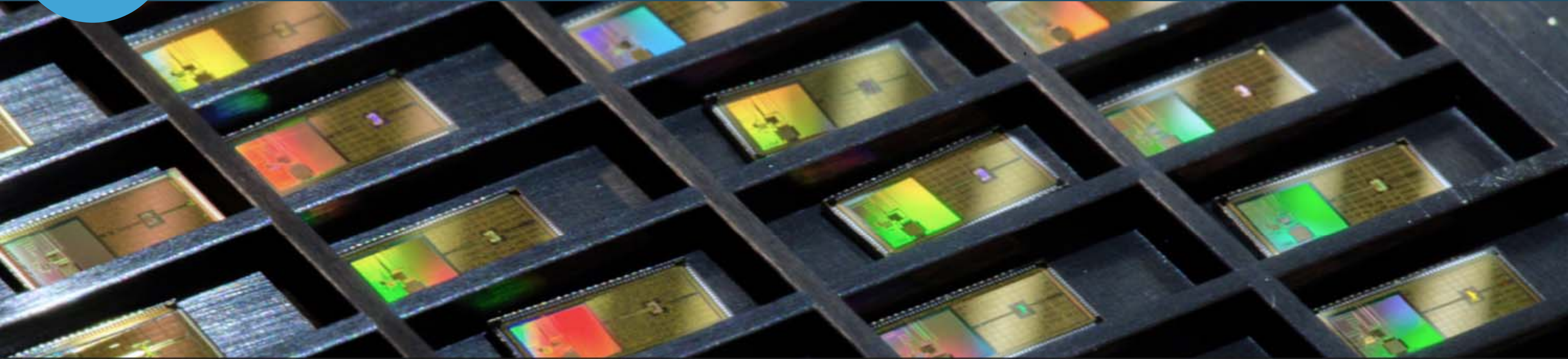
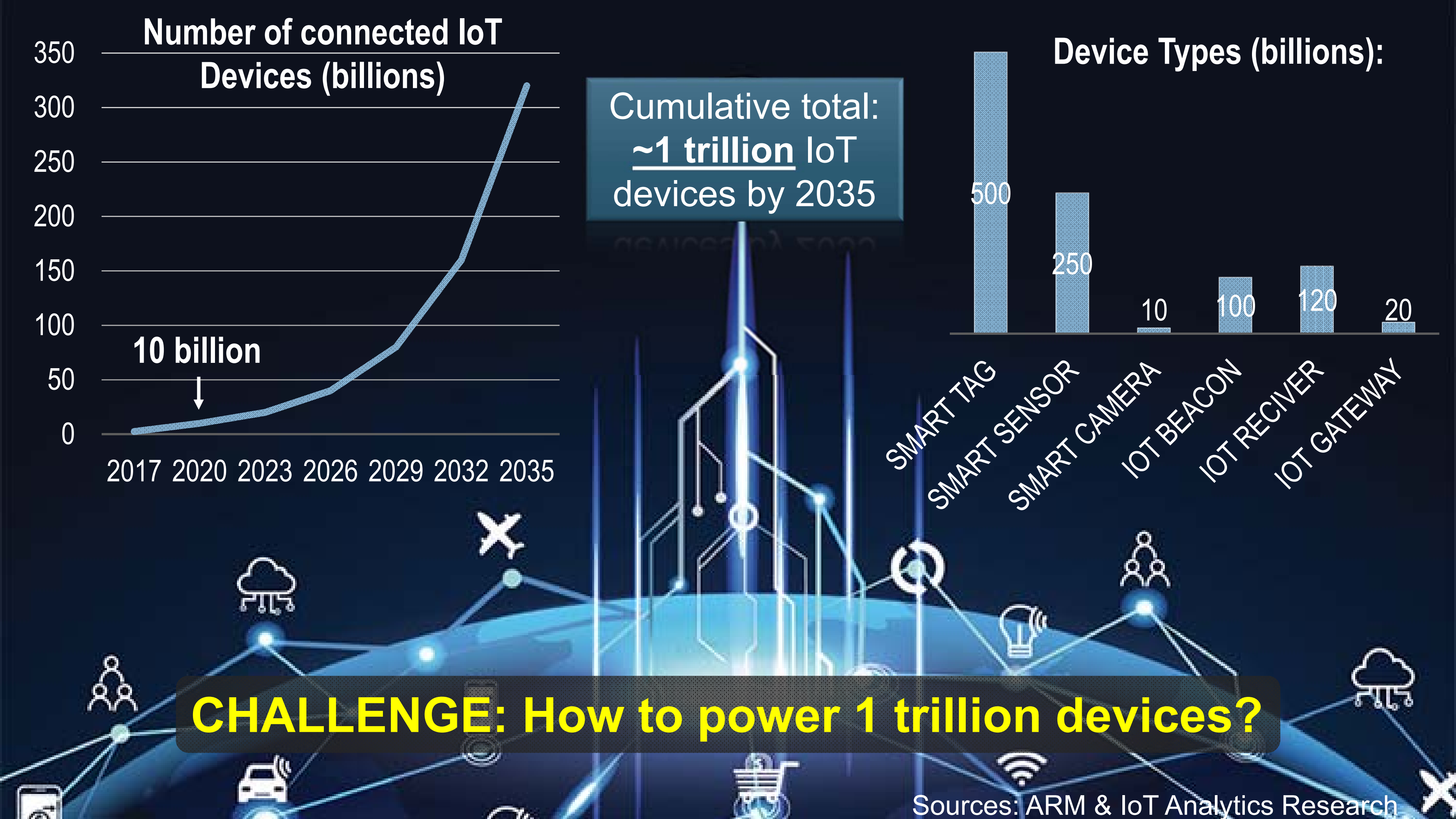
UCSD

UC San Diego
Jacobs School of Engineering



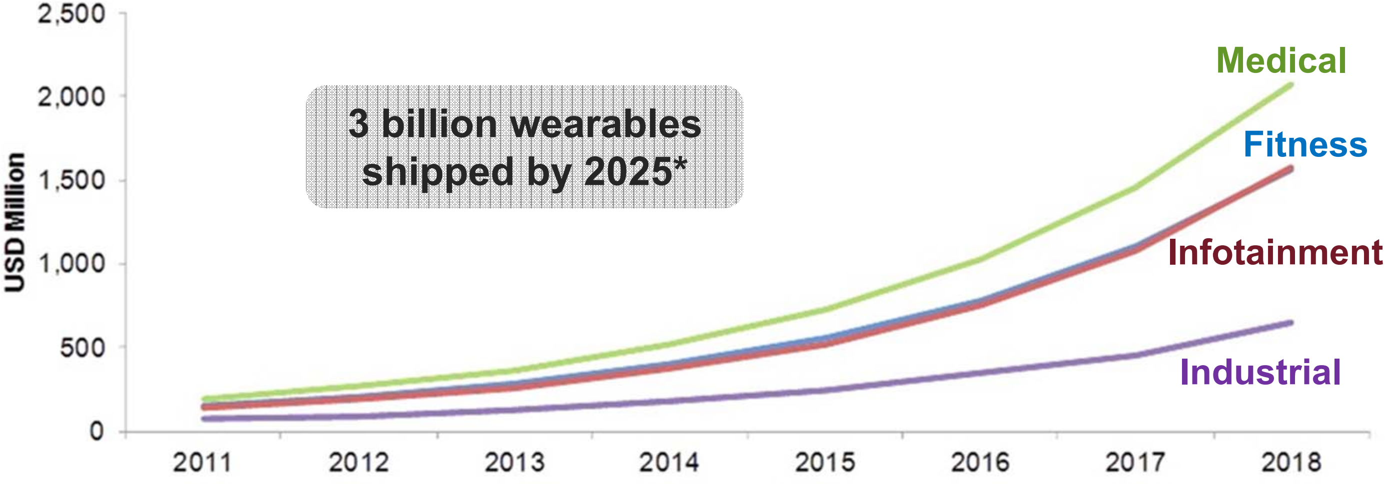
Energy Harvesting and Self-Powered Sensing for Next-Generation “Unaware-ables” and IoT

Patrick Mercier
University of California, San Diego



Number of connected IoT Devices (billions)
350
300
250
200
150
100
50
0
10 billion
2017 2020 2023 2026 2029 2032 2035
Cumulative total: ~1 trillion IoT devices by 2035
Device Types (billions):
500
250
10
100
120
20
SMART TAG
SMART SENSOR
SMART CAMERA
IOT BEACON
IOT RECIVER
IOT GATEWAY
CHALLENGE: How to power 1 trillion devices?
Sources: ARM & IoT Analytics Research

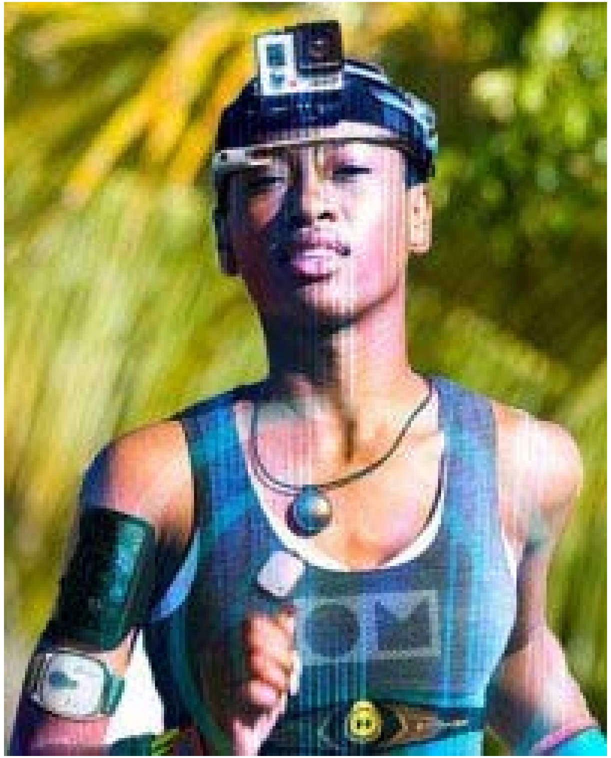
Wearables:
an exciting high-growth market



*IDTechEx 2015 Report

Source: Transparency Market Research

Why aren't we there now?



Size & Usability:

Need to develop sensors that are small & seamlessly integrated into daily life

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Battery Life:

Need ultra-low-power and/or energy harvesting to minimize re-charging

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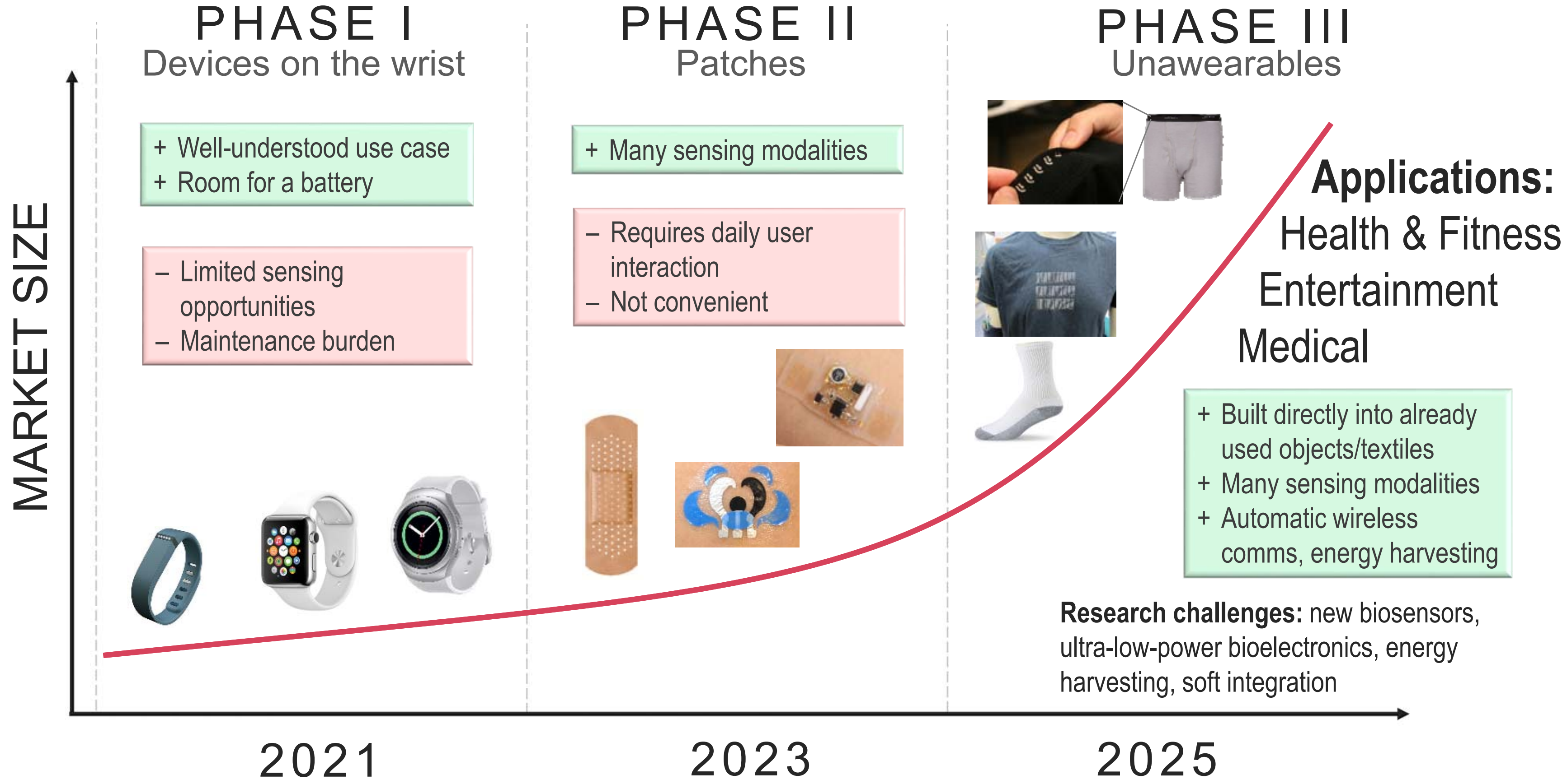
Utility:

Need to develop sensors that are actually useful

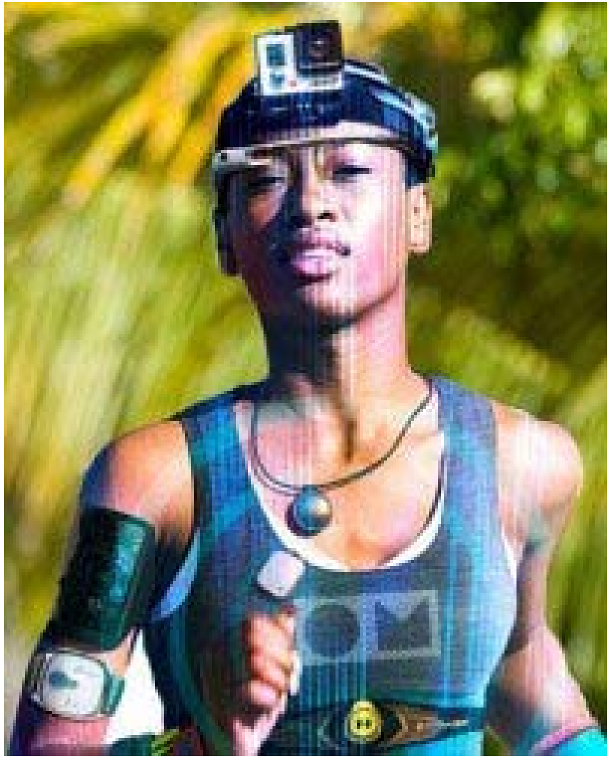
Mission:

Address these issues through innovative transdisciplinary research

Wearables Roadmap



Why aren't we there now?



