Architecture Exploration for Ambient Energy Harvesting Nonvolatile Processors

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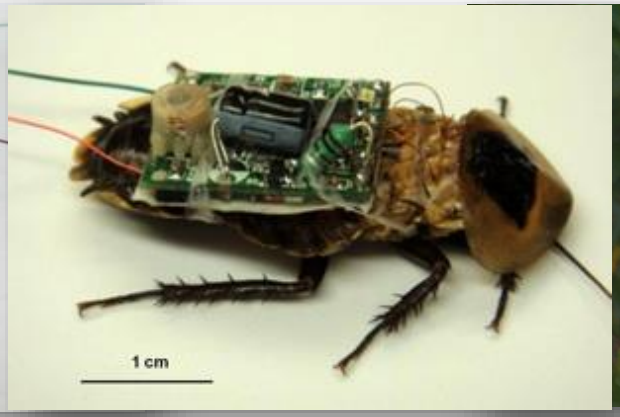
- **Motivation and Background**
- Architecture Exploration
  - Non-Pipelined
  - N-Stage Pipelined
  - Out-of-Order
- Simulation Overview
- Model Validation through a Fabricated Nonvolatile Processor (NVP)
- Design Guidelines
- Conclusion

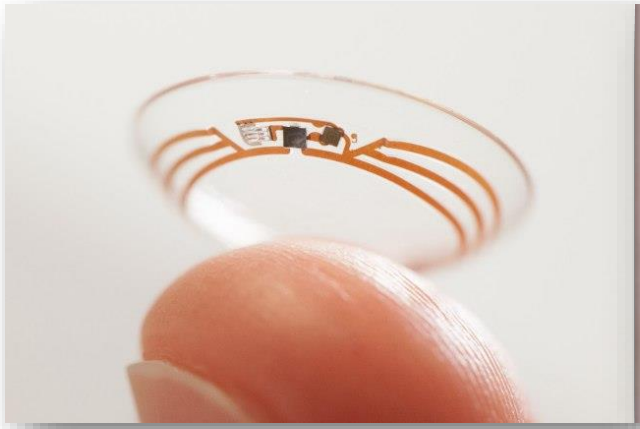
Motivation – Energy Harvesting Applications

University of Washington (UW)
Reynolds,Joshua R.
David J. Wetherall

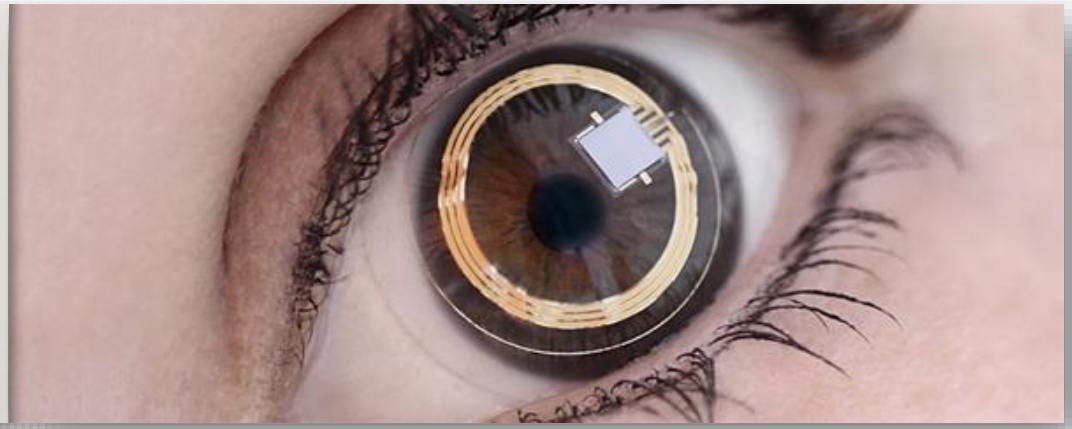


DARPA, N66001-07-1-2006.

