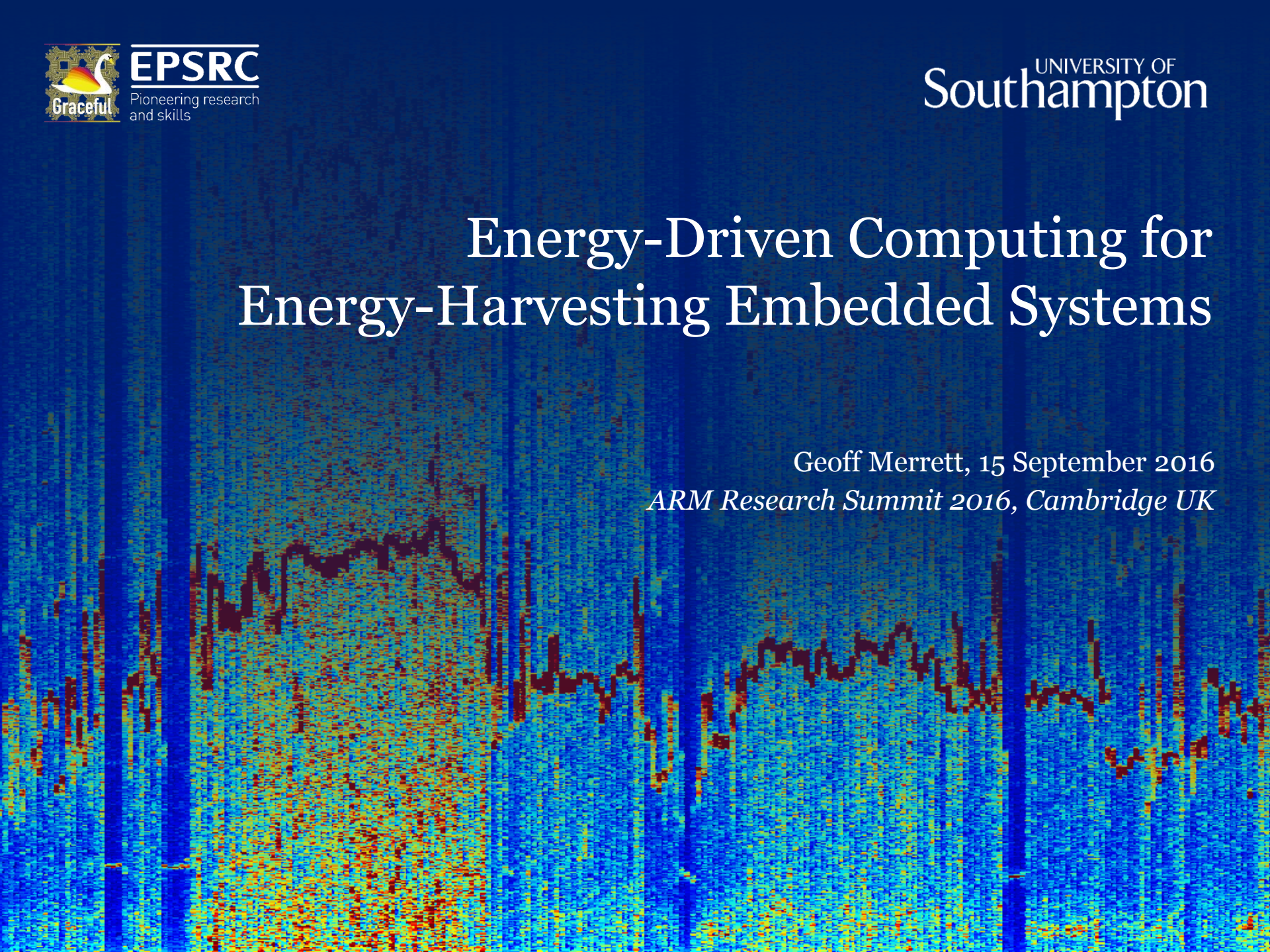
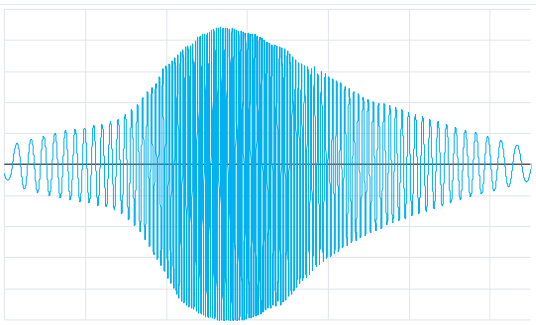


Energy-Driven Computing for Energy-Harvesting Embedded Systems

Geoff Merrett, 15 September 2016

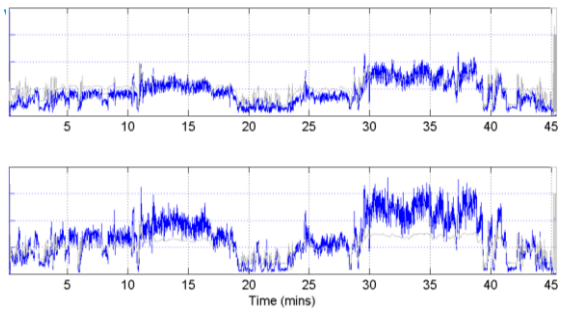
ARM Research Summit 2016, Cambridge UK

varies temporally



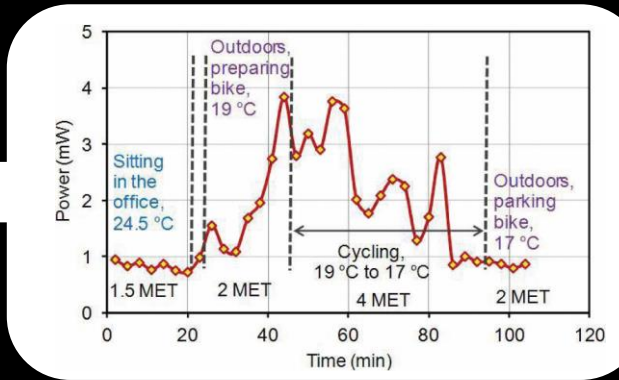
D. Balsamo et al. Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. IEEE TCAD, 1-13.