Size & Usability:

Need to develop sensors that are small & seamlessly integrated into daily life

Battery Life:

Need ultra-low-power and/or energy harvesting to minimize re-charging

Utility:

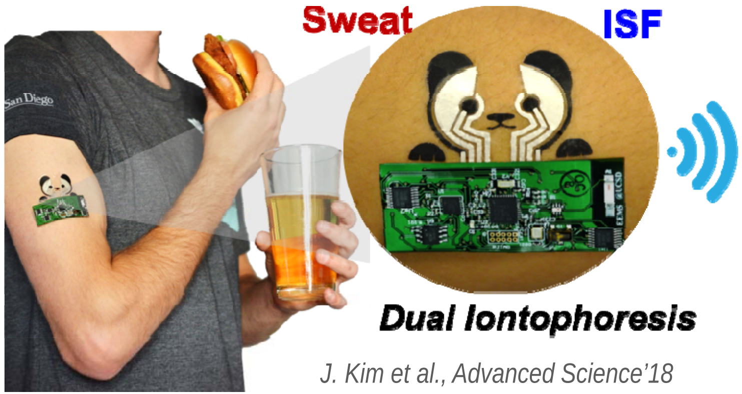
Need to develop sensors that are actually useful

Mission:

Address these issues through innovative transdisciplinary research

Pushing the frontier on new wearable sensing technologies

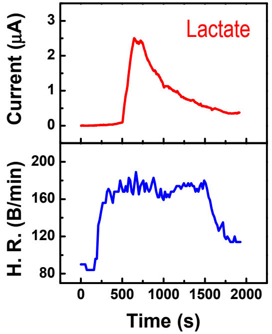
Non-invasive glucose and alcohol sensing



J. Kim et al., Advanced Science'18

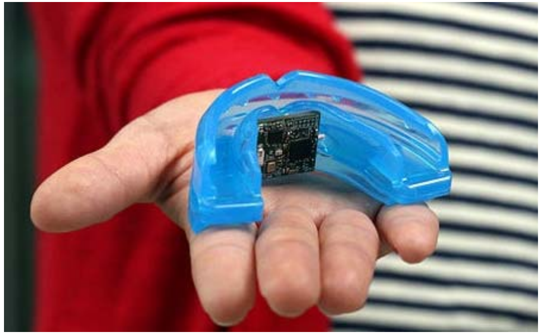
Hybrid physiochemical & electrophysiological sensing

S. Imani et al., Nature Communications'16



First demonstration of real-time ECG+lactate recording

Real-time saliva sensors



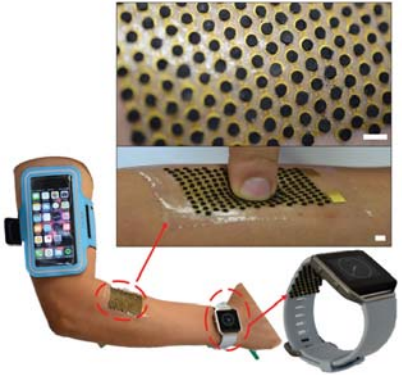
Physiochemical analysis in saliva

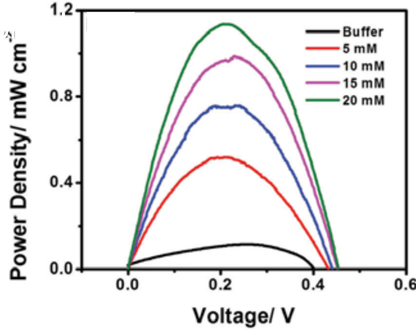
Startup company:

TRAQ

J. Kim et al., Biosensors & Bioelectronics'15

Bio-energy harvesting

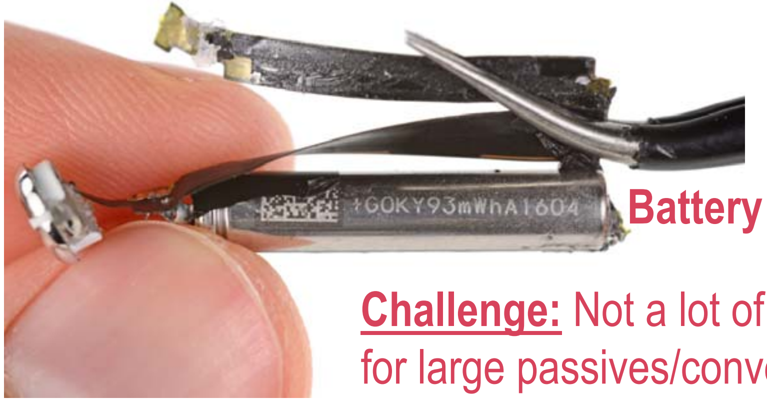




1mW/cm2 harvested from sweat

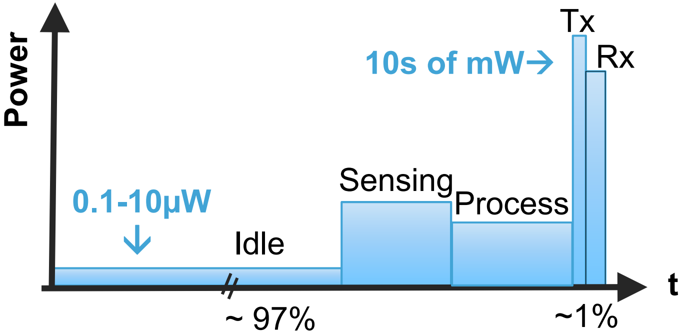
A.J. Bandodkhar et al., EES'17

Major limiter in IoT devices: battery size / battery life



Challenge: Not a lot of room for large passives/converters

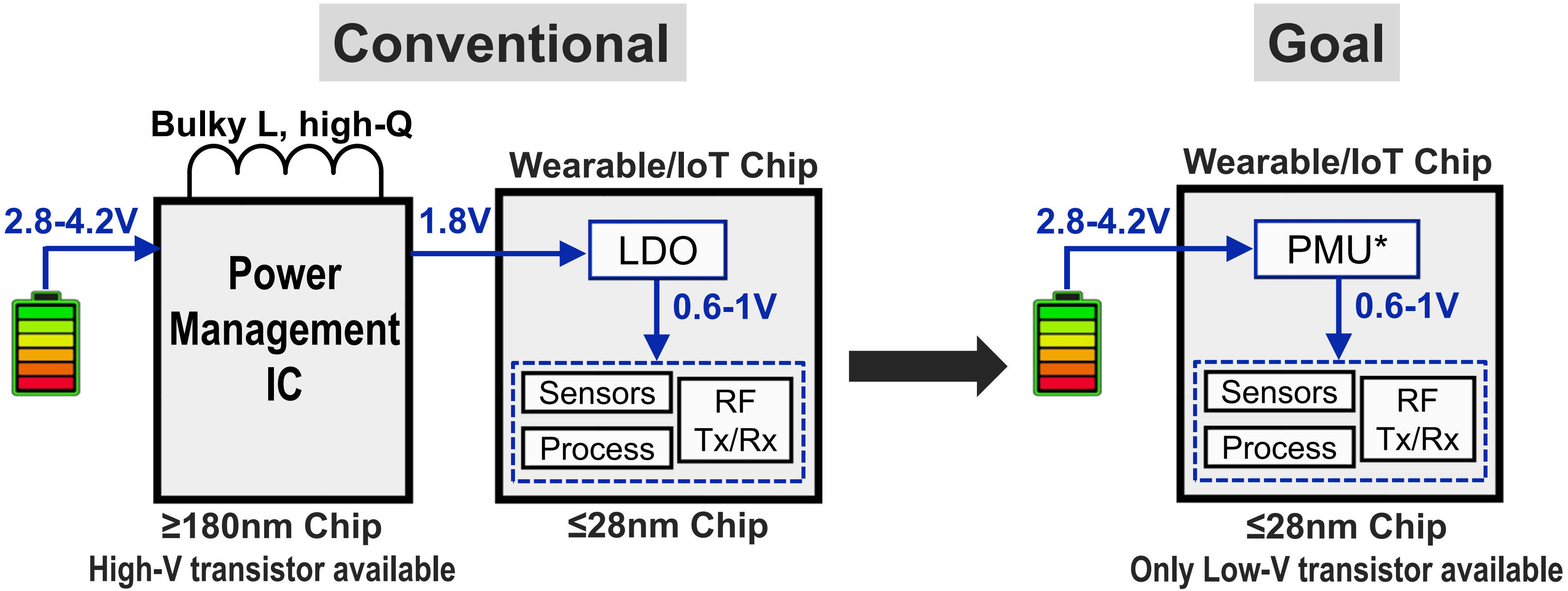
Challenge: Require high efficiency over 1,000,000x dynamic range



Research goal:

Simultaneously increase efficiency *and* power density over a wide dynamic range

Powering IoT and Wearables in Scaled-CMOS



PMU*: Power Management Unit
with or without off-chip inductor

Li-ion Fully-Integrated PMU Challenges in 28nm FDSOI

Scaled-CMOS Challenges

Only Low-V transistors available

Transistors stacking required

- High switching & conduction losses
- Complex power-hungry drivers
- Many level shifters

Poor efficiency

Only Low-V capacitors available

Capacitors stacking required

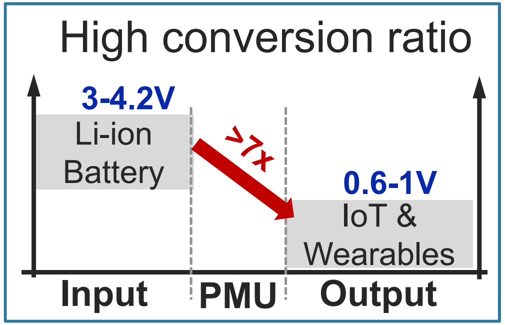
Large area

Low power density

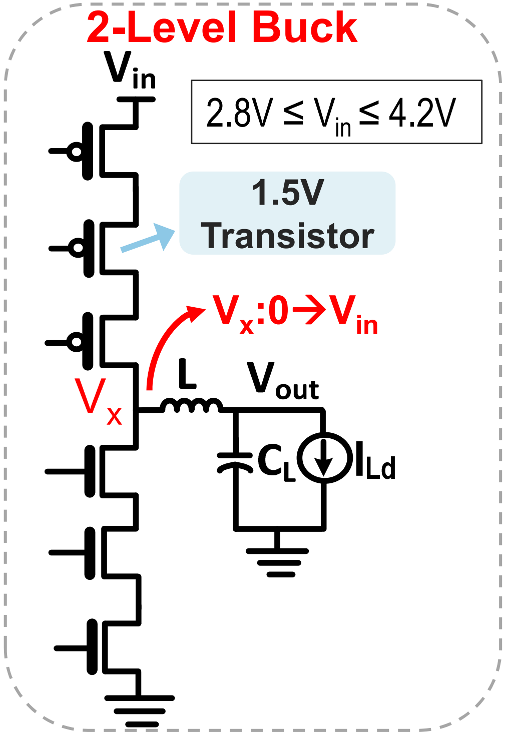
Poor quality on-chip passives

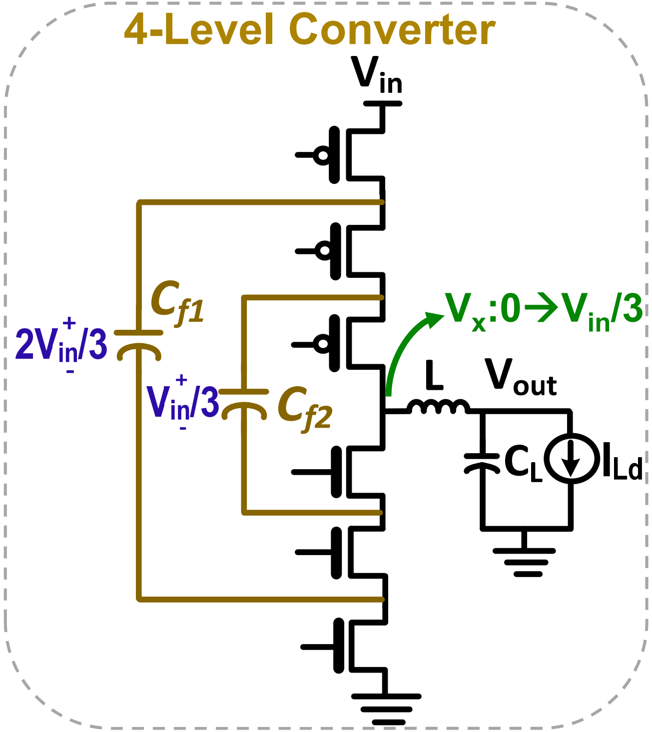
- Large ESR, parasitic cap
- Low density

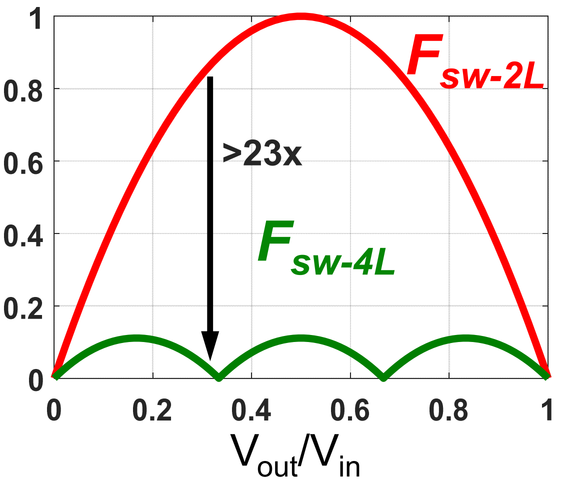
Poor efficiency
Low power density



Towards Fully-Integrated Li-ion PMU in Scaled CMOS







$$\frac{F_{sw\_4L}}{F_{sw\_2L}} = \frac{1/3 - V_{out}/V_{in}}{1 - V_{out}/V_{in}}$$