Piezoelectric material generates energy from the motion of a bird's wings in flight. (Michael Shafer, NAU)



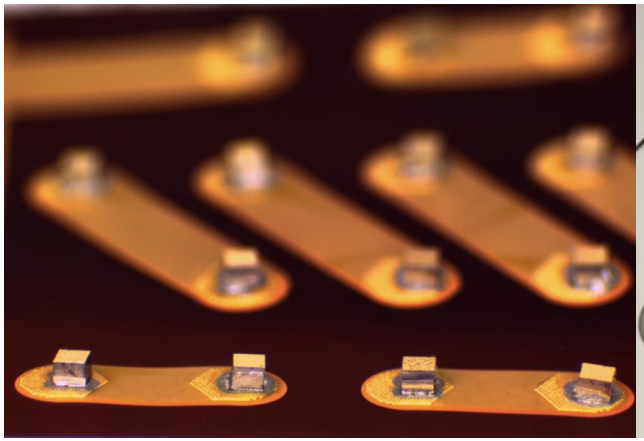
Google Contact Lenses:
to help diabetics track glucose levels



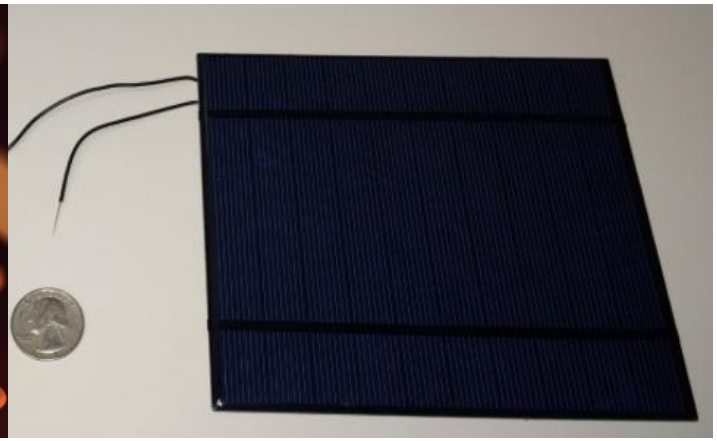
Swiss producer: to monitor pressure fluctuation in the eyes for glaucoma treatment.