varies spatially

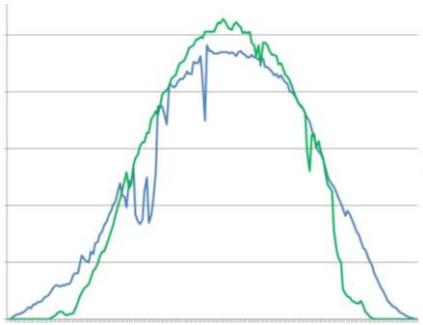


Beeby, S.P. et al. A comparison of power output from linear and non-linear kinetic energy harvesters using real vibration data. Smart Materials and Structures, 22, (7), 075022.

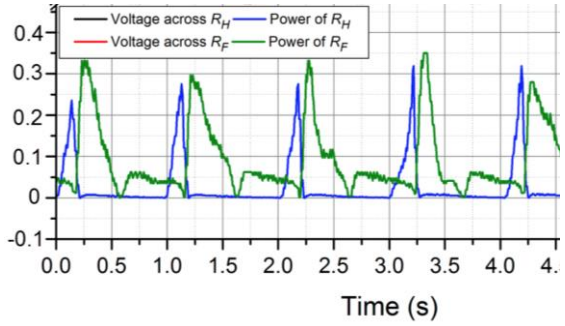
Power/ Energy



V. Leonov, "Thermoelectric Energy Harvesting of Human Body Heat for Wearable Sensors," IEEE Sensors Journal, vol.13, no.6, pp.2284-91, June13



http://solar.rainham-kent.co.uk

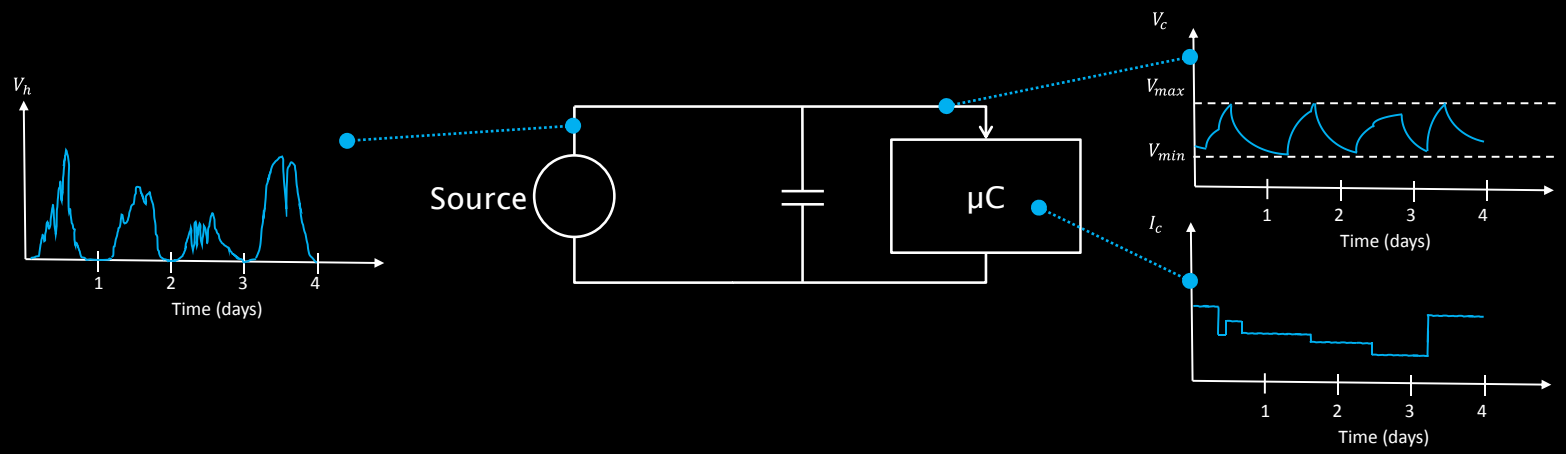


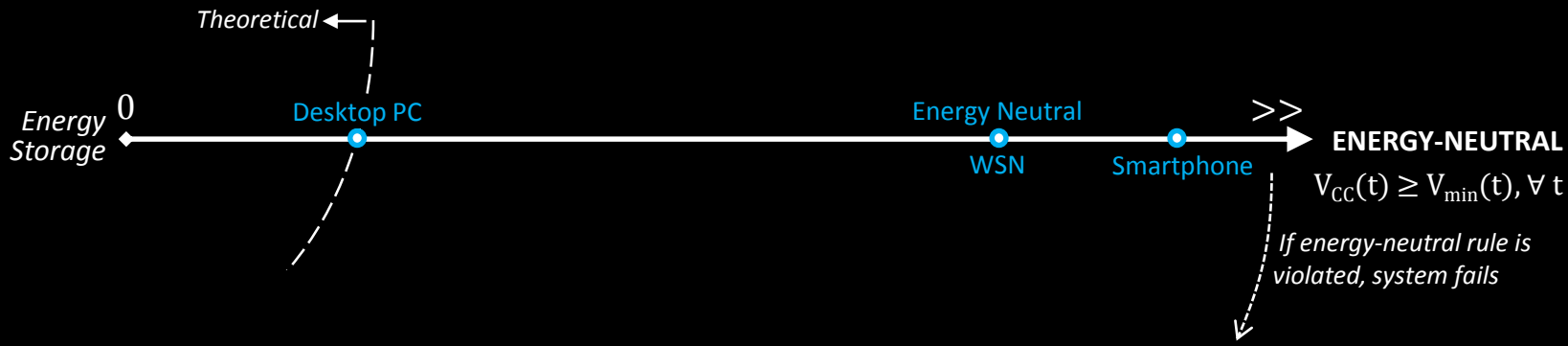
Zhao, J. et al. "A Shoe-Embedded Piezoelectric Energy Harvester for Wearable Sensors," Sensors 2014, 14, 12497-12510.