Small on-chip L, large ESR

-High Switching & conduction losses

-Poor efficiency

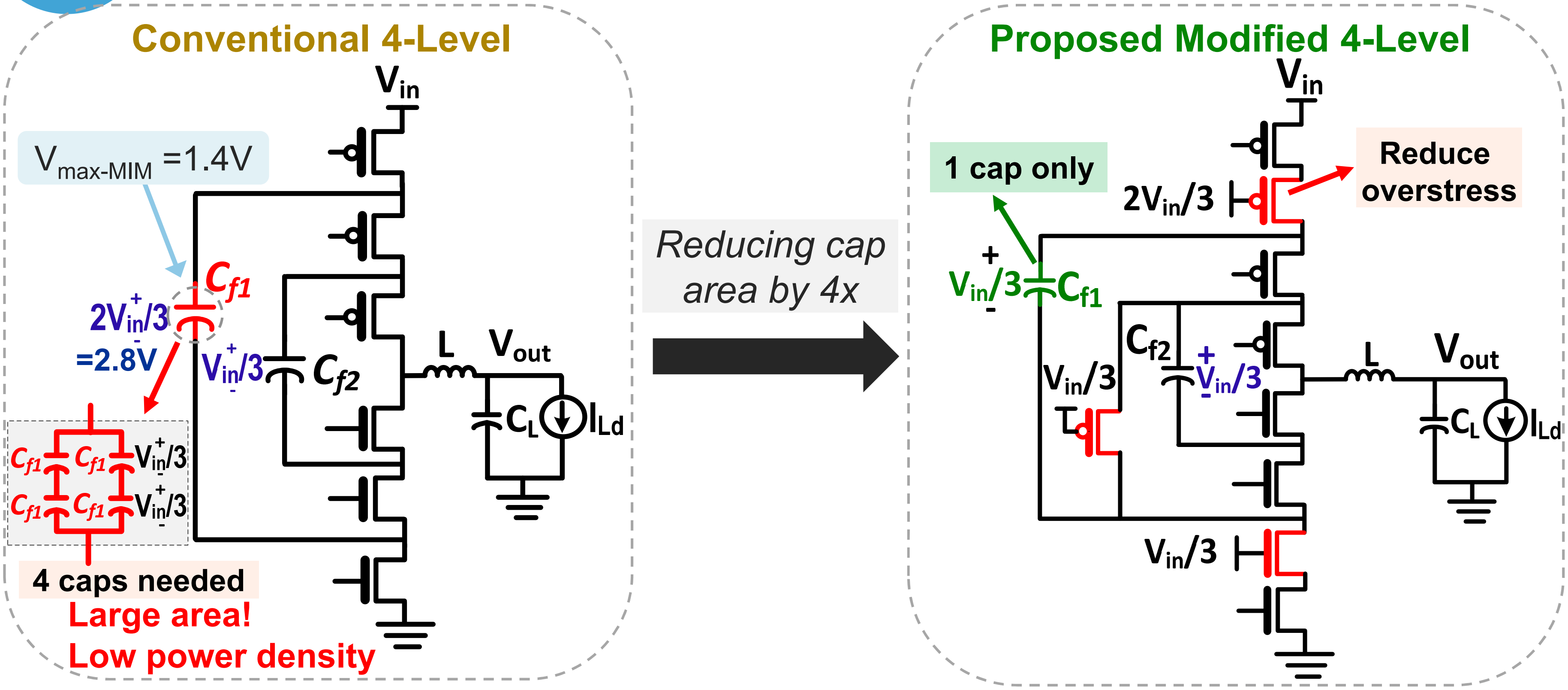
Reduced swing at Vx

F_{sw} reduced by > 23x

& efficiency by up to 33%

S.S. Amin et al., JSSC'19

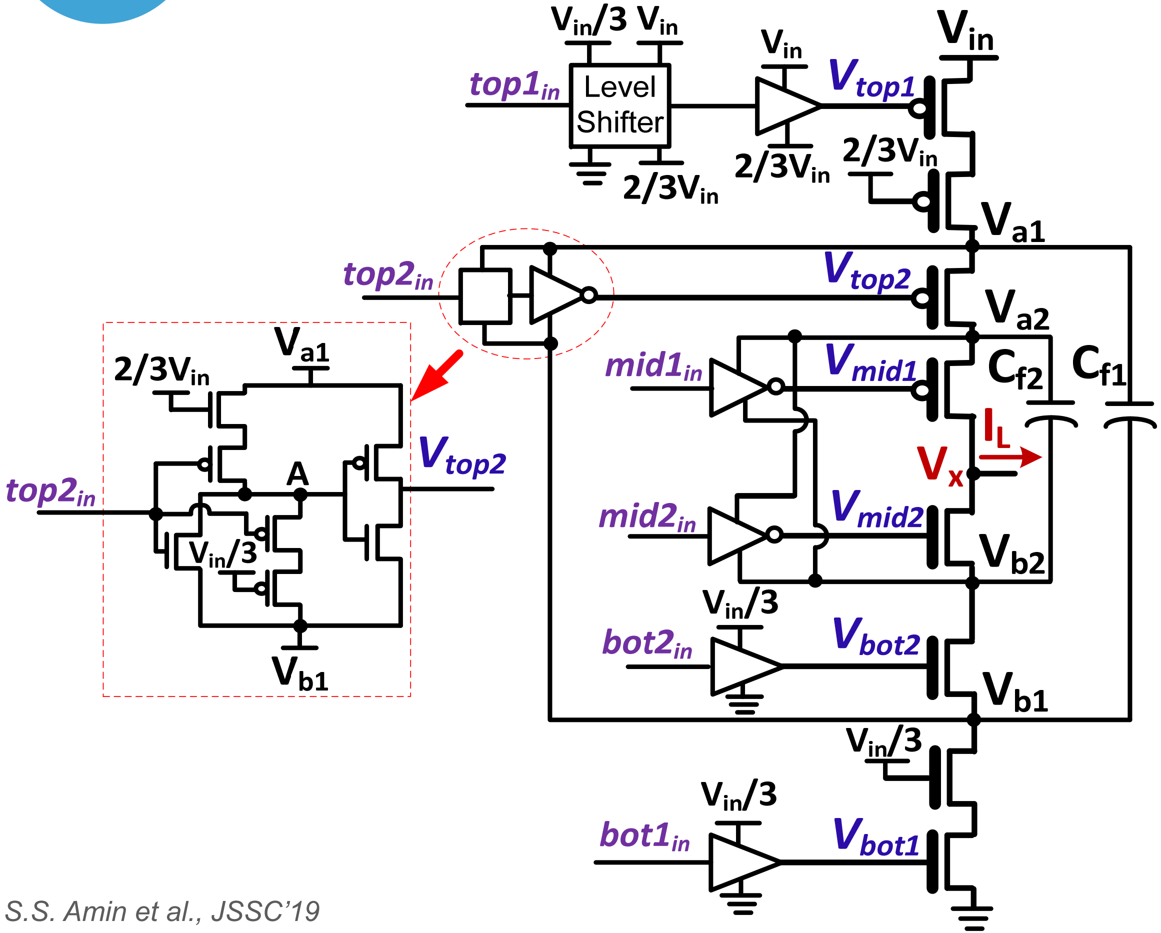
Conventional 4-Level Converter Area Penalty

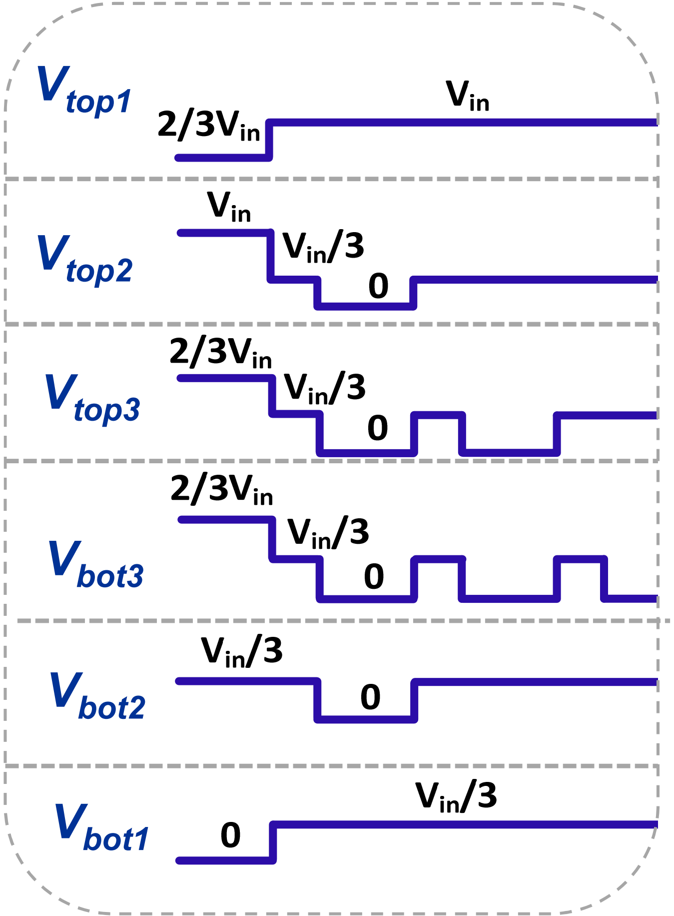


Changing the switching states of flying caps reduces the cap voltage stress

S.S. Amin et al., JSSC'19

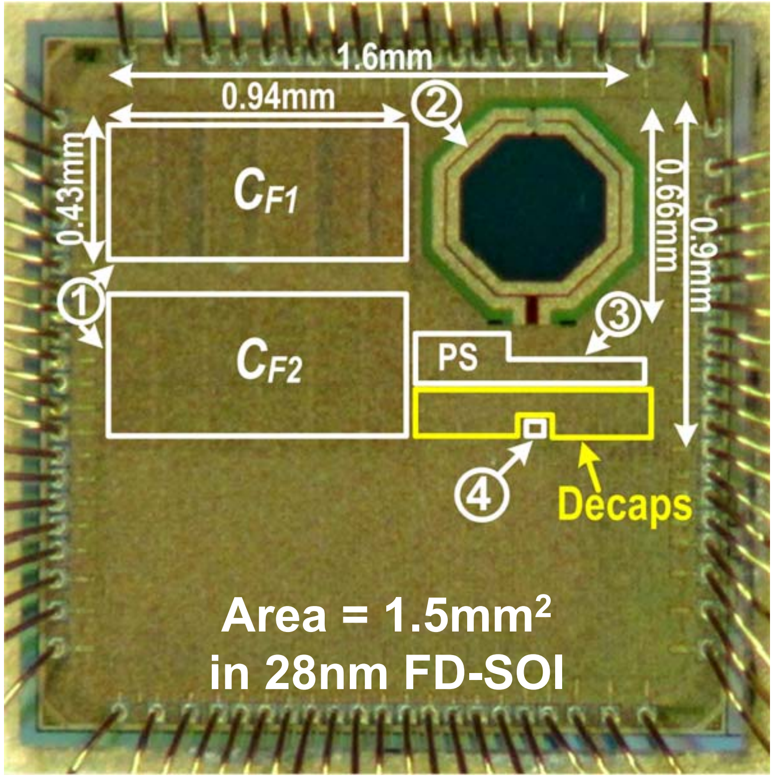
Driver Architecture

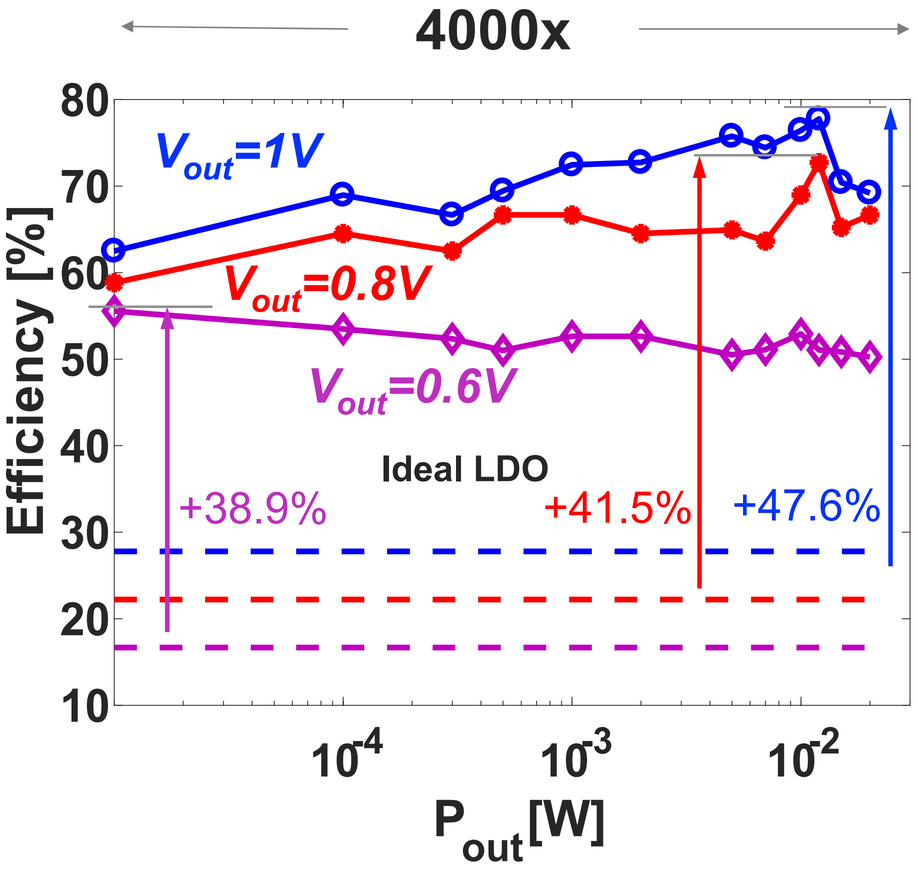




S.S. Amin et al., JSSC'19

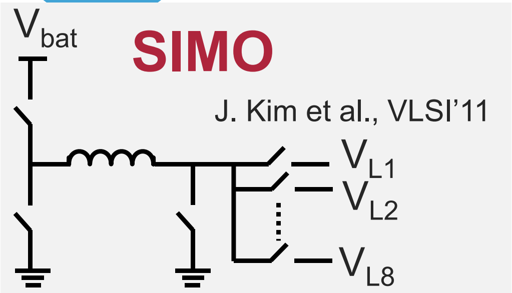
Measurement Results

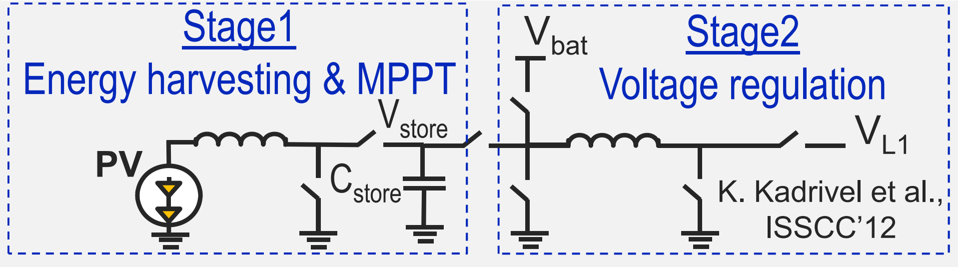




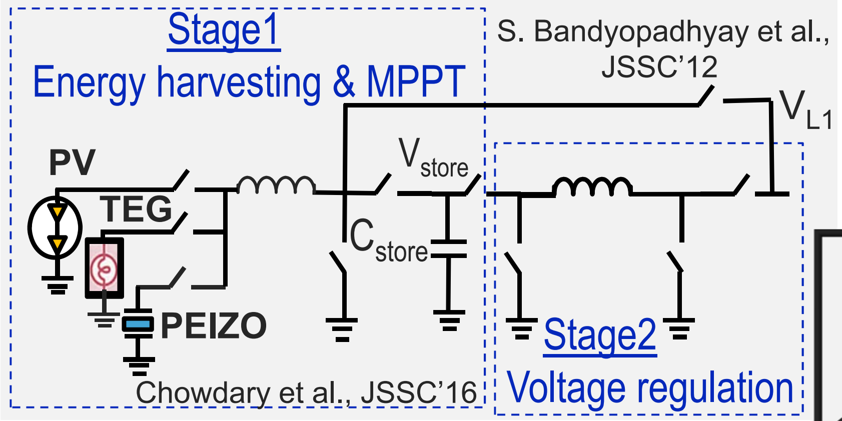
S.S. Amin et al., JSSC'19

Towards Small Form-Factor Single-Inductor Converters

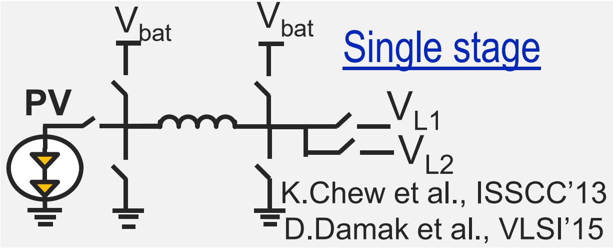




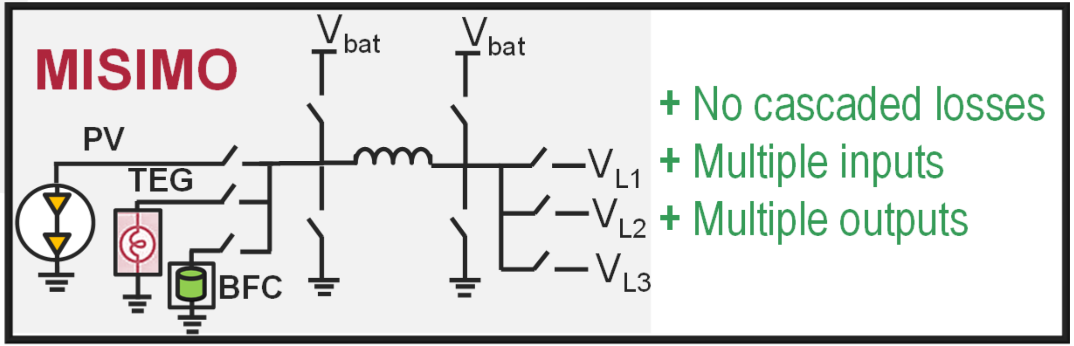
- Single input
- Single output
- Cascaded losses