Motivation – Energy Harvesting Sources

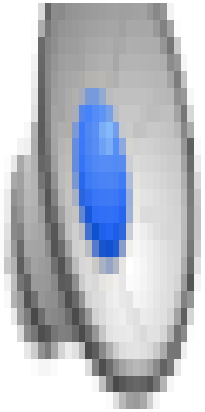
RF Energy



Thermal Energy
ASSIT, Mehmet Ozturk, NCSU

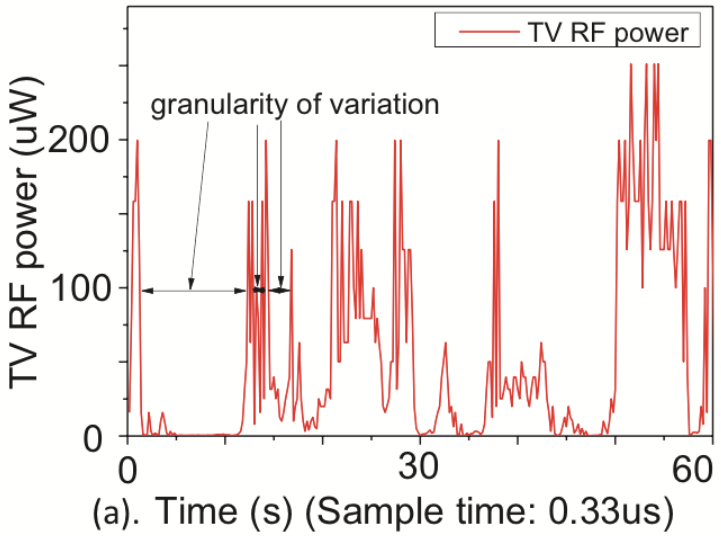


Solar Energy

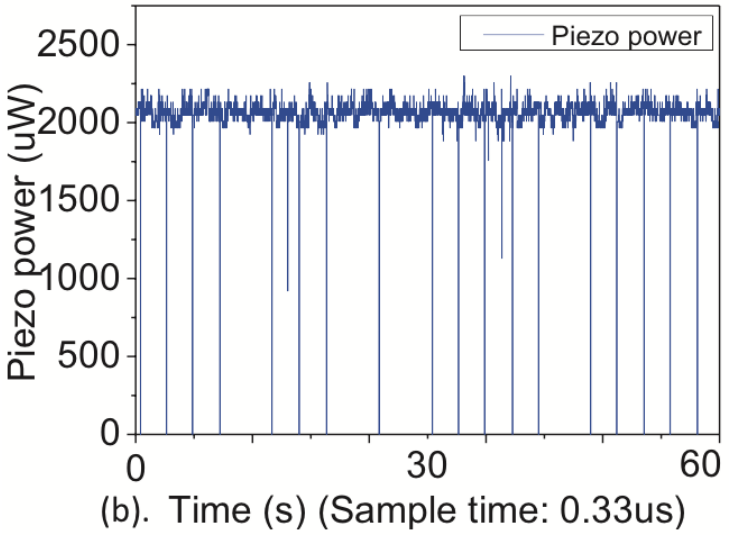


Piezoelectric/Vibration Energy ASSIT, Susan McKinstry PSU

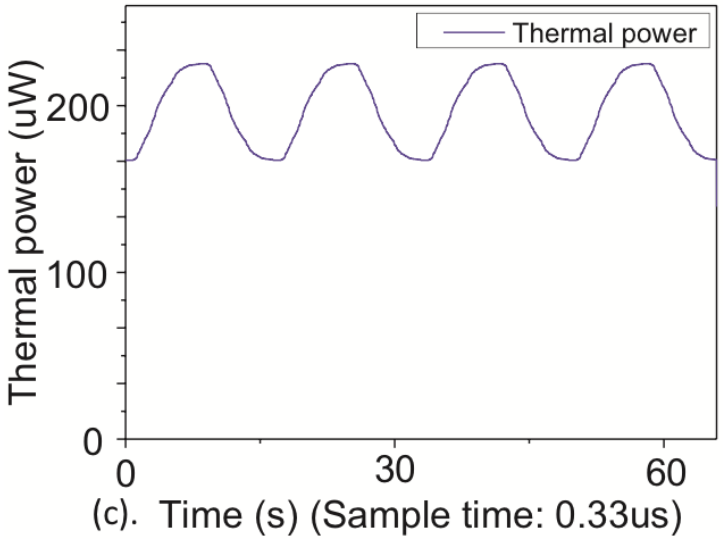
Signal Magnitude & Variability and Granularity