Highly variable supply + variable consumption

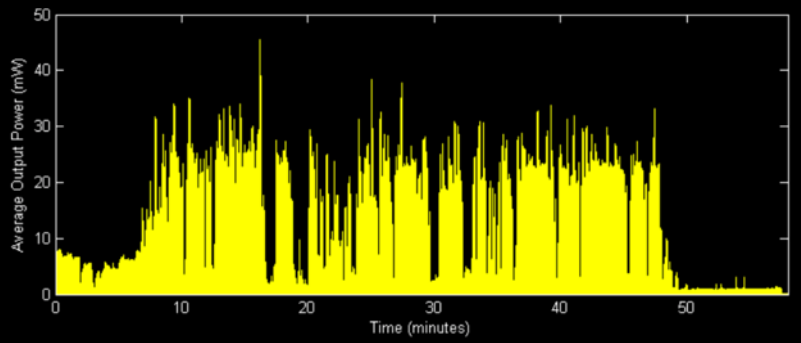
Energy-Neutral Computing

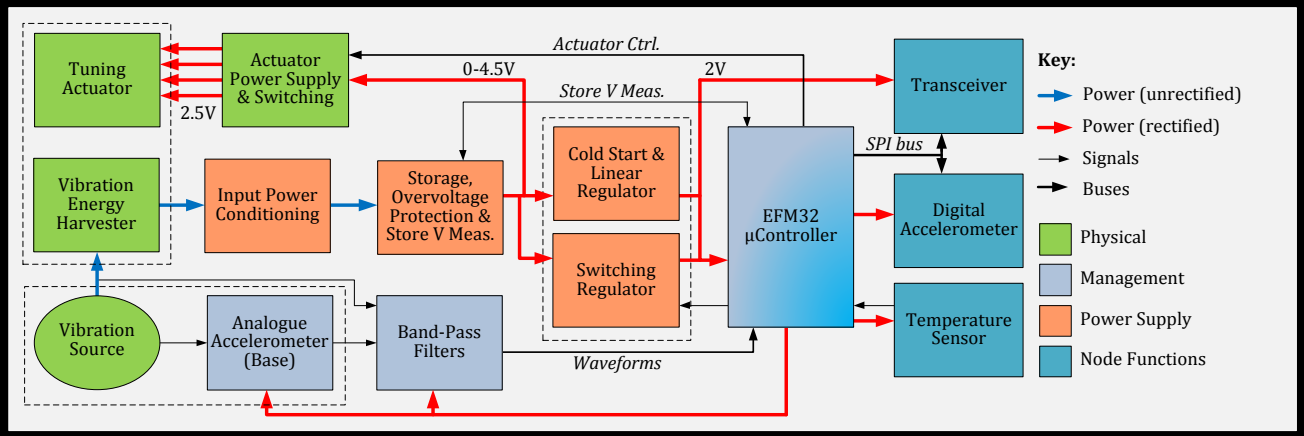
$$\int_{(n-1)\cdot T}^{n\cdot T} P_h(t)dt = \int_{(n-1)\cdot T}^{n\cdot T} P_c(t)dt$$

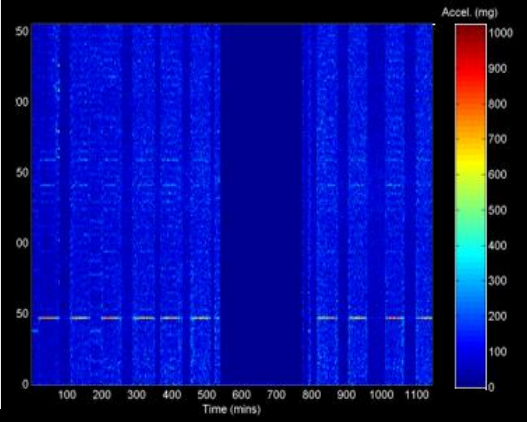




Energy-Neutral Case Study







www.holistic.ecs.soton.ac.uk

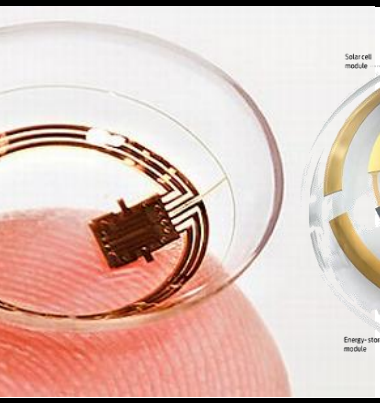
EPSRC
Pioneering research and skills

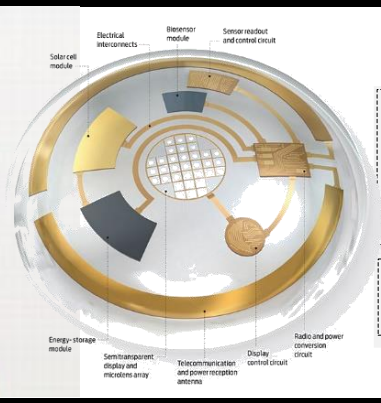
A.S. Weddell, D. Zhu, G.V. Merrett, S.P. Beeby, B.M. Al-Hashimi, (2012) A practical self-powered sensor system with a tunable vibration energy harvester. In, PowerMEMS 2012, Atlanta, US, 02 - 05 Dec 2012.

