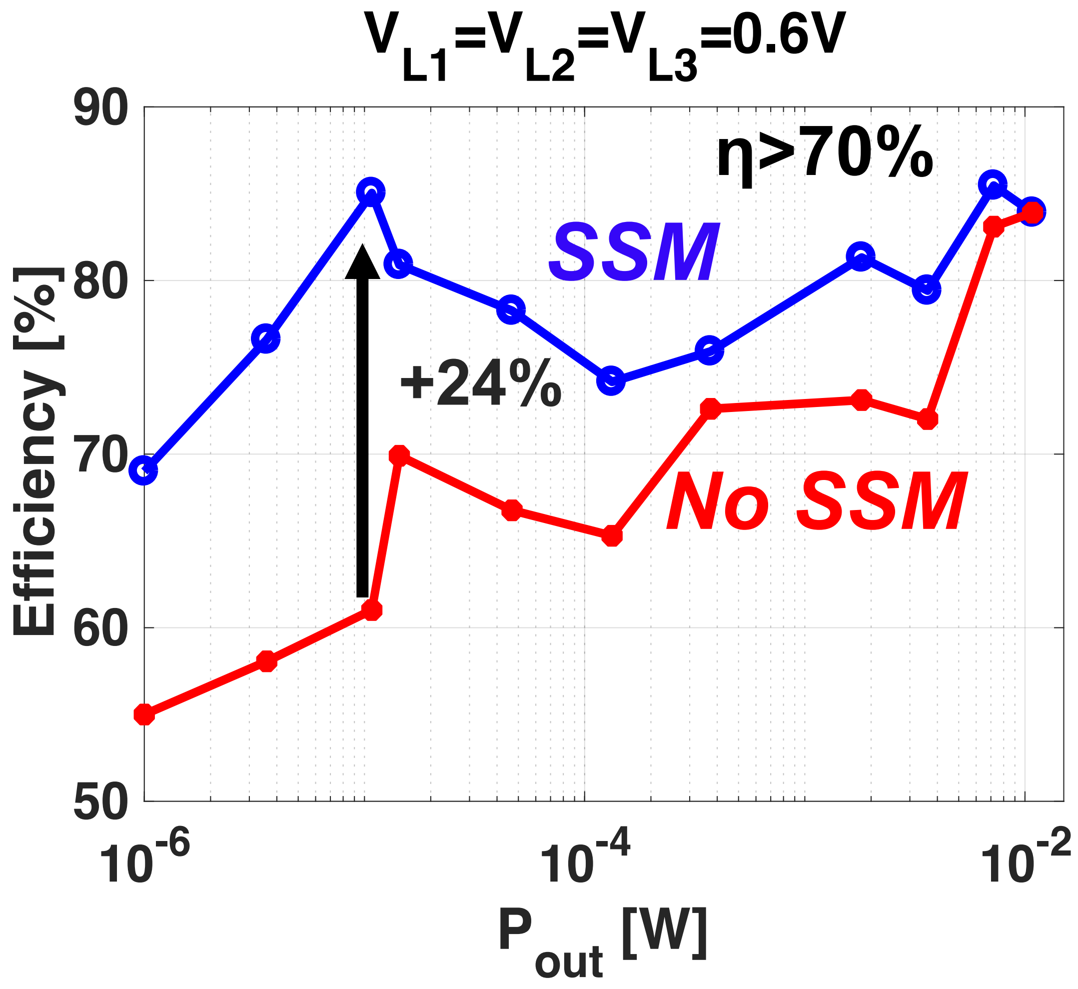


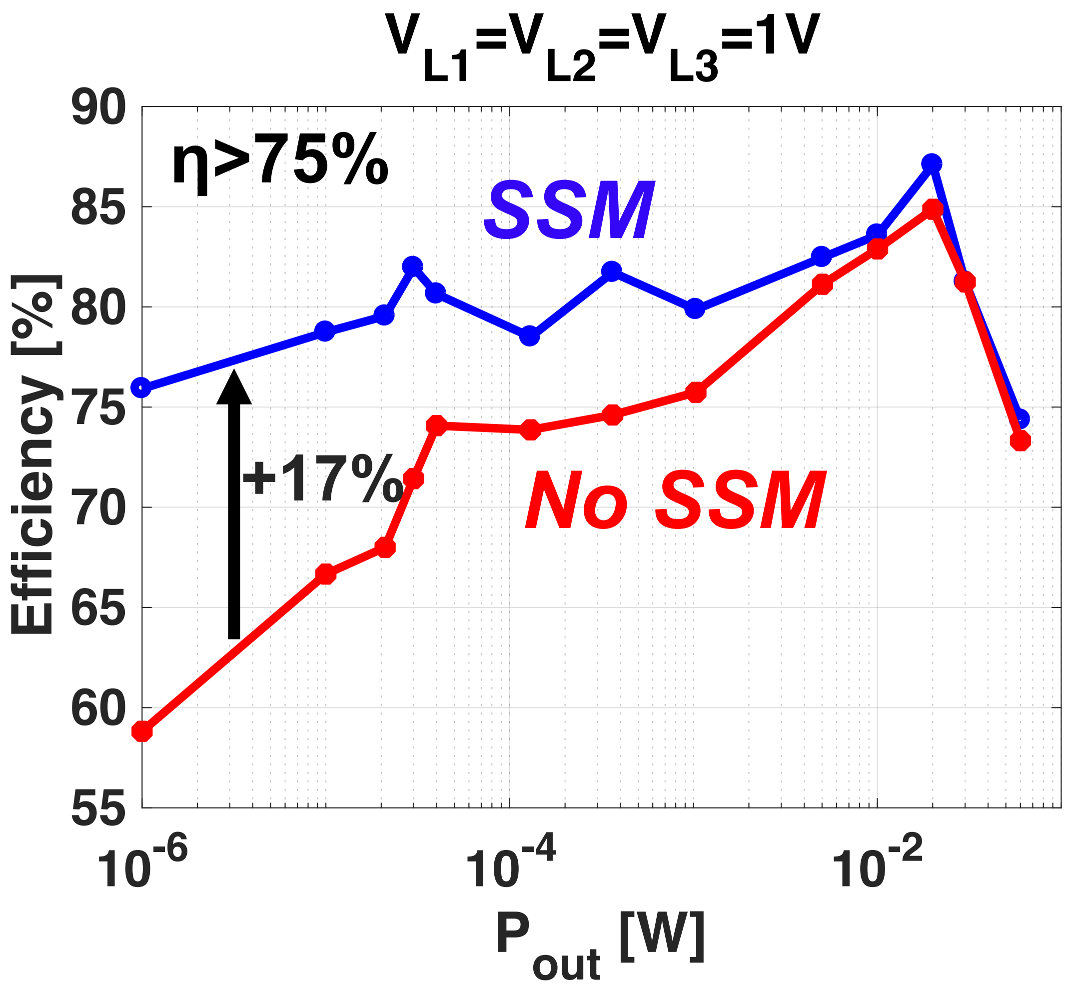


PV deliver power to load & charge battery

Measured light step demonstrates the capability of MISIMO to switch dynamically between different configurations