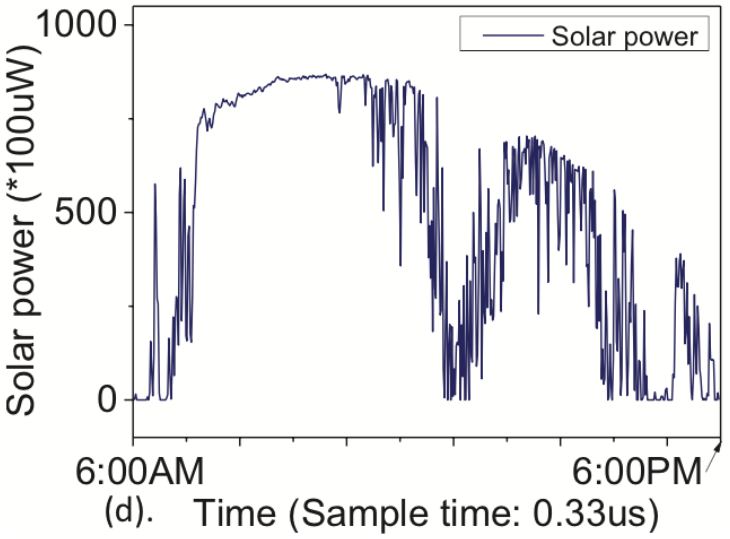
TV RF



Piezo

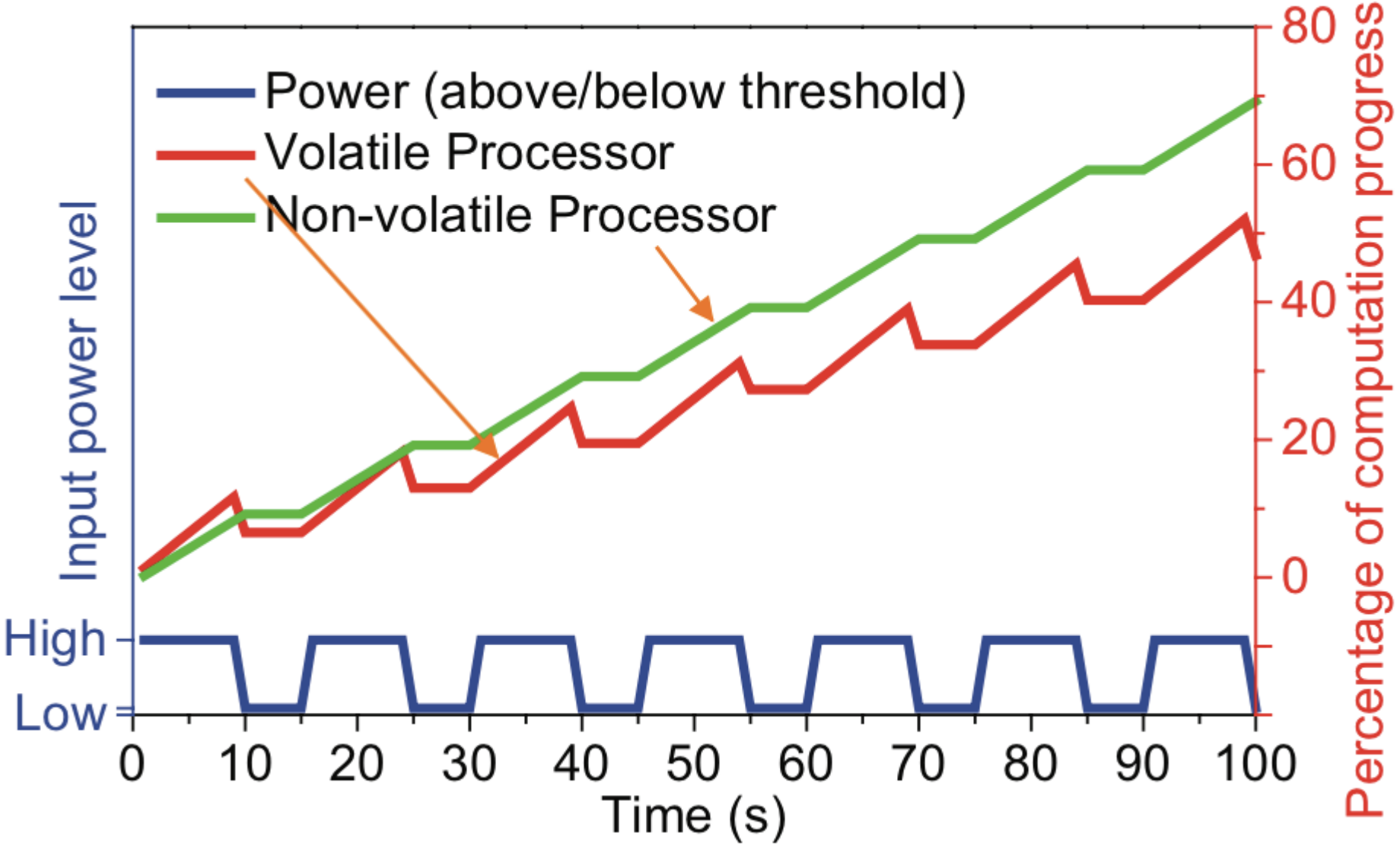


Thermal



Solar

Volatile or Nonvolatile ?