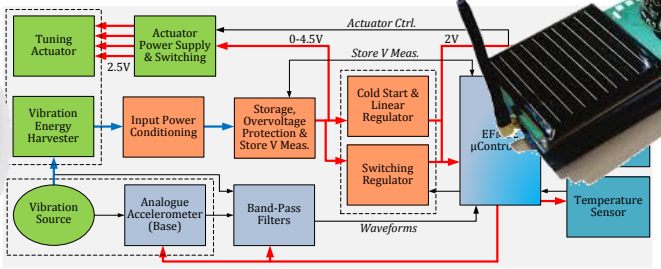
holistic energy harvesting

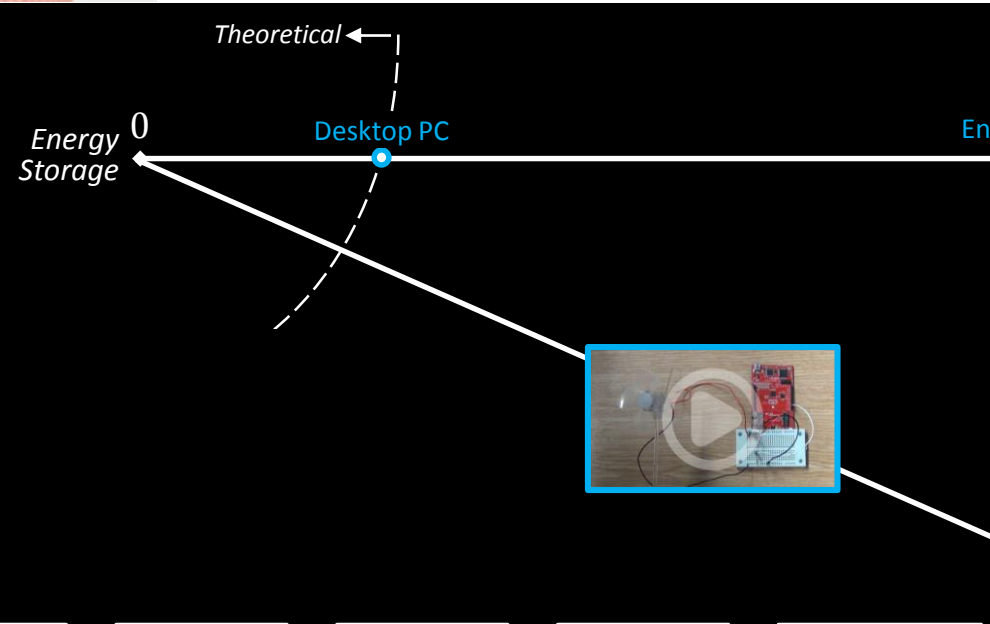
"Transient" Computing

A. Weddell et al., "A practical self-powered sensor system with a tunable vibration energy harvester," PowerMEMS 2012, Atlanta
C. Renner et al., "State-of-charge assessment for supercap-powered sensor nodes: Keep it simple stupid!," INSS'12, Antwerp
TelosB Crossbow Mote | Drexel University | SENSIMED's Triggerfish® | Emily Cooper