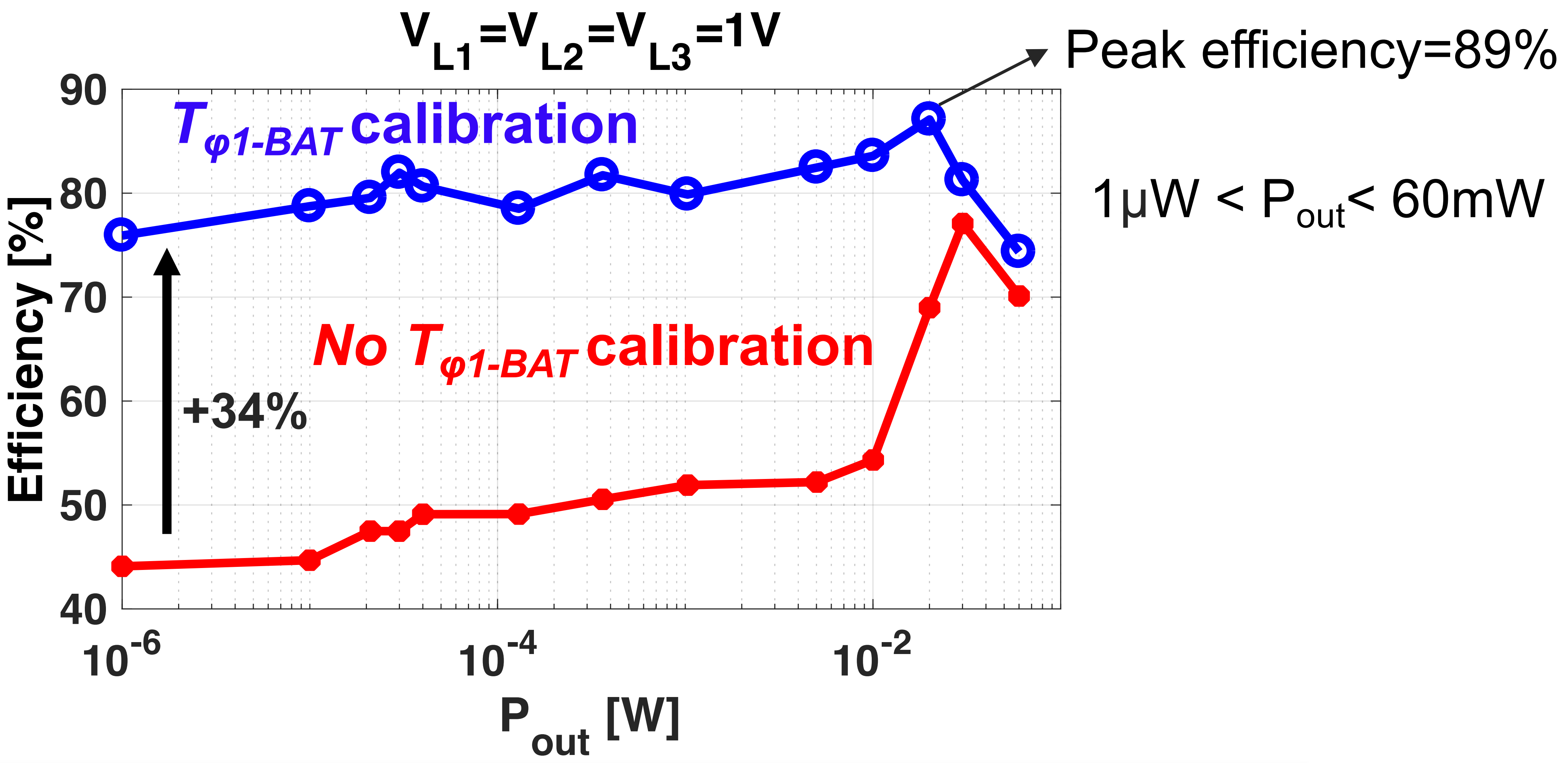
Effect of SSM on MISIMO Efficiency





SSM Improve MISIMO Efficiency by up to 24%

Effect of $T_{\varphi1\text{-}BAT}$ Calibration on MISIMO Efficiency



$T_{\varphi1\text{-}BAT}$ calibration improve MISIMO efficiency by up to 34%

Comparison to State-of-Art

	Bandyopadhyay, JSSC'12	K. Chew ISSCC'13	Shrivastava, VLSI'14	Chen, ISSCC'15	Chowdary, JSSC'16	This Work
Technology	0.35µm	0.18µm	0.13µm	0.5µm	0.18µm	**28nm FDSOI**
No of inputs	3+battery	1+battery	1+battery	1+battery	3+supercap	**3+battery**
No of outputs	1+battery	2+battery	3+battery	1+battery	1+supercap	**3+battery**
Converter Architecture	2-stage, 1-ind Buck/Boost	1 stage, 1-ind Buck-Boost	2-stage, 1-ind Buck/Boost	1-stage, 1-ind Buck/Boost	2-stage, 1-ind Buck-Boost	1-stage, 1-ind Buck-Boost
Load regulation mechanism	PFM	PFM	PFM I_{PK} Control	PFM	PFM	**PFM+PWM +SSM**
MPPT mechanism	Adaptive T_{ON} Fixed F_{SW}	Constant T_{ON} Vary F_{SW}	Constant T_{ON} Vary F_{SW}	Constant T_{ON} Vary F_{SW}	Constant I_{PK} Vary F_{SW}	**Adaptive T_{ON} Adaptive F_{SW}**
L	22µH	10µ	20µH	4.7µH	47µH	10µH
Die Area (mm²)	~15	4.62	2.25	0.5	1.1	0.5
V_{out} (V)	1.8V	1V, 1.8V	1.2, 1.5, 3.3V	1~3.3V	1.2V~1.8V	0.4~1.4V
Quiescent P/I	2.7µA@V_{DD}=1.8V	0.4µA@V_{DD}=1V	1.2 µW	1µA@V_{DD}=4V	18nA	**262nW**
P_{out}	9µW~540µW	1µW ~ 10mW	<100mW	1µW~15mW	60nW~40µW‡	**1µW~60mW**
Dynamic Range (DR) for η>70%	60X	10,000X	16,500X‡	15,000X	667X‡	**60,000X**
Peak Efficiency	90%	83%	92%	93%	87%	89%