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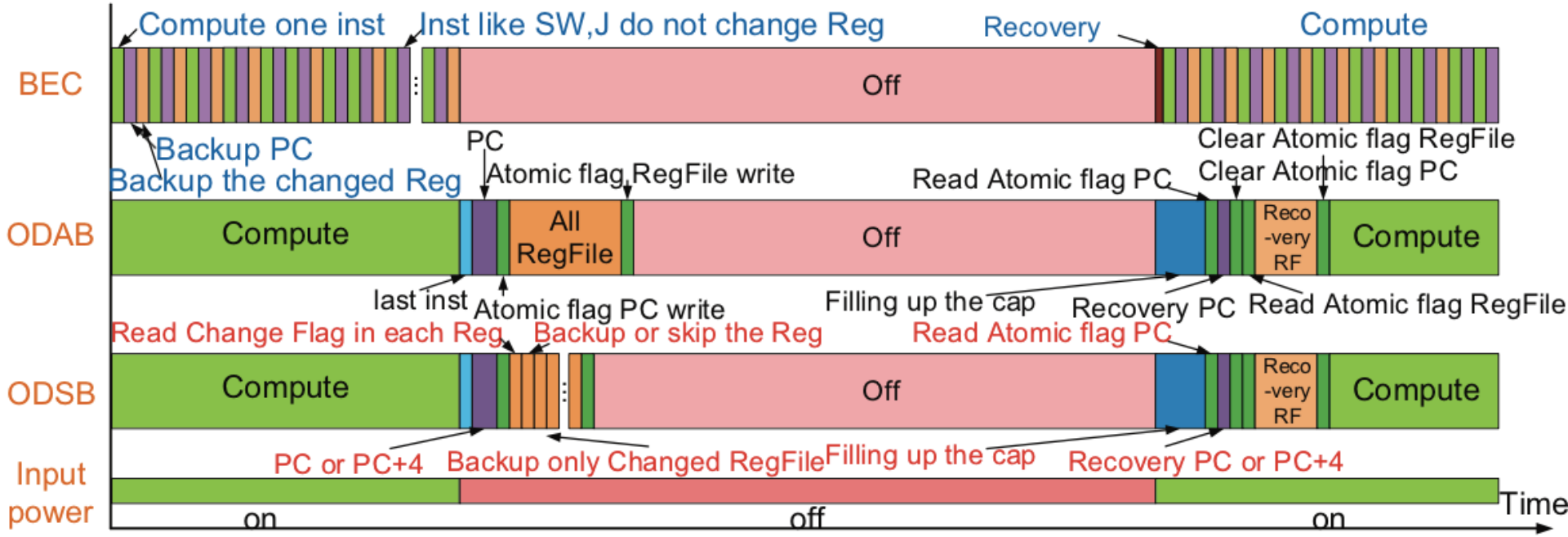
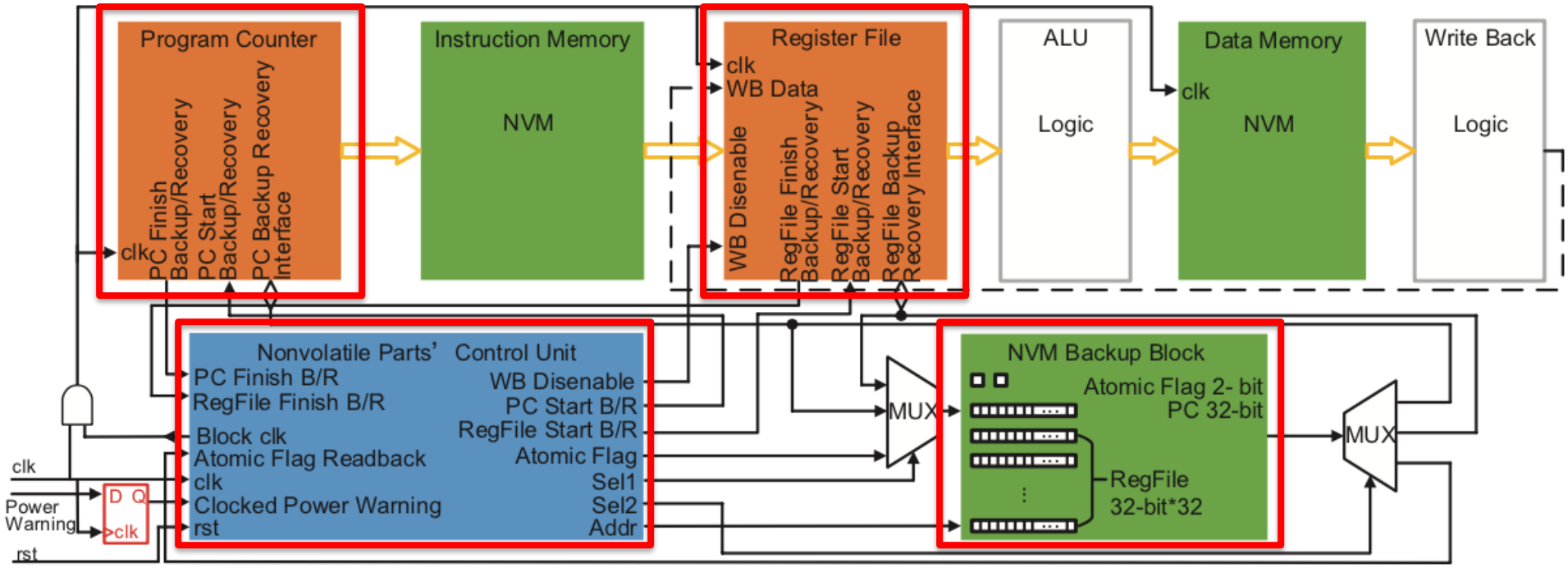
Non-Pipelined (NP)