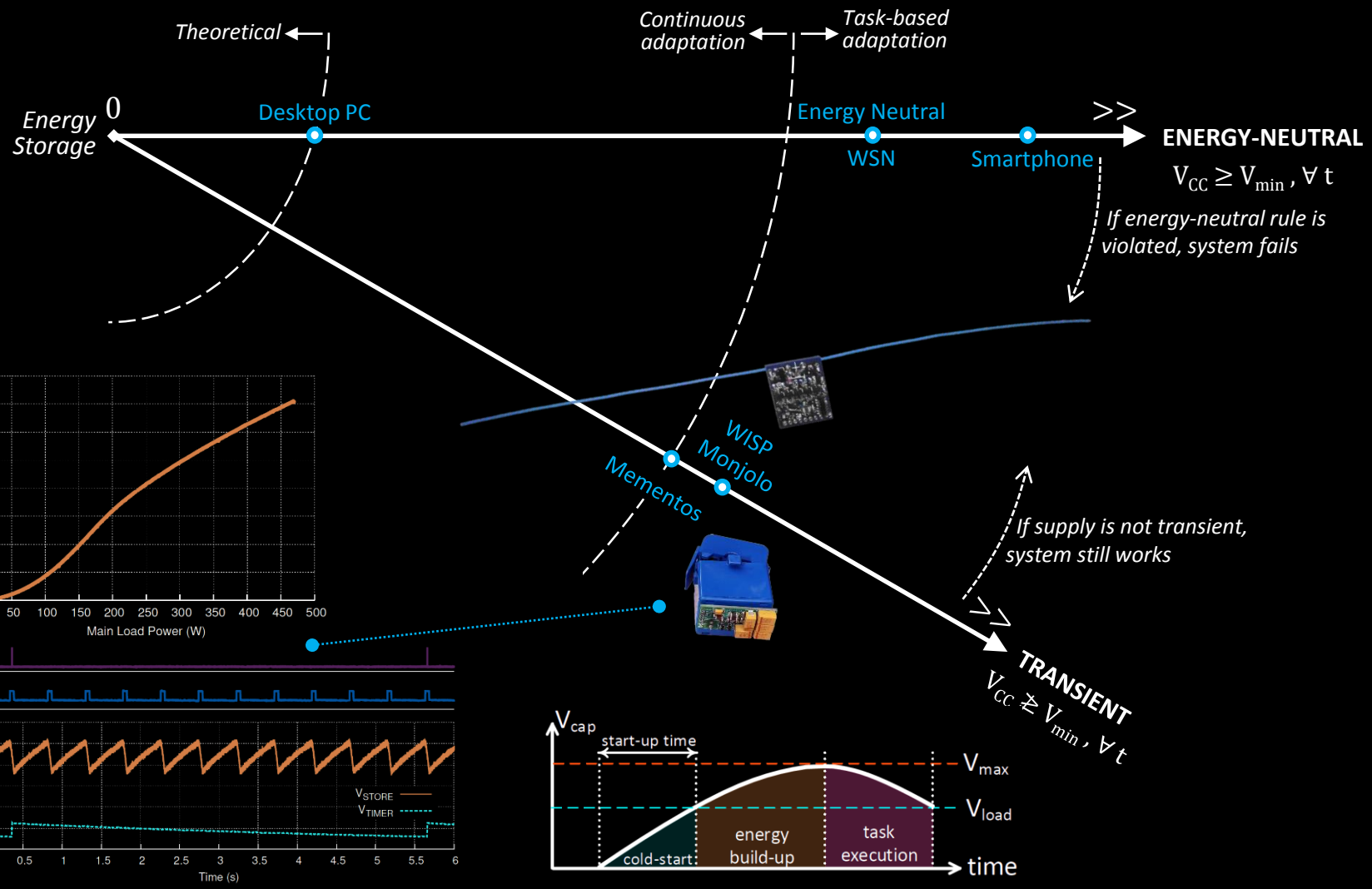








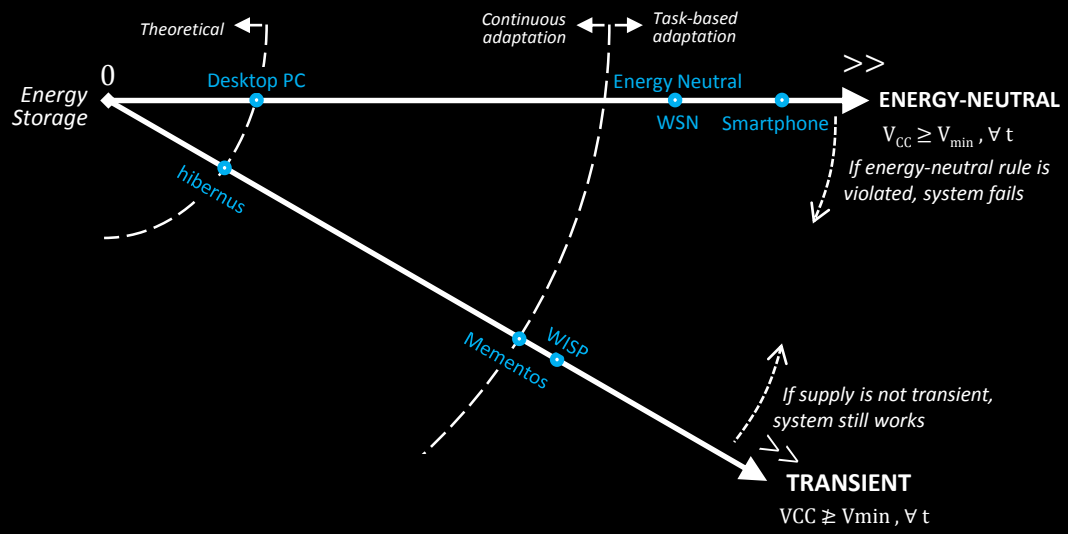
Transient Computing

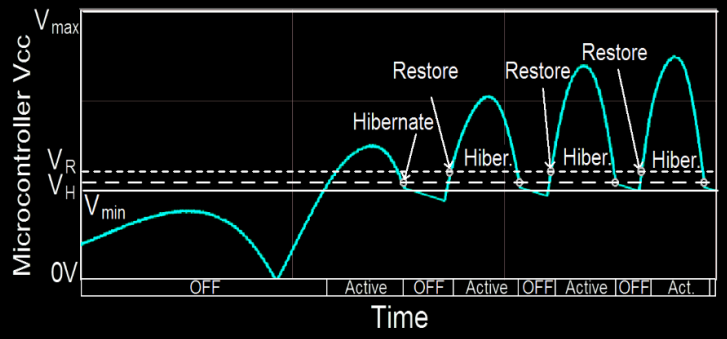


Monjolo: S. DeBruin et al., Monjolo: An Energy-Harvesting Energy Meter Architecture, ACM SenSys'13
A. Gomez et al., "Dynamic energy burst scaling for transiently powered systems," *DATE 2016*, Dresden, 2016, pp. 349-354.
WISP: A. P. Sample et a., "Design of an RFID-Based Battery-Free Programmable Sensing Platform," in IEEE Transactions on Instrumentation and Measurement, vol. 57, no. 11, pp. 2608-2615, Nov. 2008.
Mementos: B. A. Ransford, J. M. Sorber and K. Fu, "Mementos: System Support for Long-Running Computation on RFID-Scale Devices", *ASPLOS'11*, March 5–11, 2011, Newport Beach, California, USA.

hibernus

- Use the principle of checkpointing to NVM
- Detect when supply is 'failing', and (always) make a single snapshot
  - Removes wasted snapshots created through polling (increases efficiency)
  - Ensures that a valid snapshot is always made (improves reliability)
- Make it as late as possible
  - Avoids re-executing code (increases efficiency)
  - Maximises execution time (increases efficiency)





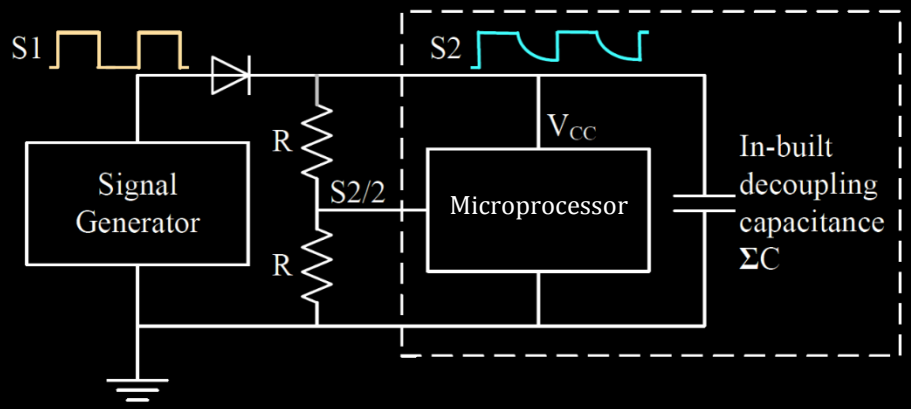
$$T_{\text{mementos}} = \overbrace{T_a}^{\text{Algorithm}} + \underbrace{n_\iota}_{\text{No. interruptions}} \left(\overbrace{T_r}^{\text{Restore snapshot}} + \underbrace{\frac{T_a}{2n_m}}_{\text{Backtrack}} \right) + \overbrace{n_m(T_m + \rho_s T_s)}^{\text{Monitoring and save snapshot}}$$

$$\underbrace{T_{\text{Hibernus}}}_{\text{Total execution}} = \overbrace{T_a}^{\text{Algorithm}} + \underbrace{n_\iota}_{\text{No. interruptions}} \left(\overbrace{T_s}^{\text{Save snapshot}} + \underbrace{T_r}_{\text{Restore snapshot}} + \overbrace{T_\lambda}^{\text{Sleep}} \right)$$