+ Multiple inputs
- Cascaded losses
- Single output



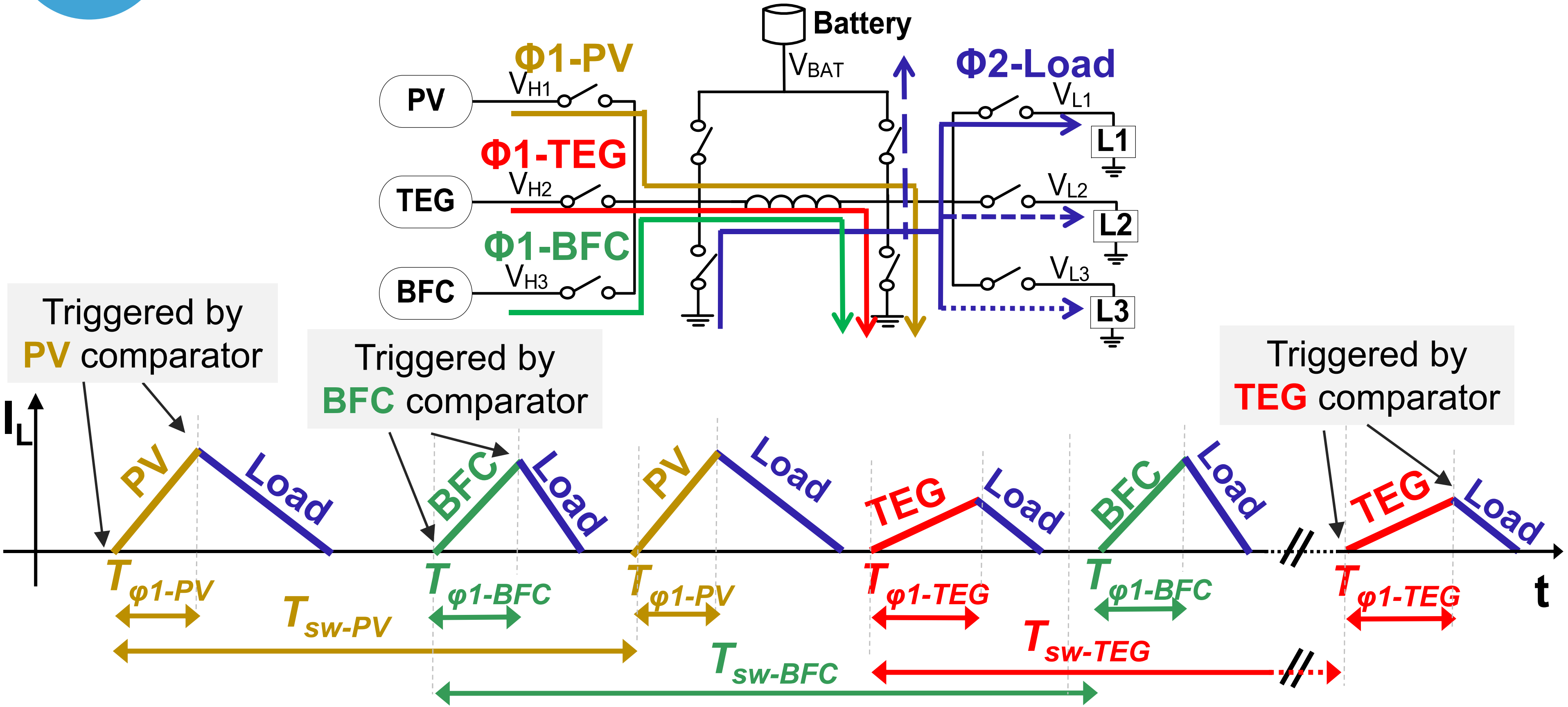
+ No cascaded losses
+ Multiple outputs
- Single input