Comparison to State-of-Art

	Bandyopadhyay, JSSC'12	K. Chew ISSCC'13	Shrivastava, VLSI'14	Chen, ISSCC'15	Chowdary, JSSC'16	This Work
Technology	0.35µm	0.18µm	0.13µm	0.5µm	0.18µm	**28nm FDSOI**
No of inputs	3+battery	1+battery	1+battery	1+battery	3+supercap	**3+battery**
No of outputs	1+battery	2+battery	3+battery	1+battery	1+supercap	**3+battery**
Converter Architecture	2-stage, 1-ind Buck/Boost	1 stage, 1-ind Buck-Boost	2-stage, 1-ind Buck/Boost	1-stage, 1-ind Buck/Boost	2-stage, 1-ind Buck-Boost	1-stage, 1-ind Buck-Boost
Load regulation mechanism	PFM	PFM	PFM I_{PK} Control	PFM	PFM	**PFM+PWM +SSM**
MPPT mechanism	Adaptive T_{ON} Fixed F_{SW}	Constant T_{ON} Vary F_{SW}	Constant T_{ON} Vary F_{SW}	Constant T_{ON} Vary F_{SW}	Constant I_{PK} Vary F_{SW}	**Adaptive T_{ON} Adaptive F_{SW}**
L	22µH	10µ	20µH	4.7µH	47µH	10µH
Die Area (mm²)	~15	4.62	2.25	0.5	1.1	0.5
V_{out} (V)	1.8V	1V, 1.8V	1.2, 1.5, 3.3V	1~3.3V	1.2V~1.8V	0.4~1.4V
Quiescent P/I	2.7µA@V_{DD}=1.8V	0.4µA@V_{DD}=1V	1.2 µW	1µA@V_{DD}=4V	18nA	**262nW**
P_{out}	9µW~540µW	1µW ~ 10mW	<100mW	1µW~15mW	60nW~40µW‡	**1µW~60mW**
Dynamic Range (DR) for η>70%	60X	10,000X	16,500X‡	15,000X	667X‡	**60,000X**
Peak Efficiency	90%	83%	92%	93%	87%	89%

Comparison to State-of-Art

	Bandyopadhyay, JSSC'12	K. Chew ISSCC'13	Shrivastava, VLSI'14	Chen, ISSCC'15	Chowdary, JSSC'16	This Work
Technology	0.35µm	0.18µm	0.13µm	0.5µm	0.18µm	**28nm FDSOI**
No of inputs	3+battery	1+battery	1+battery	1+battery	3+supercap	**3+battery**
No of outputs	1+battery	2+battery	3+battery	1+battery	1+supercap	**3+battery**
Converter Architecture	2-stage, 1-ind Buck/Boost	1 stage, 1-ind Buck-Boost	2-stage, 1-ind Buck/Boost	1-stage, 1-ind Buck/Boost	2-stage, 1-ind Buck-Boost	1-stage, 1-ind Buck-Boost
Load regulation mechanism	PFM	PFM	PFM I_{PK} Control	PFM	PFM	**PFM+PWM +SSM**
MPPT mechanism	Adaptive T_{ON} Fixed F_{SW}	Constant T_{ON} Vary F_{SW}	Constant T_{ON} Vary F_{SW}	Constant T_{ON} Vary F_{SW}	Constant I_{PK} Vary F_{SW}	**Adaptive T_{ON} Adaptive F_{SW}**
L	22µH	10µ	20µH	4.7µH	47µH	10µH
Die Area (mm²)	~15	4.62	2.25	0.5	1.1	0.5
V_{out} (V)	1.8V	1V, 1.8V	1.2, 1.5, 3.3V	1~3.3V	1.2V~1.8V	0.4~1.4V
Quiescent P/I	2.7µA@V_{DD}=1.8V	0.4µA@V_{DD}=1V	1.2 µW	1µA@V_{DD}=4V	18nA	**262nW**
P_{out}	9µW~540µW	1µW ~ 10mW	<100mW	1µW~15mW	60nW~40µW‡	**1µW~60mW**
Dynamic Range (DR) for η>70%	60X	10,000X	16,500X‡	15,000X	667X‡	**60,000X**
Peak Efficiency	90%	83%	92%	93%	87%	89%

Outline

- State-of-the-Art and Single-Inductor Challenges
- Decoupling Source MPPT and Load Regulation
- Circuit Techniques for Wide Dynamic Range
- Measurement Results
- Conclusion

Conclusion

- Small form factor MISIMO architecture enabled by techniques that decouple the source side 2-D MPPT and load side regulation
- MISIMO achieves η_{pk}= 89% and $\eta \geq$70% across 1µW<Pout<60mW by employing efficiency enhancement techniques including:
  - Switch Size Modulation (SSM) [improve efficiency by up to 24%]
  - $T_{\varphi 1\text{-}BAT}$ calibration (PWM) [improve efficiency by up to 34%]
  - Cascoded PS switch-structure [reduce leakage by 9x]
  - Duty-cycled ZCD [reduce P_Q by >2000x]