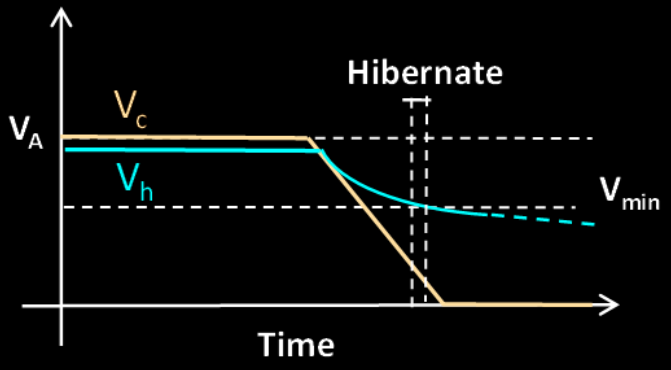
D. Balsamo, A.S. Weddell, G.V. Merrett, B.M. Al-Hashimi, D. Brunelli, and L. Benini, "Hibernus: Sustaining Computation during Intermittent Supply for Energy-Harvesting Systems," IEEE Embedded Systems Letters, 2014

hibernus: When to hibernate and restore?

- Adaptive, run-time:
  - Platform calibration
  - Source classification

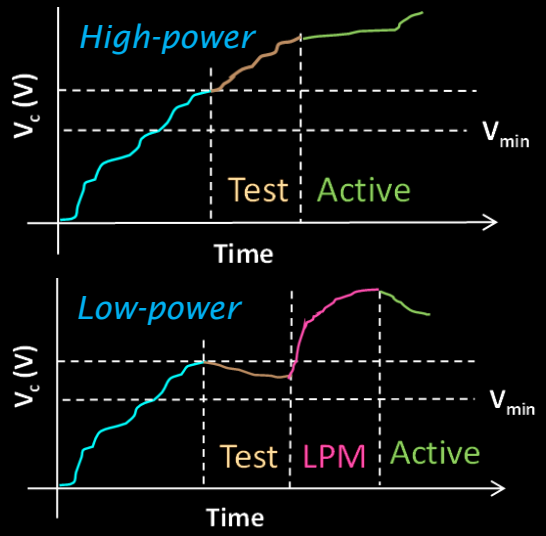


- Hibernate threshold (platform calibration)



Hibernation voltage, V_H, chosen such that $E_\sigma \leq \frac{V_H^2 - V_{min}^2}{2} \sum C$

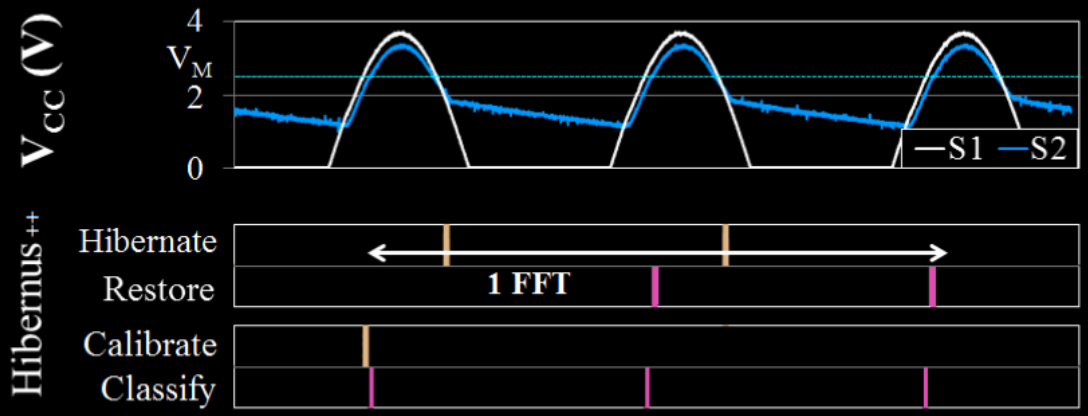
- Restore policy (source classification)



D. Balsamo, A.S. Weddell, A. Das, A. Rodriguez Arreola, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, L. Benini, (2016) Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. *IEEE TCAD*, 1-13.