+ No cascaded losses
+ Multiple inputs
+ Multiple outputs

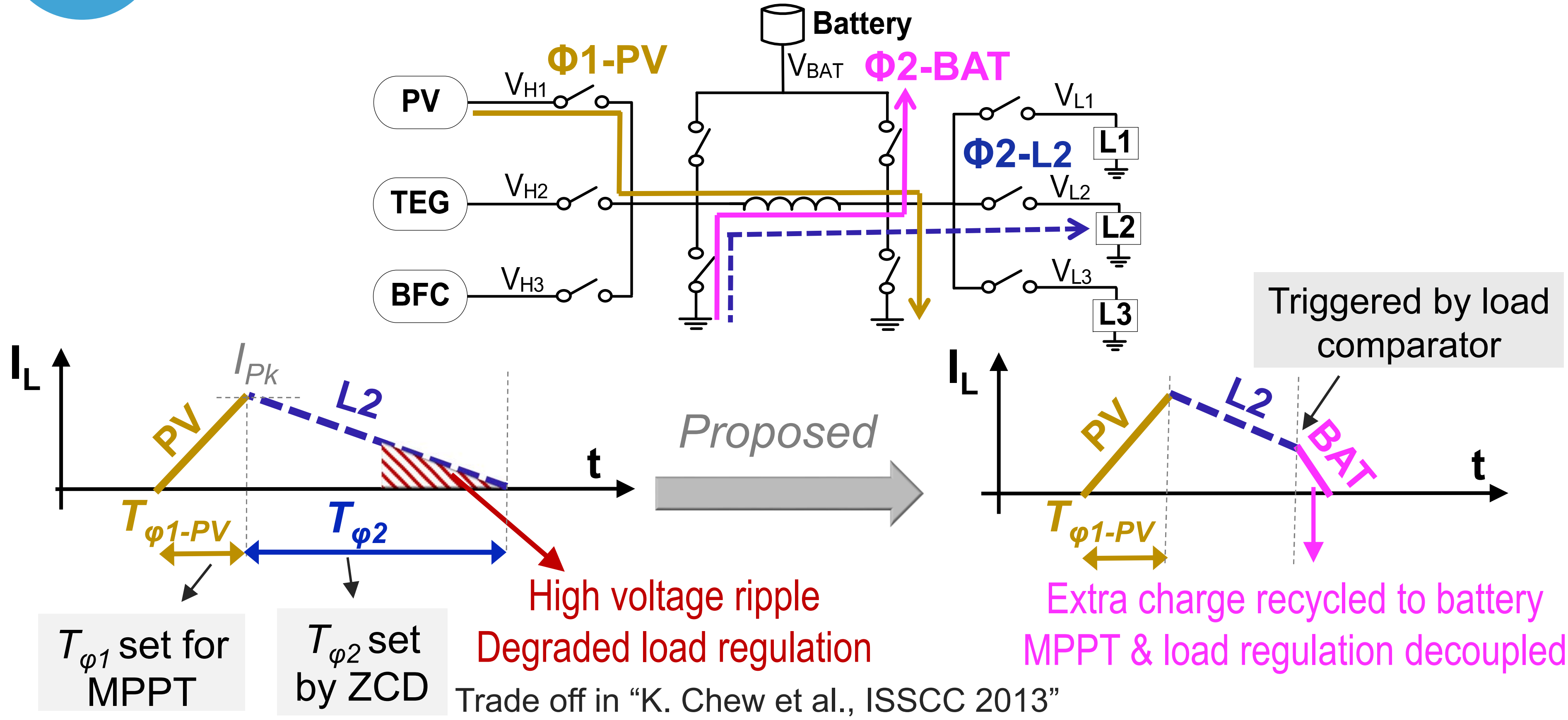
S.S. Amin et al., ISSCC'18/JSSC'18

Time-Shared Inductor for Multi-Input Harvesting



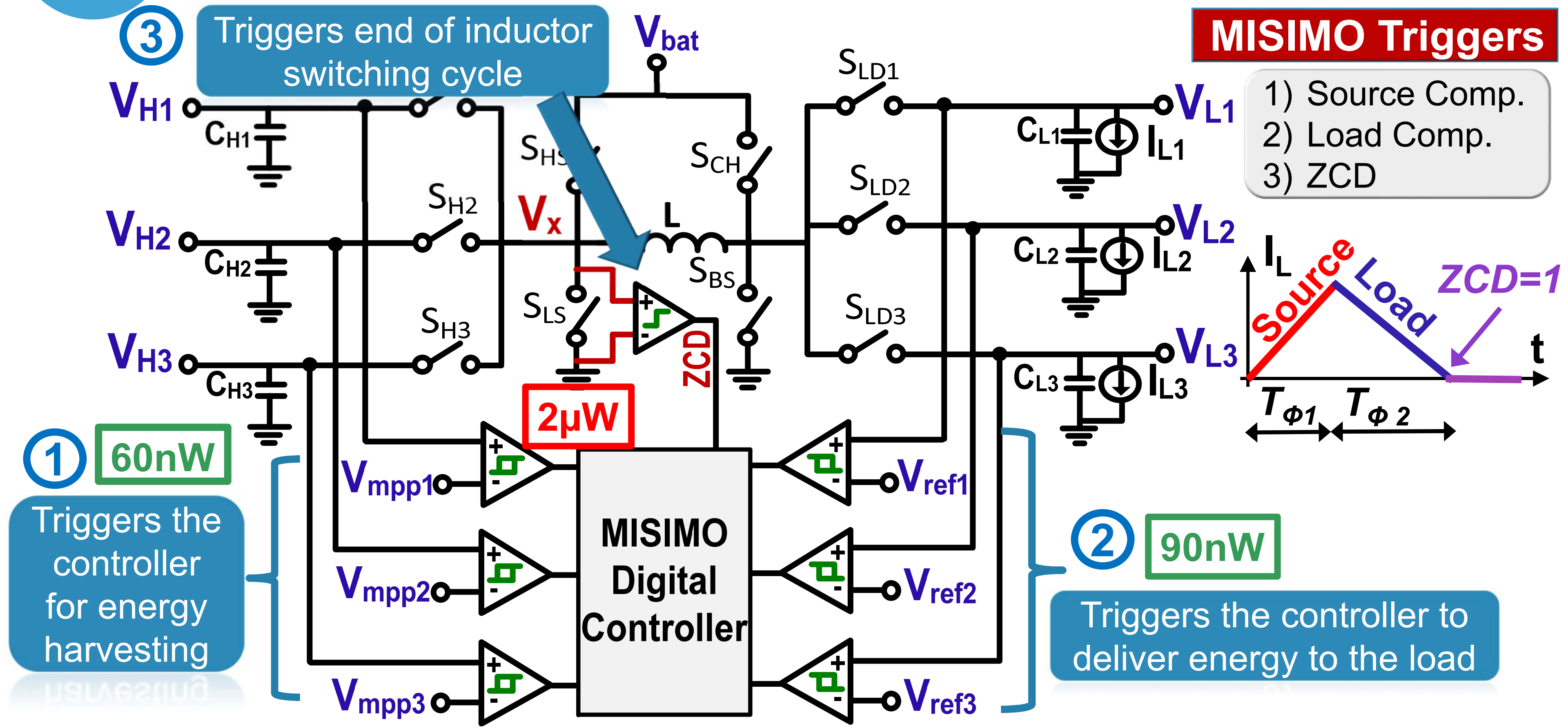
S.S. Amin et al., ISSCC’18/JSSC’18

Challenge: decoupling MPPT and Load Regulation



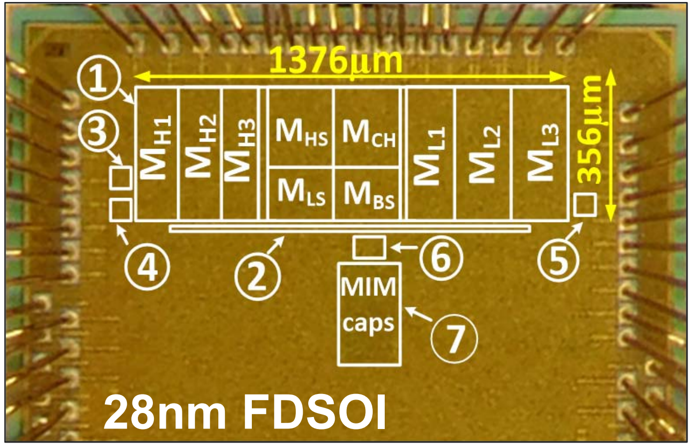
S.S. Amin et al., ISSCC'18/JSSC'18

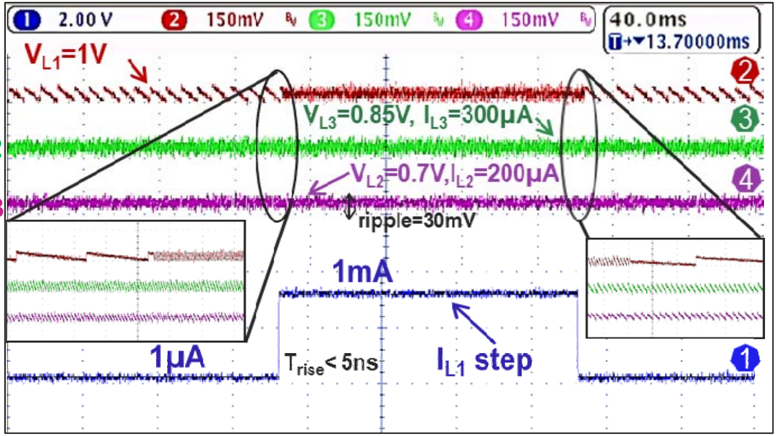
MISIMO Event Driven Controller

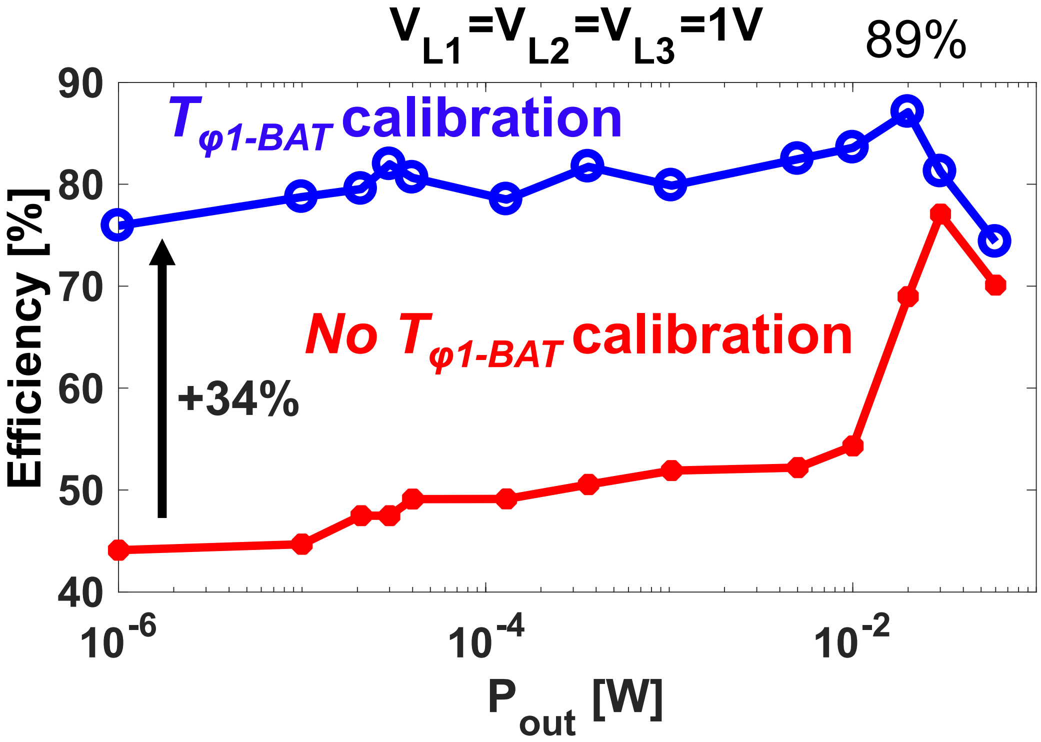


S.S. Amin et al., ISSCC'18/JSSC'18

MISIMO Measurement Results





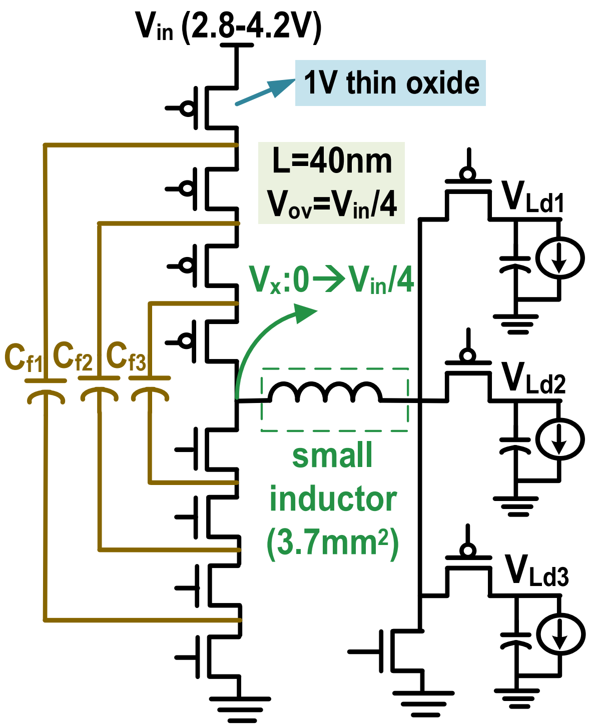


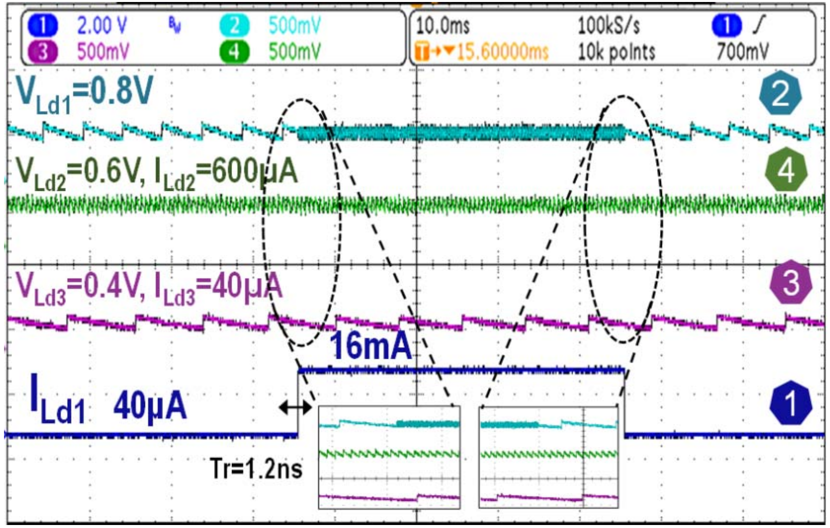
1μW - 60mW

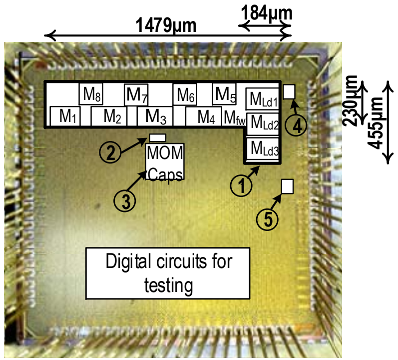
S.S. Amin et al., ISSCC'18/JSSC'18

Hybrid SIMO

H-SIMO: Hybrid SIMO



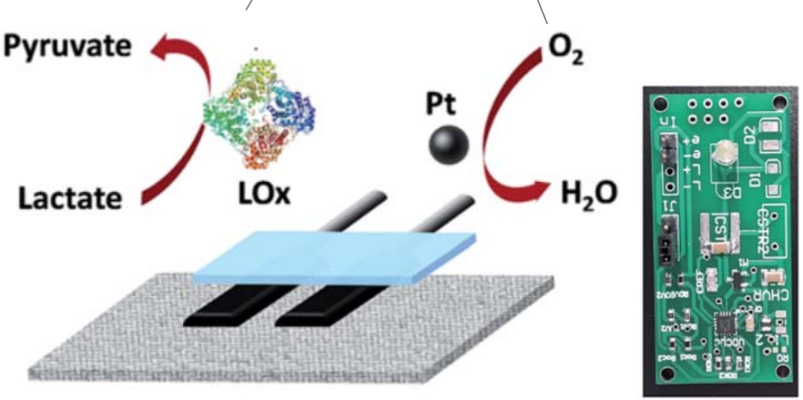


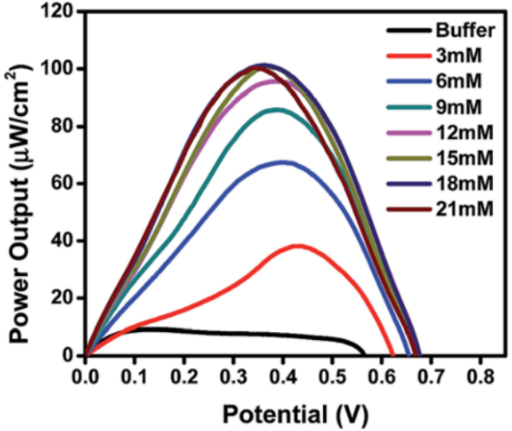


- Li-ion compatible in 28nm FDSOI
- Simultaneously regulates 3 loads w/ one inductor
- Peak efficiency = 91.4%
- 4,000x dynamic range w/ >70% efficiency

S.S. Amin et al., CICC'20

Harvesting energy from human perspiration via lactate biofuel cells

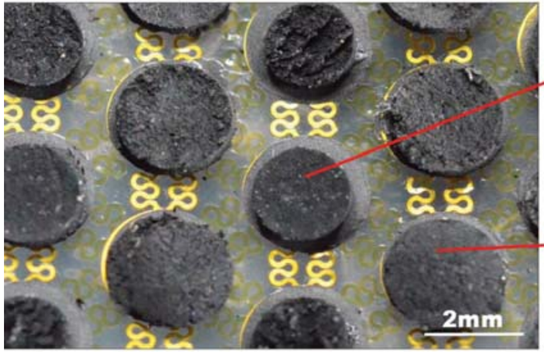


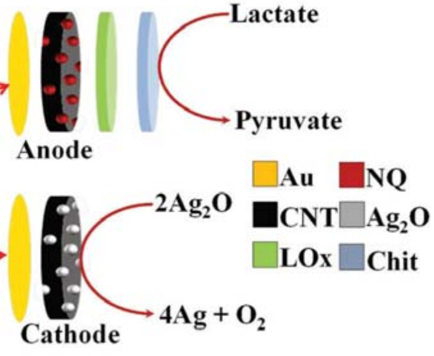


J. Wenzhao et al., J. Mat. Chem., 2014

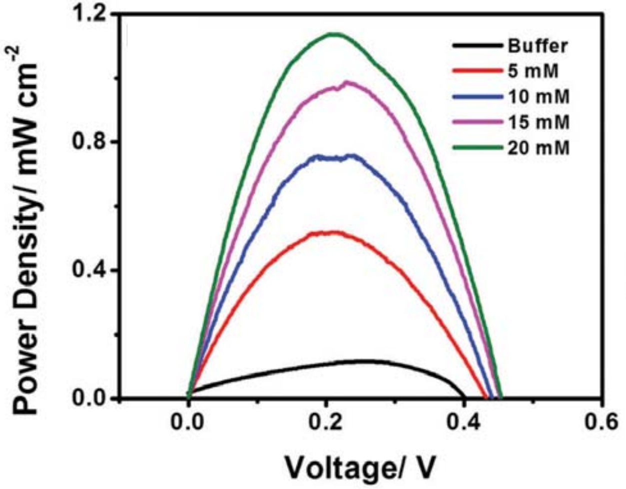
Increasing BFC power density

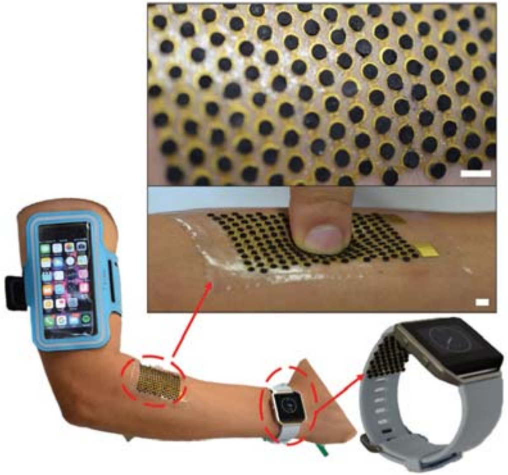
Islands-bridge structure enables high power density (**1mW/cm²**) while retaining stretchability

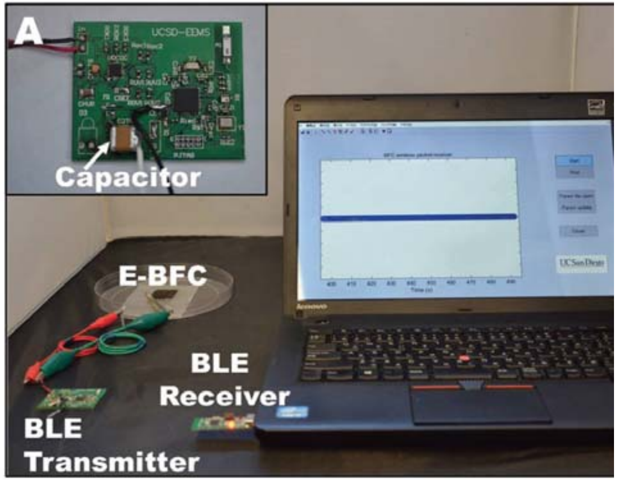




Sufficient power to operate a Bluetooth radio

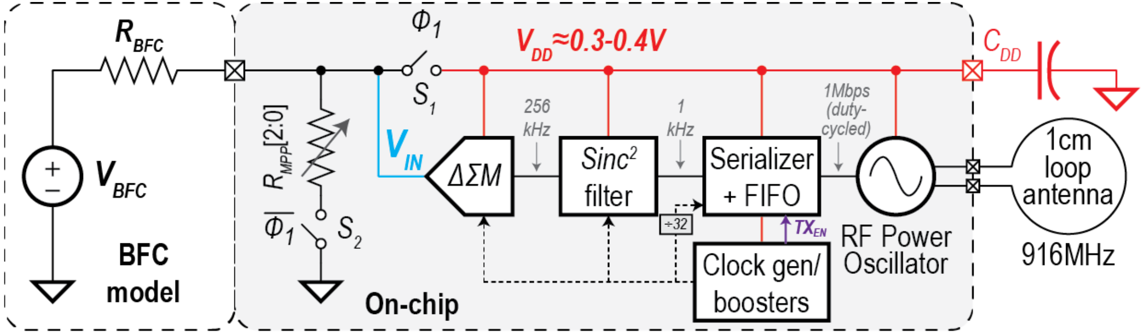




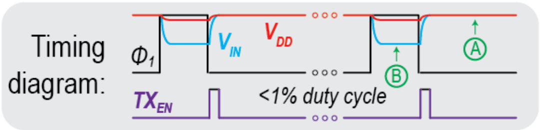


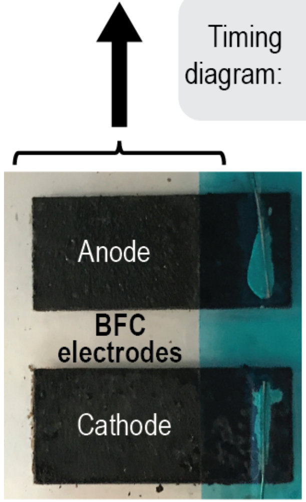
A.J. Bandodkar et al., Energy & Environmental Science, 2017

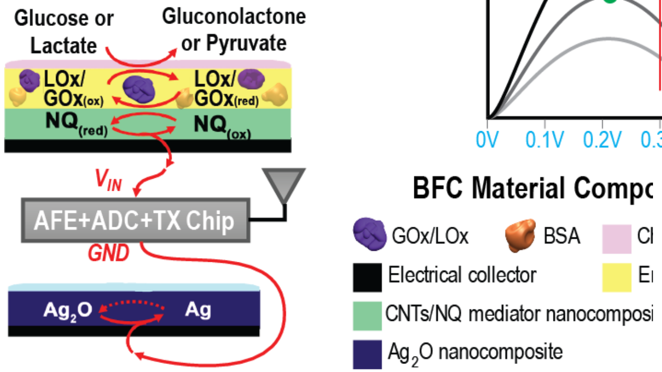
Self-powered glucose sensing

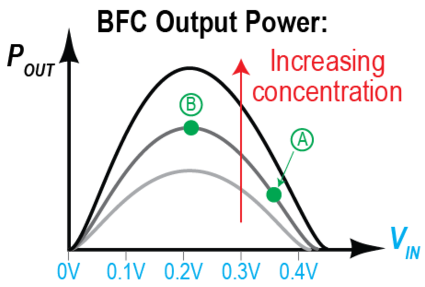


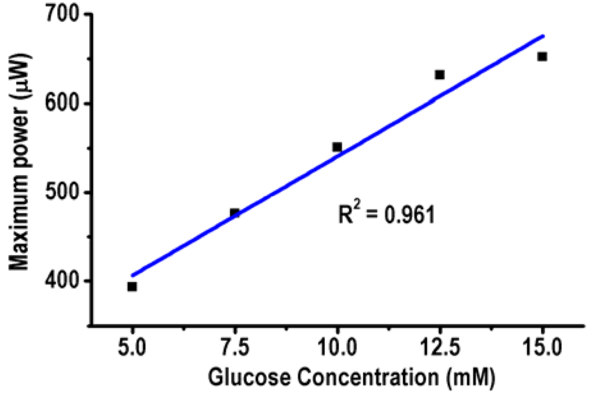
- No DC-DC converter
  - All circuits optimized to operate at 0.3V
- Full wireless capabilities
- 1μW average power