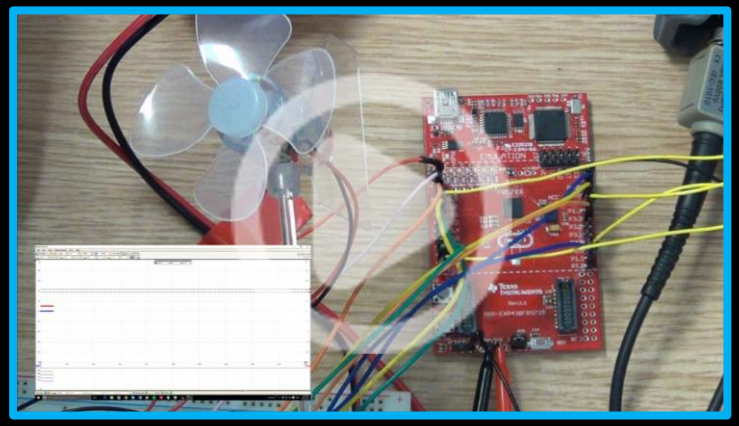
hibernus: Results

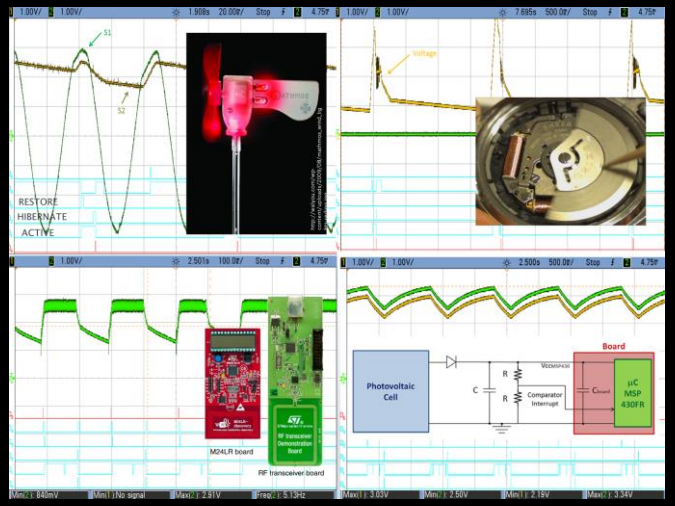
- Controlled source (signal generator)



Time overheads reduced by 75-100%
Energy overheads reduced by 50-80%

- Real energy harvesting sources

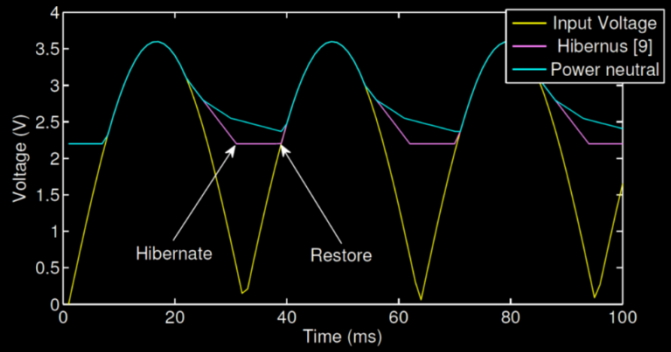




D. Balsamo, A.S. Weddell, A. Das, A. Rodriguez Arreola, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, L. Benini, (2016) Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. *IEEE TCAD*, 1-13.

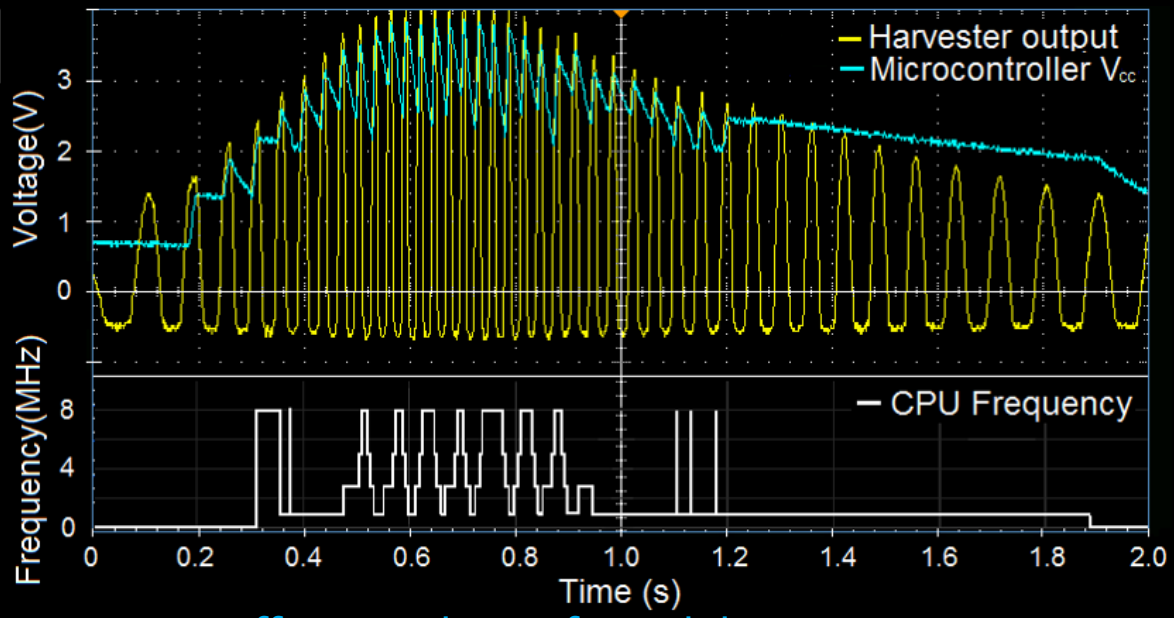
Power-Neutral Operation

- In energy-neutral computing, $\int_{(n-1)\cdot T}^{n\cdot T} P_h(t)dt = \int_{(n-1)\cdot T}^{n\cdot T} P_c(t)dt$ over a 'large' T
- In power-neutral computing, $P_h(t) = P_c(t)$ (*or as close as is possible*)
- Modulate power consumption, e.g. by changing the clock frequency



Input Frequency (Hz)	Existing System [19]	Power-Neutral System
1	2.77×10^6	2.69×10^6
2	1.61×10^6	1.53×10^6
5	0.91×10^6	1.04×10^6
10	0.68×10^6	1.04×10^6
20	0.57×10^6	1.04×10^6

Useful instructions executed in one power cycle

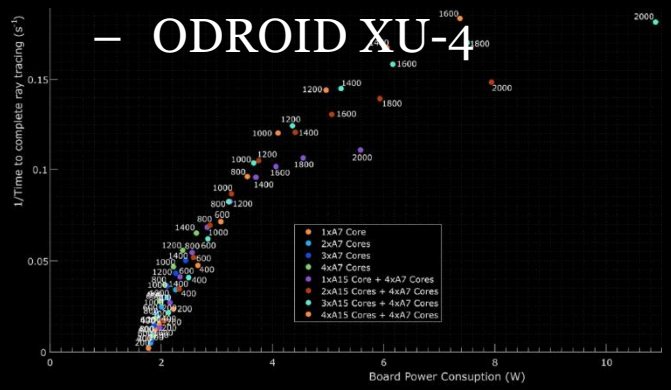


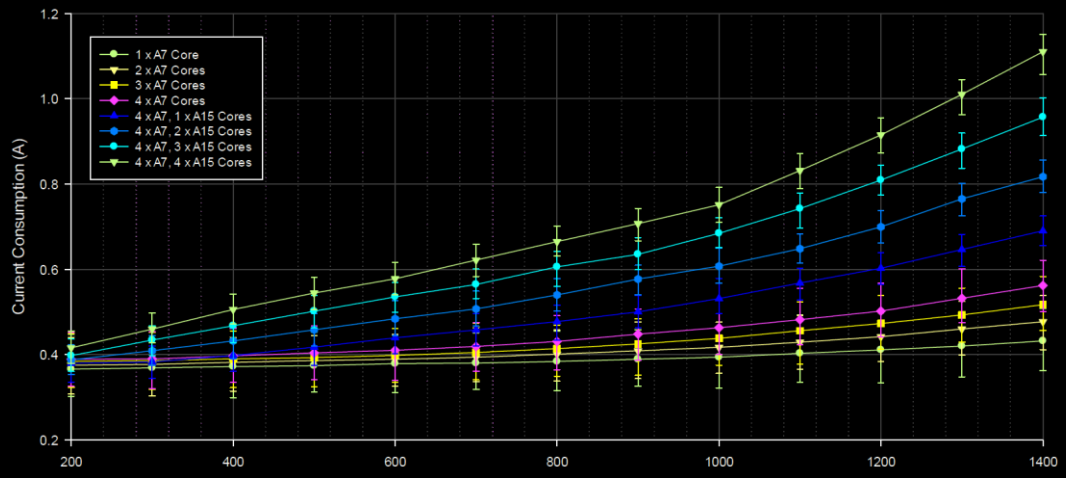
Increase in efficiency due to fewer hibernations + restores

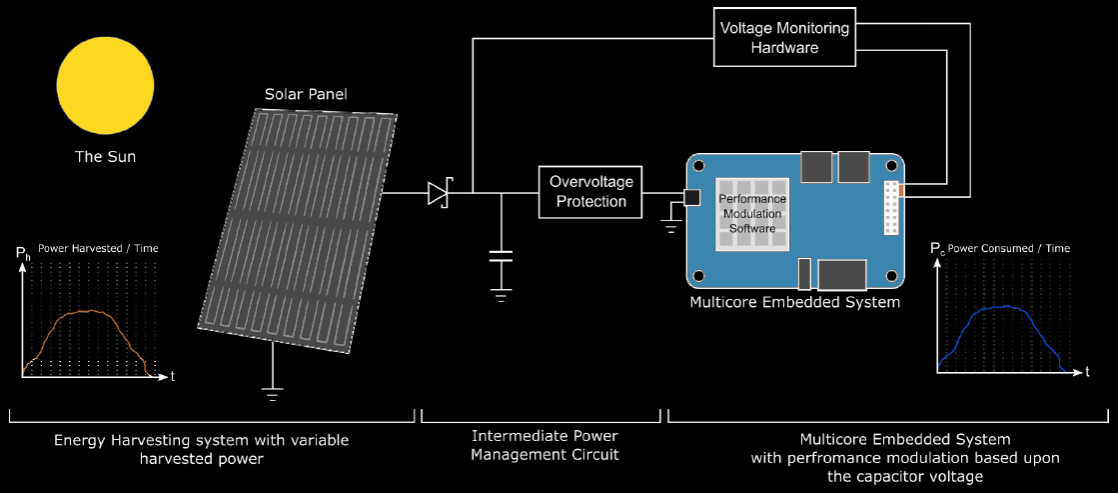
D. Balsamo, A. Das, A.S. Weddell, D. Brunelli, B.M. Al-Hashimi, G.V. Merrett, L. Benini, (2016) Graceful Performance Modulation for Power-Neutral Transient Computing Systems. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*

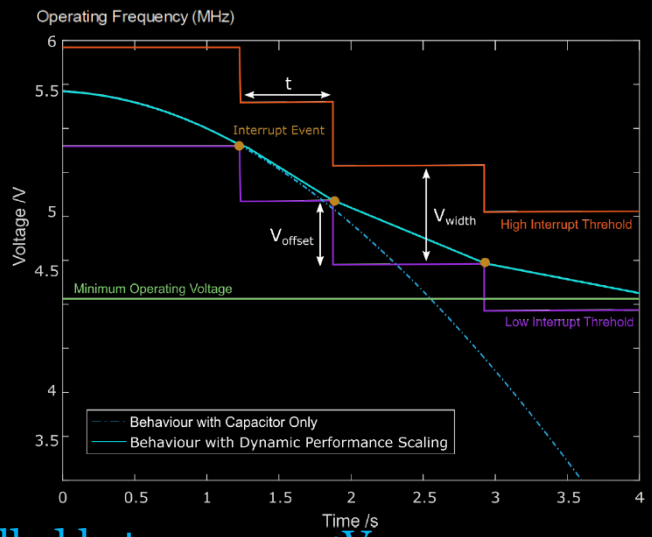
Power-Neutral Operation

- Obtain greater power proportionality?
  - DVFS + core scaling
  - ODROID XU-4









- Uninterrupted for an hour (end of test) with V_{CC} controlled between 5-5.4V

Conclusions

Energy-Harvesting and Energy-Neutral Systems

Often demonstrate significant complexity to make 'battery-like'

TRADITIONAL SYSTEMS

ENERGY-DRIVEN SYSTEMS

Transient Computing

Computation when power is available

Power-Neutral Operation

Adaptive computation when power is available

But, there are Significant Challenges

For example, transitioning to energy-driven applications!

Thank you!

Any Questions?

UNIVERSITY OF Southampton

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Associate Professor

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