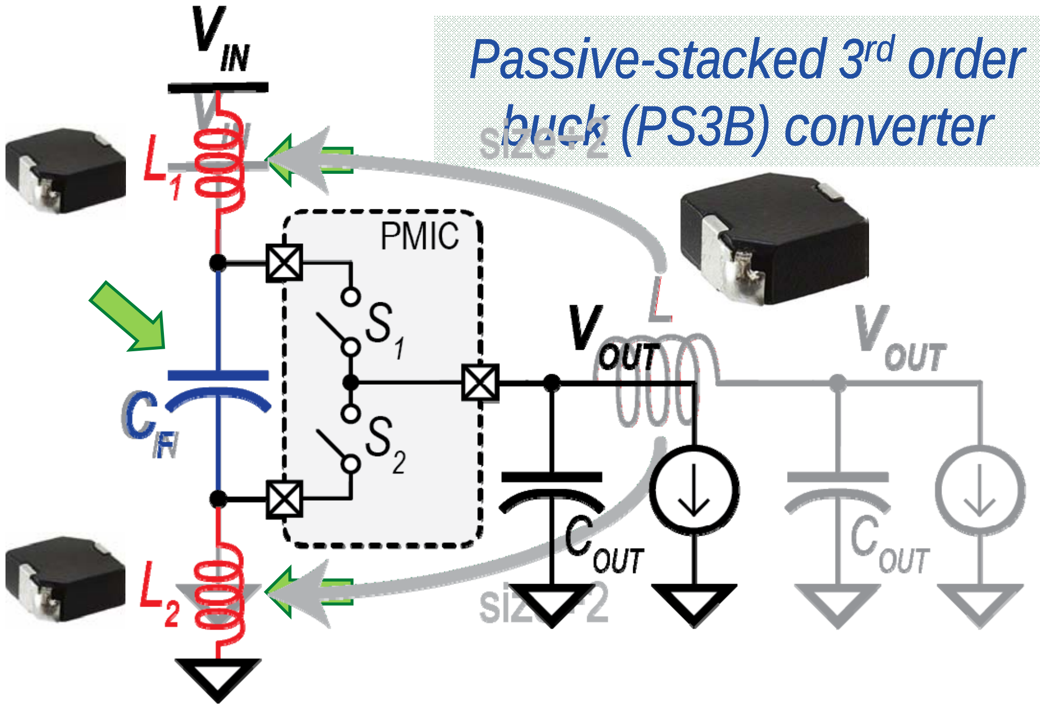


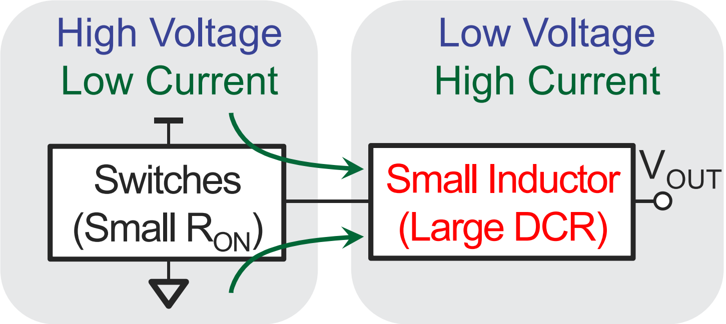


A.F. Yeknami et al., ISSCC/JSSC, 2018

Inductor-first conversion

Passive-stacked 3rd order buck (PS3B) converter





Split into two half-sized inductors and stack at input

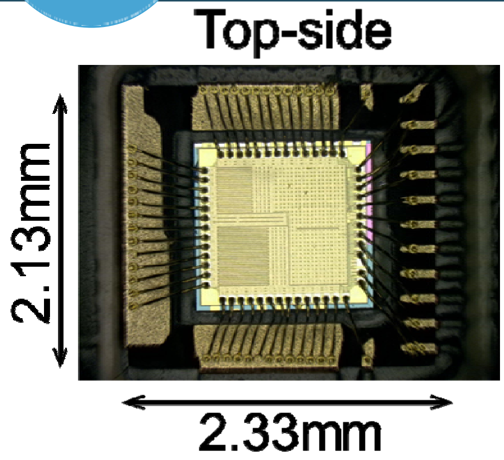
The input capacitor is now flying

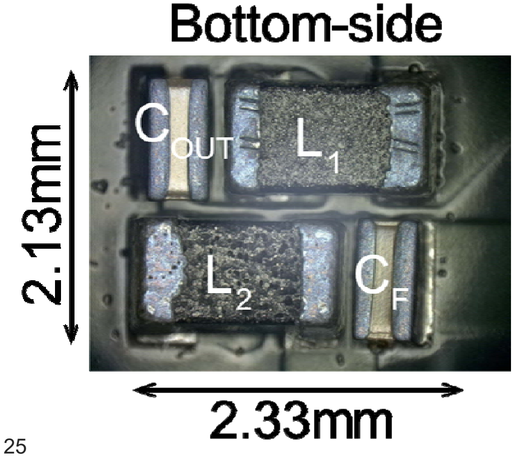
All passives are stacked at input

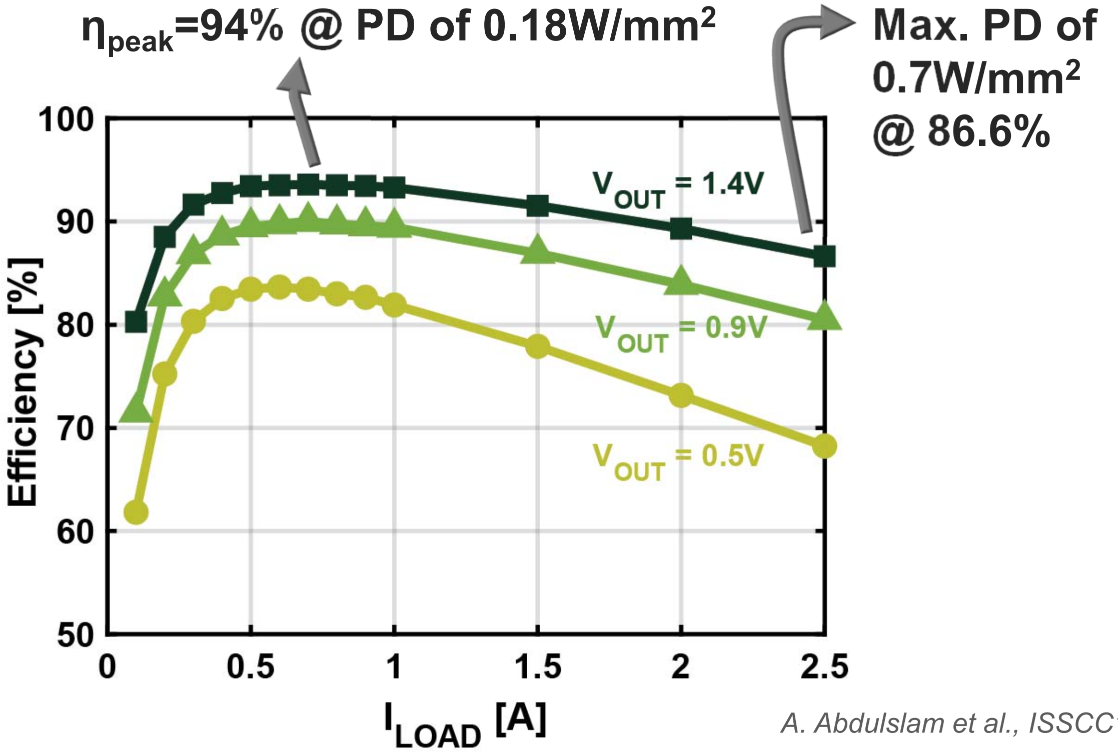
Inductors are placed at the low-current side of the converter

A. Abdulslam et al., ISSCC'19

PS3B Measurement Results





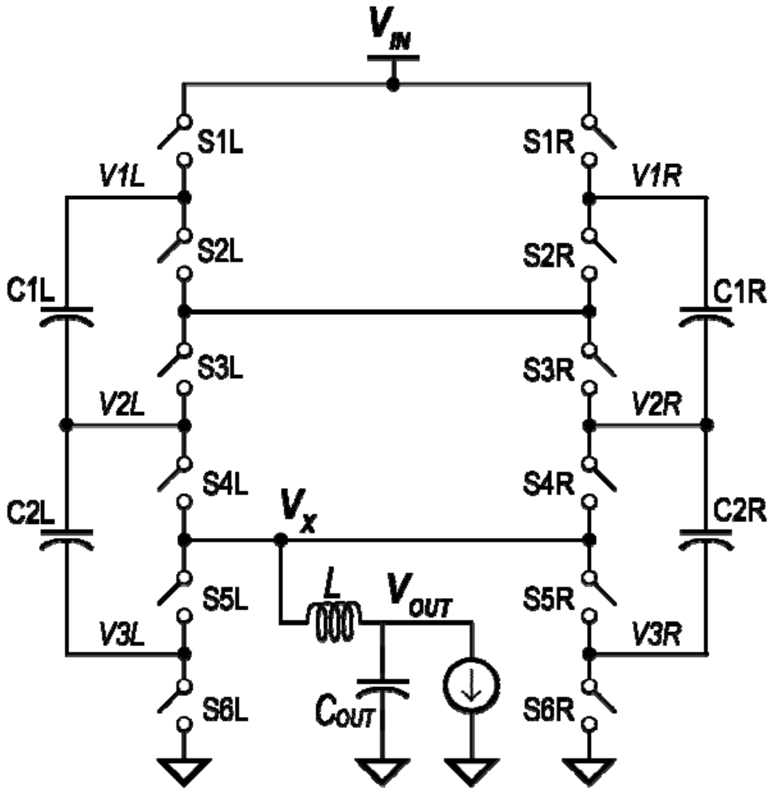


A. Abdulslam et al., ISSCC'19

Benefits: reduced EMI and input noise, area-efficient stacked-passives, smaller inductors volume

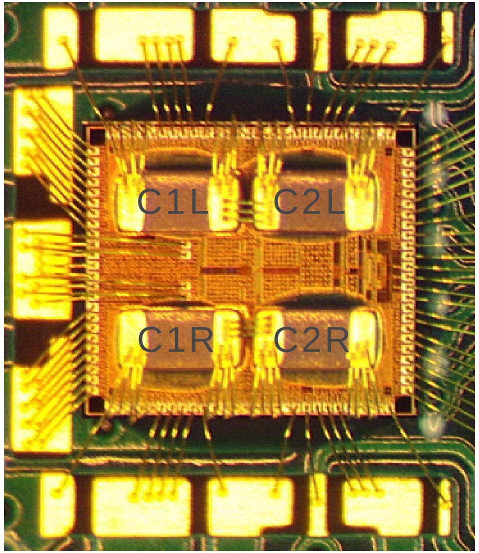
Li-ion-compatible SMML Converter

- A symmetric modified multilevel ladder (SMML) converter:
  - Consists of two sides each with 2 capacitors and 6 switches.
- Features:
  - ✓ **Decreased conduction losses** due to inherent phase interleaving.
  - ✓ **Minimum blocking voltage** on all switches/capacitors.
  - ✓ **No need for voltage balancing modules** flying capacitors are naturally stable.
  - ✓ **All necessary supplies are generated internally** to power drivers and level shifters.

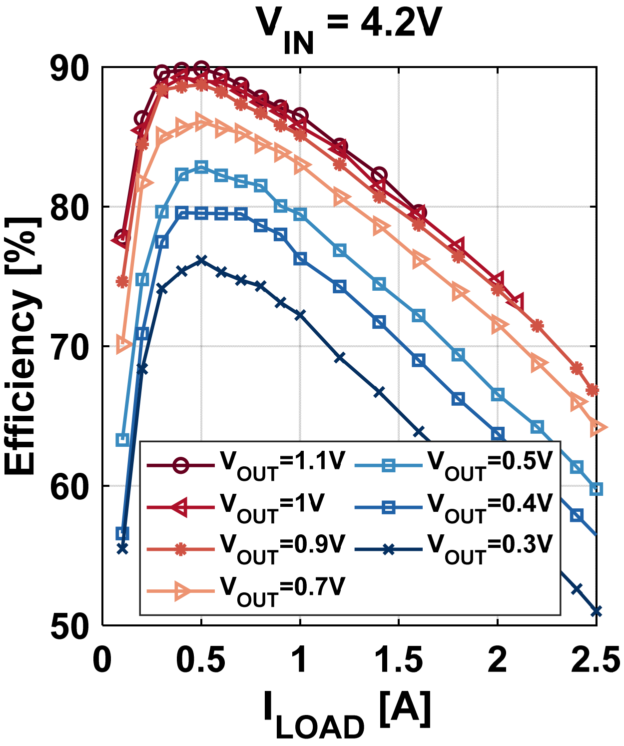


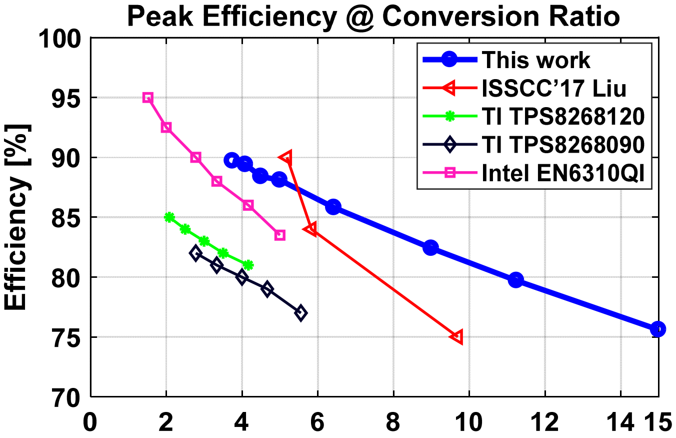
A. Abdulslam et al., JSSC'20

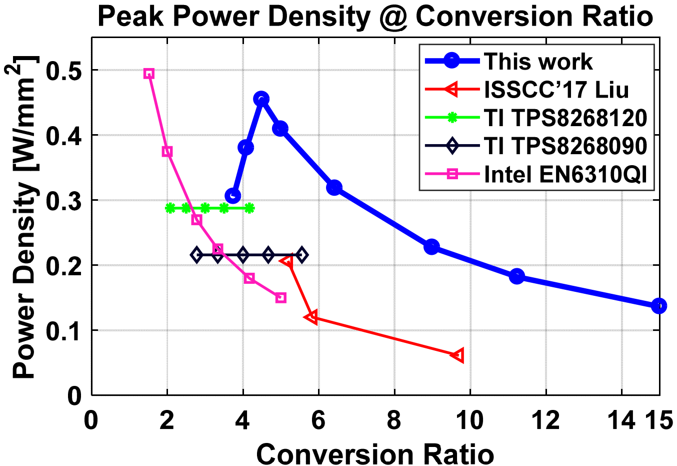
SMML Measurement Results



The inductor and the output capacitor are mounted under the chip

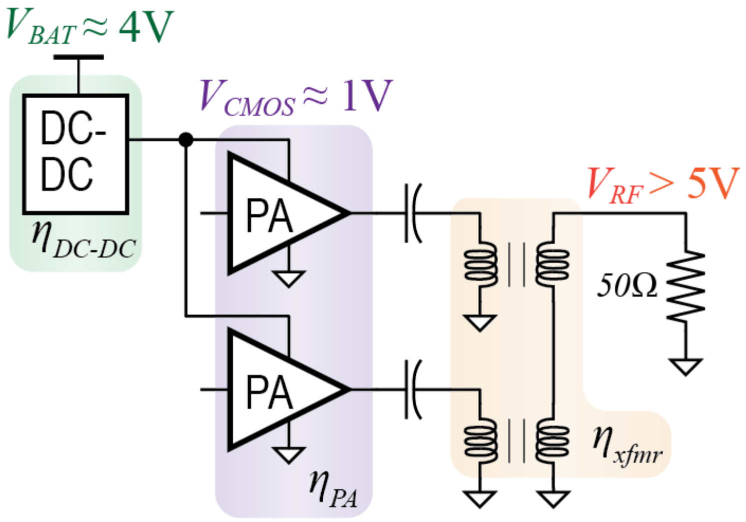






A. Abdulslam et al., JSSC'20

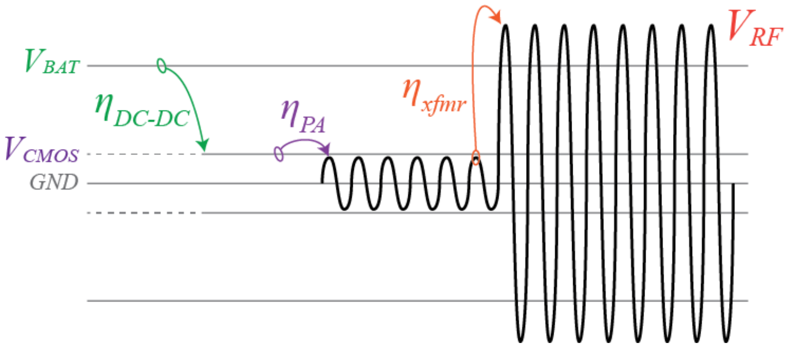
CMOS Power Amplifier Voltage Challenge



Idea: utilize many efficient ~1V class-D PAs and combine power with transformers

Problem: three voltage conversion stages leads to cascaded losses:

$$\eta_{tot} = \eta_{DC-DC}\,\eta_{PA}\,\eta_{xfmr} < 30\%$$



Why do we go down, then back up in voltage?
There must be a better way!

Partial Solution: PA Stacking

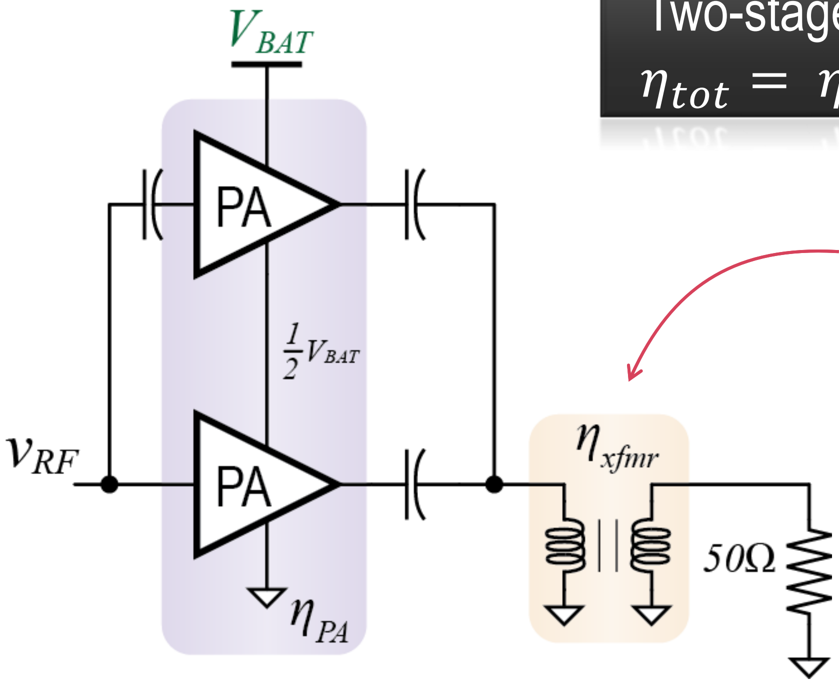
Stack entire class-D PAs for current re-use:

~100% efficient *implicit* DC-DC conversion

(each PA sees only $V_{BAT}/2$)

Two-stage cascade:

$$\eta_{tot} = \eta_{PA}\,\eta_{xfmr}$$

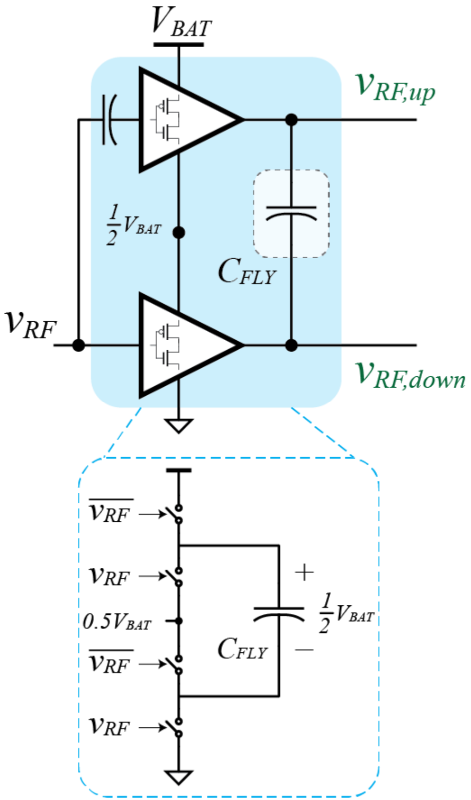


Problem: still require lossy transformer to achieve high output power in scaled CMOS

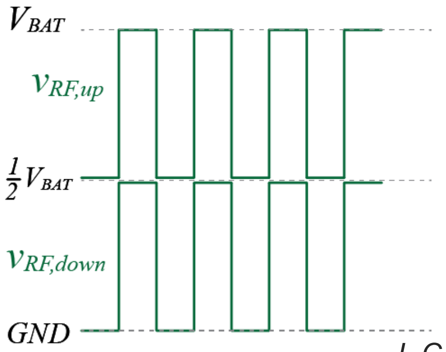
L.G. Salem et al., JSSC'17

Solid-State RF Impedance Transformation

Idea: generate large RF voltages directly from a battery using ~1V devices by stacking PAs, then flying subsequent PAs between the rails of the prior stages in a *House-of-Cards* Topology



Animation not seen in print



L.G. Salem et al., JSSC'17

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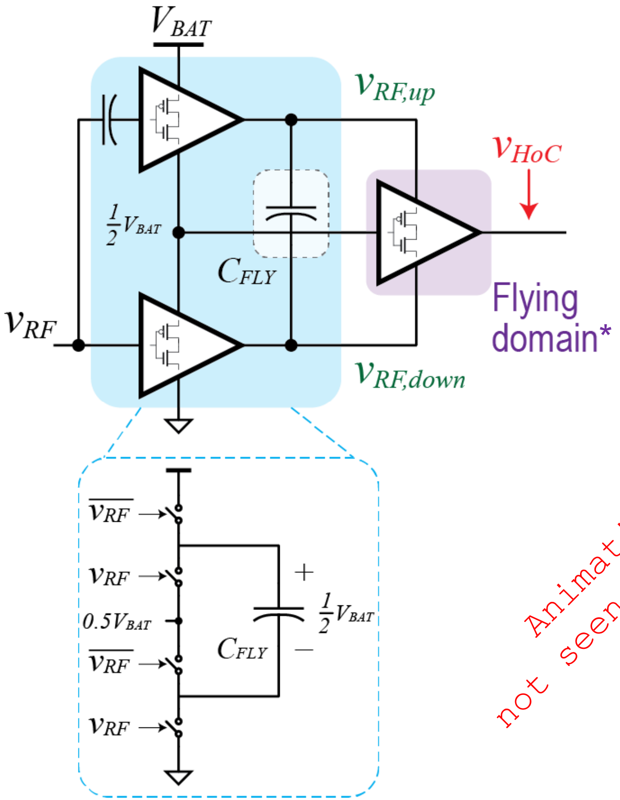
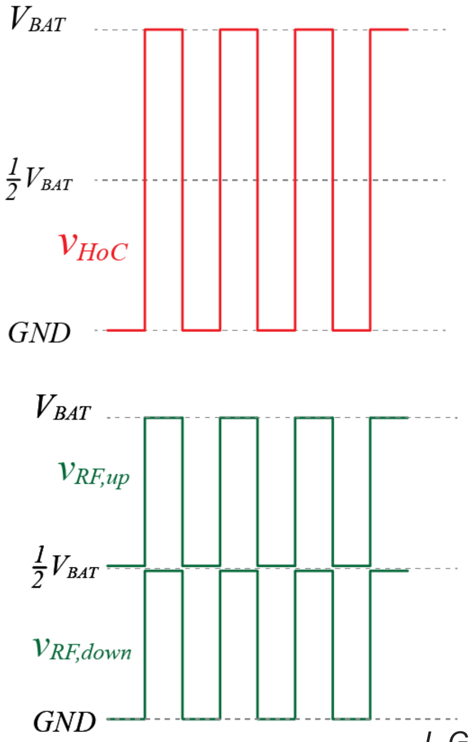


Animation not seen in print



*For more information, see Salem et al., ISSCC'16

L.G. Salem et al., JSSC'17

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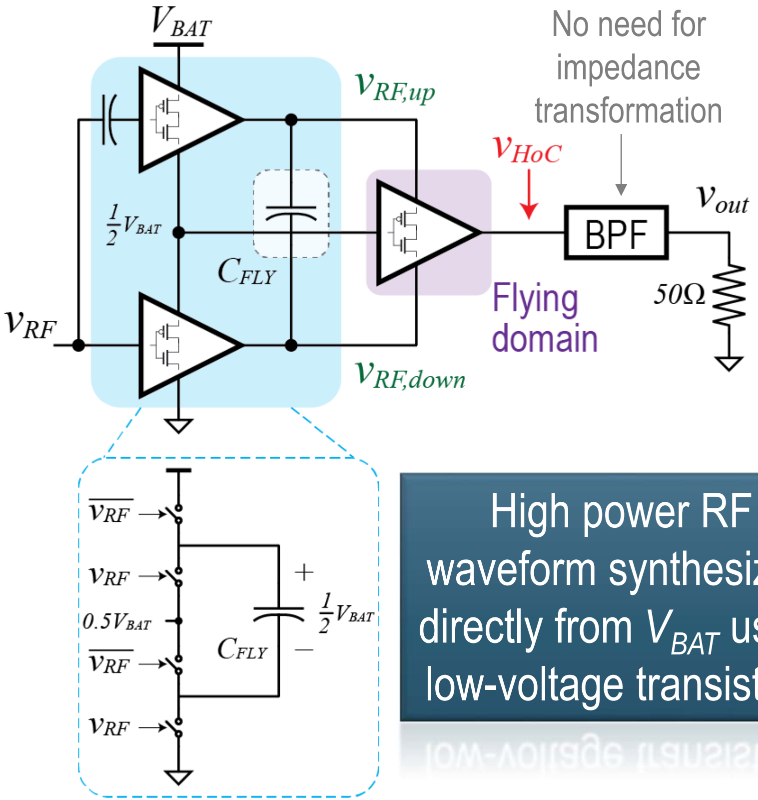
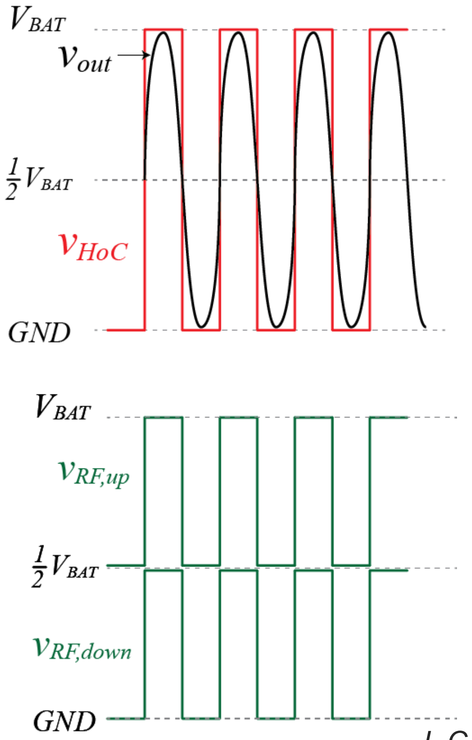


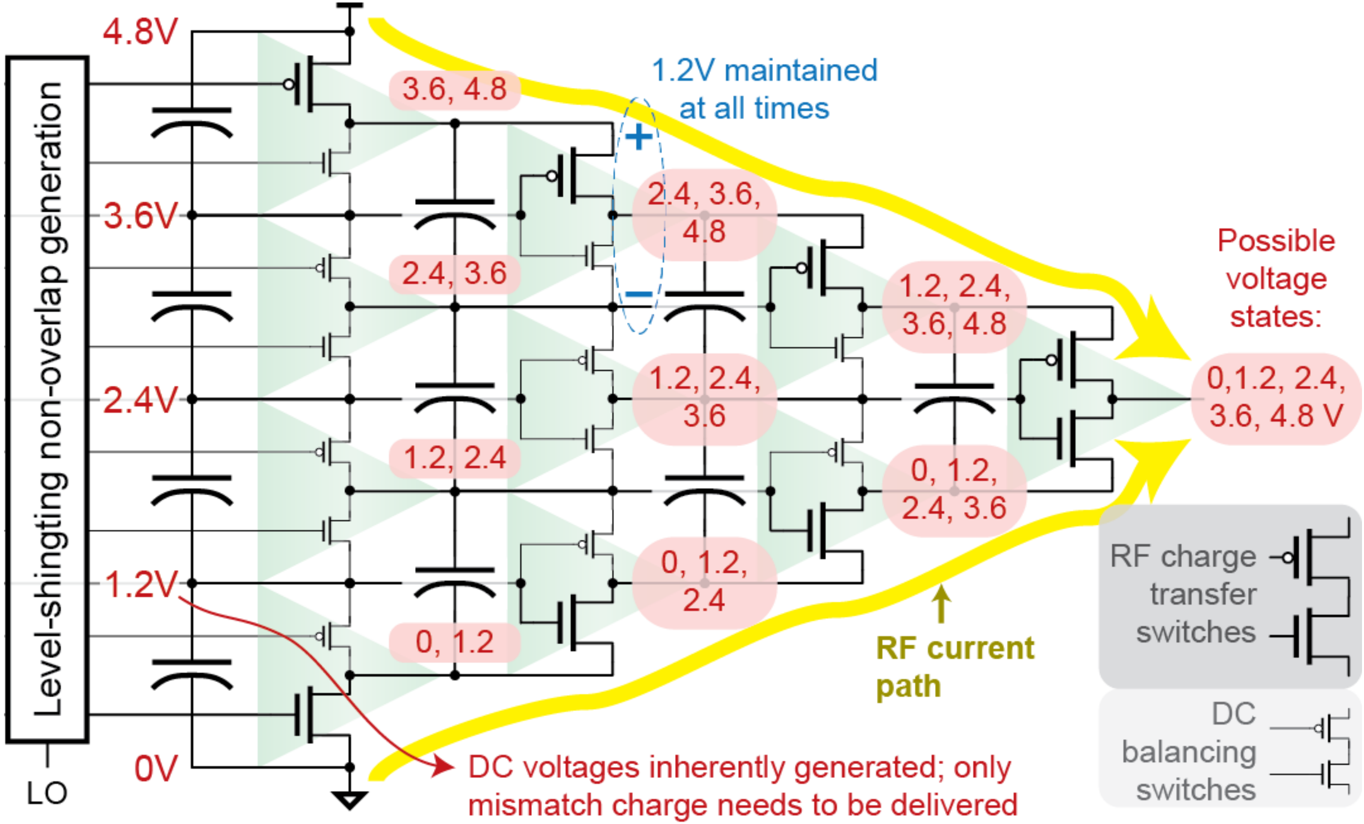


High power RF waveform synthesized directly from V_{BAT} using low-voltage transistors

*For more information, see Salem et al., ISSCC'16

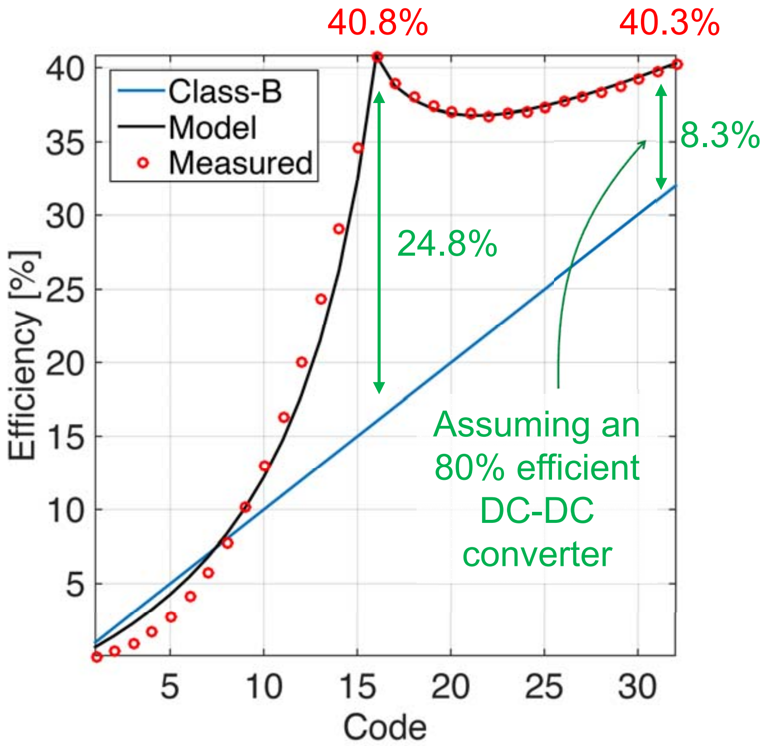
L.G. Salem et al., JSSC'17

House-of-Cards (HoC) Schematic

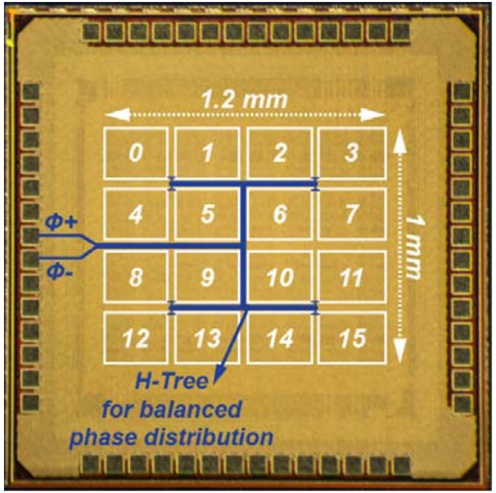


L.G. Salem et al., JSSC'17

Measurement results: PAE



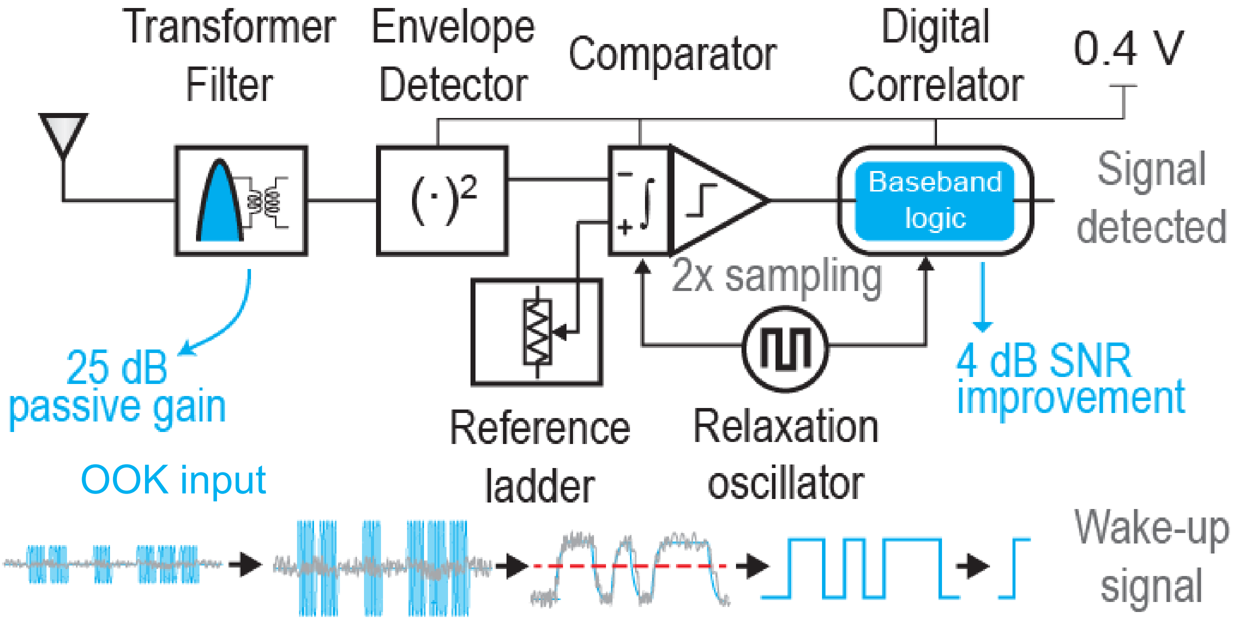
65nm LP
1.2V transistors
Direct 4.8V Li-ion battery connection



>40% battery-to-RF power-added efficiency at both peak power (23dBm) and at 6dB backoff

L.G. Salem et al., JSSC'17

A nW Wake-up Receiver

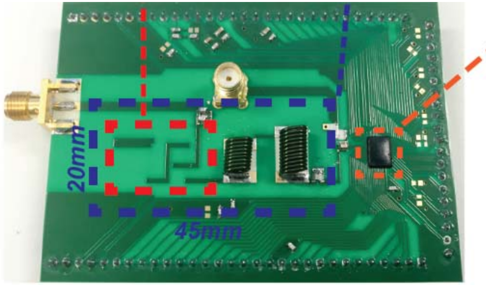


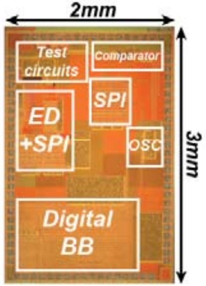
High R_{in} ED supports high passive gain front-end w/ high-*Q* filtering at low power

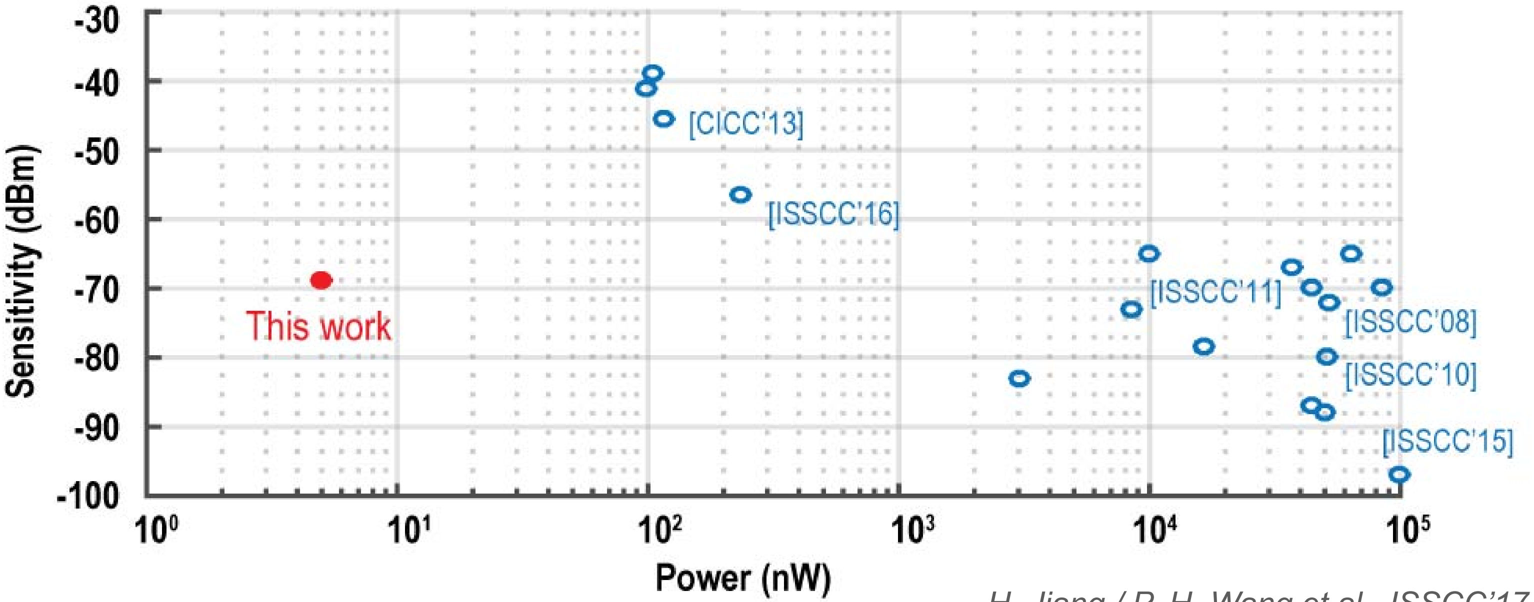
H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

WuRX Measurement Results

- Power consumption: 4.5nW
- Sensitivity: -69dBm
- Wake-up latency: 53ms







H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

Challenge: standards compliance

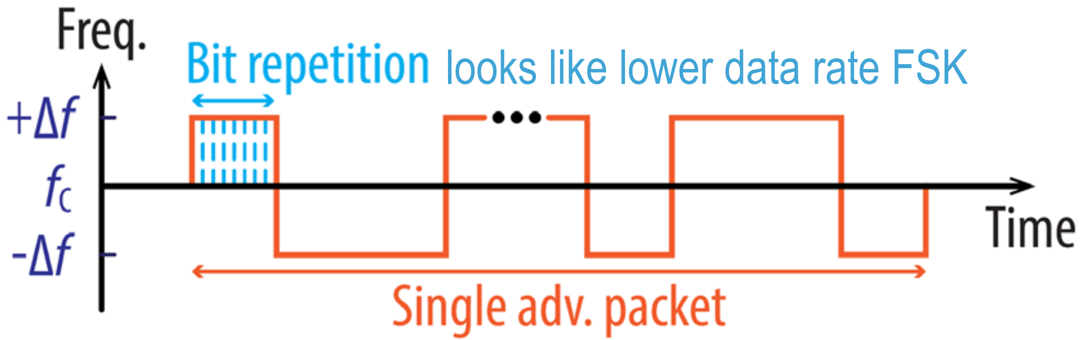
Most standards use complex modulation at high data rates
→ difficult to build an ultra-low-power RX w/ good sensitivity

Back-channel communication

N. E. Roberts et al., ISSCC'16

Hack a standard-compliant signal to look like a simpler, lower bandwidth modulation

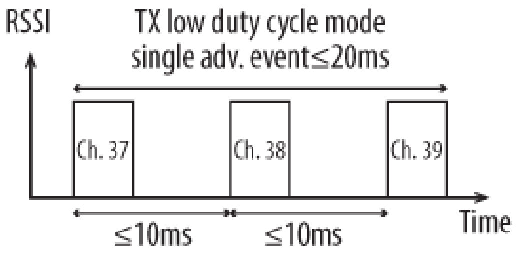
Example:



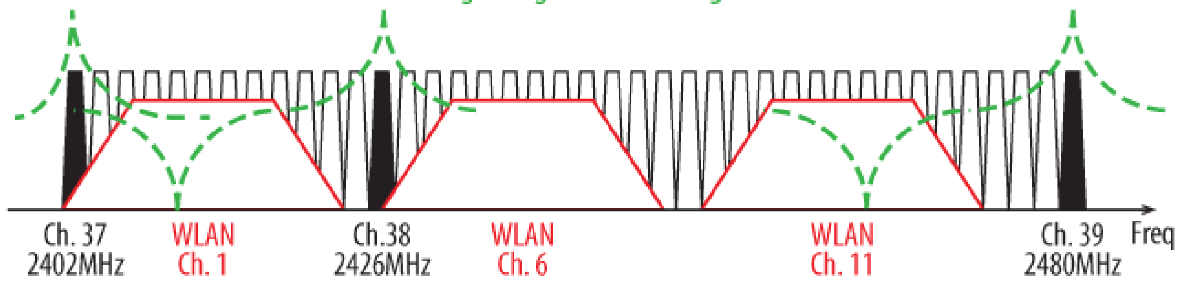
M. R. Abdelhamid et al., CICC'18

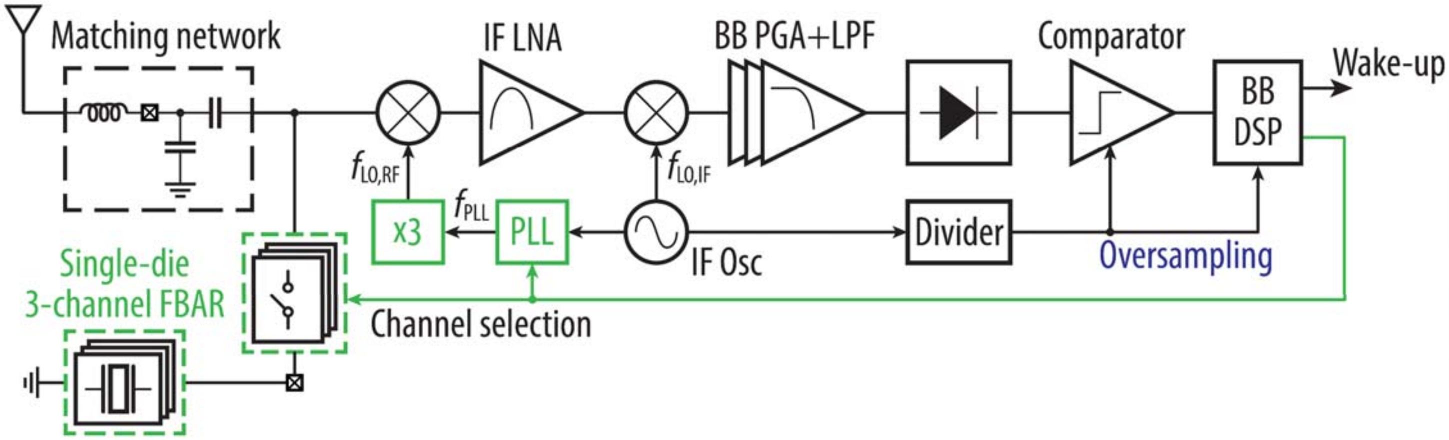
An Interference-Robust BLE-Compliant WuRX

BLE advertising event structure



BLE advertising channels and wireless co-existance @ 2.4GHz ISM band

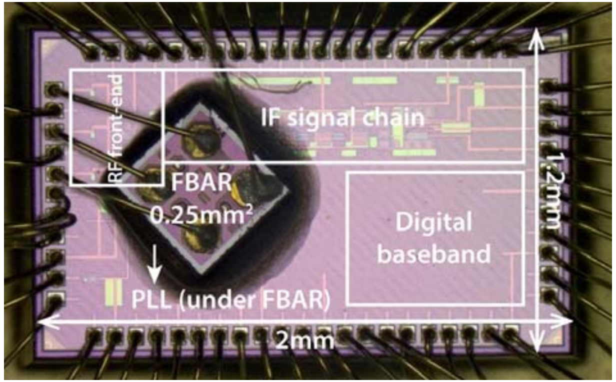




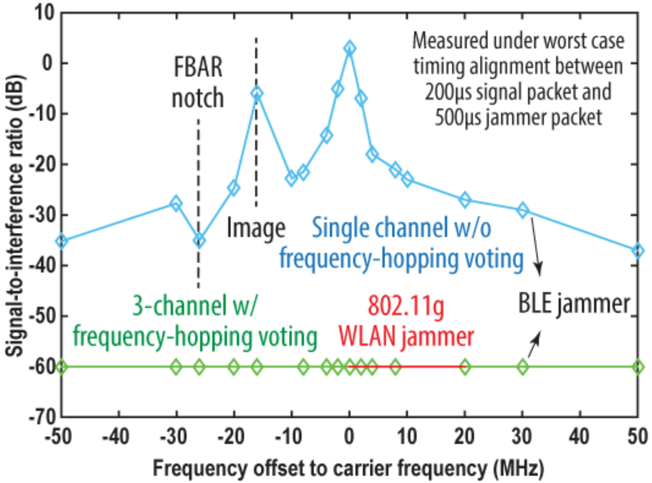
Frequency-hoping between advertising channels enables interference-resilient detection

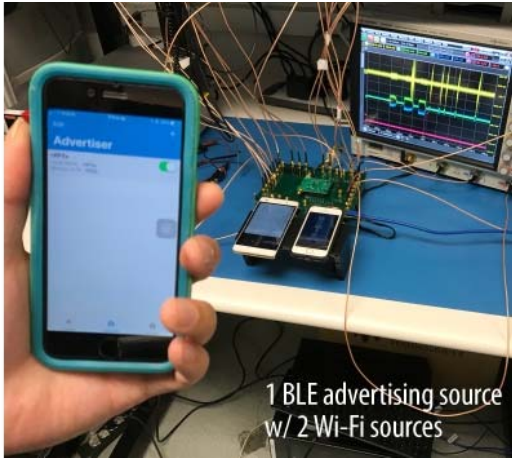
P.-H. Wang et al., ISSCC'19

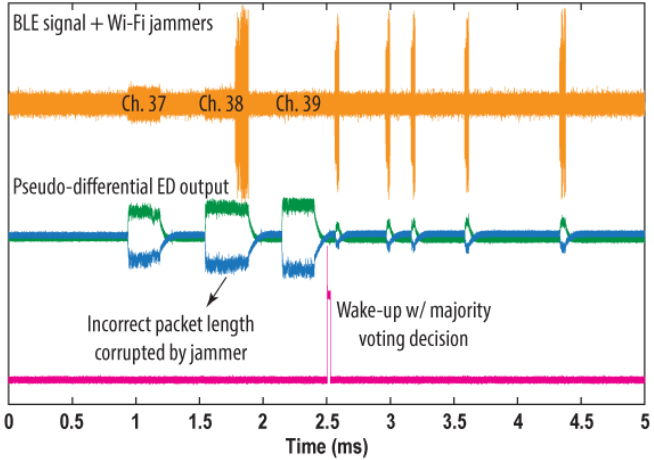
An Interference-Robust BLE-Compliant WuRX



- **Sensitivity:** -85dBm @ 220µW
  - 27.5dB better than prior-art
- **Latency:** 200µs-to-1.47ms
- **SIR:** at least -60dB SIR (limited by measurement setup)







P.-H. Wang et al., ISSCC'19

Conclusions

- Next generation IoT devices require:
  - New sensors and sensing techniques
  - Small form factors
  - Long/infinite battery life → often limited by radios
- Meet these needs through:

Application Engineering
- New communication paradigms
- New sensor development

Architectural Innovations
- New sensor transduction/digitization techniques
- New power conversion circuit topologies

New Circuit Techniques
- Topologically-defined “digitally-replaced analog”
- Deep subthreshold DTMOS



Exciting new IoT applications!



Acknowledgements

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NSF

ARL U.S. Army Research Laboratory

NEXTFLEX

TRAQ

SAMSUNG

pSemi™ A Murata Company

NIH National Institute of Biomedical Imaging and Bioengineering

Arnold and Mabel BECKMAN FOUNDATION

QUALCOMM®

UC San Diego JACOBS SCHOOL OF ENGINEERING Center for Wireless Communications

Office of Naval Research ONR Science & Technology

KETI

CBAM Center for Brain Activity Mapping

KAVLI Institute for Brain & Mind

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Quantal RF The Future of RF