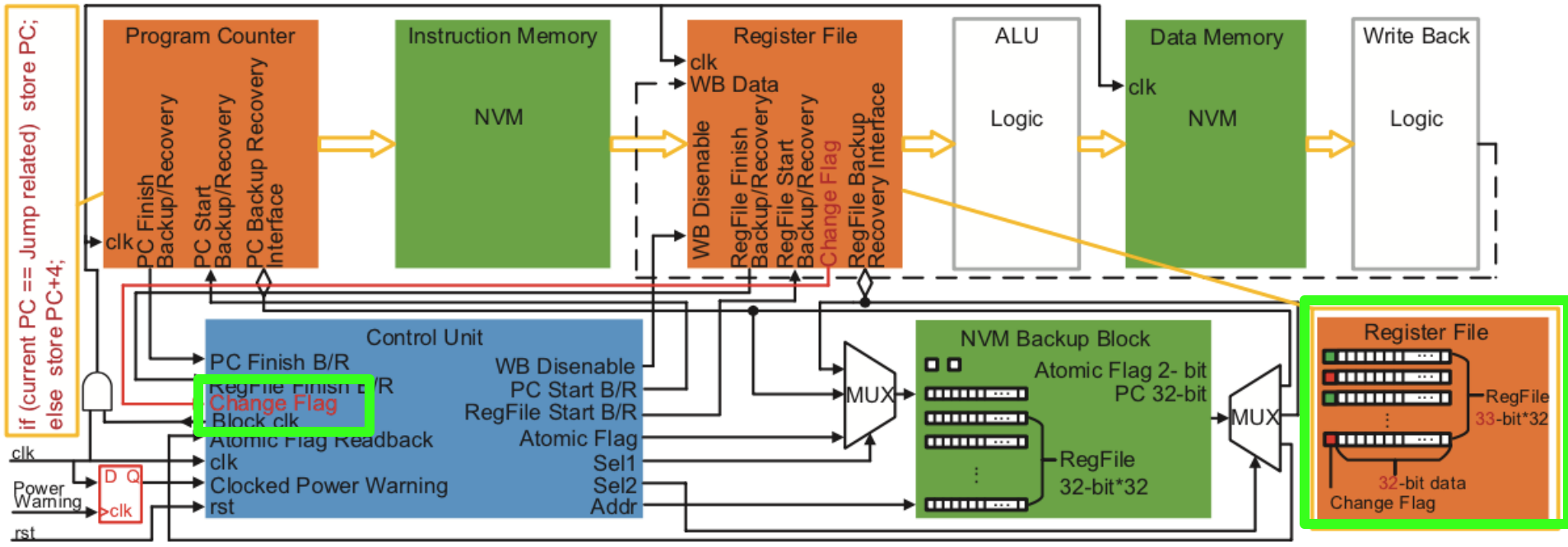
- Back up every cycle solution (BEC).
- On demand all backup solution (ODAB)
- On demand selective backup solution (ODSB)



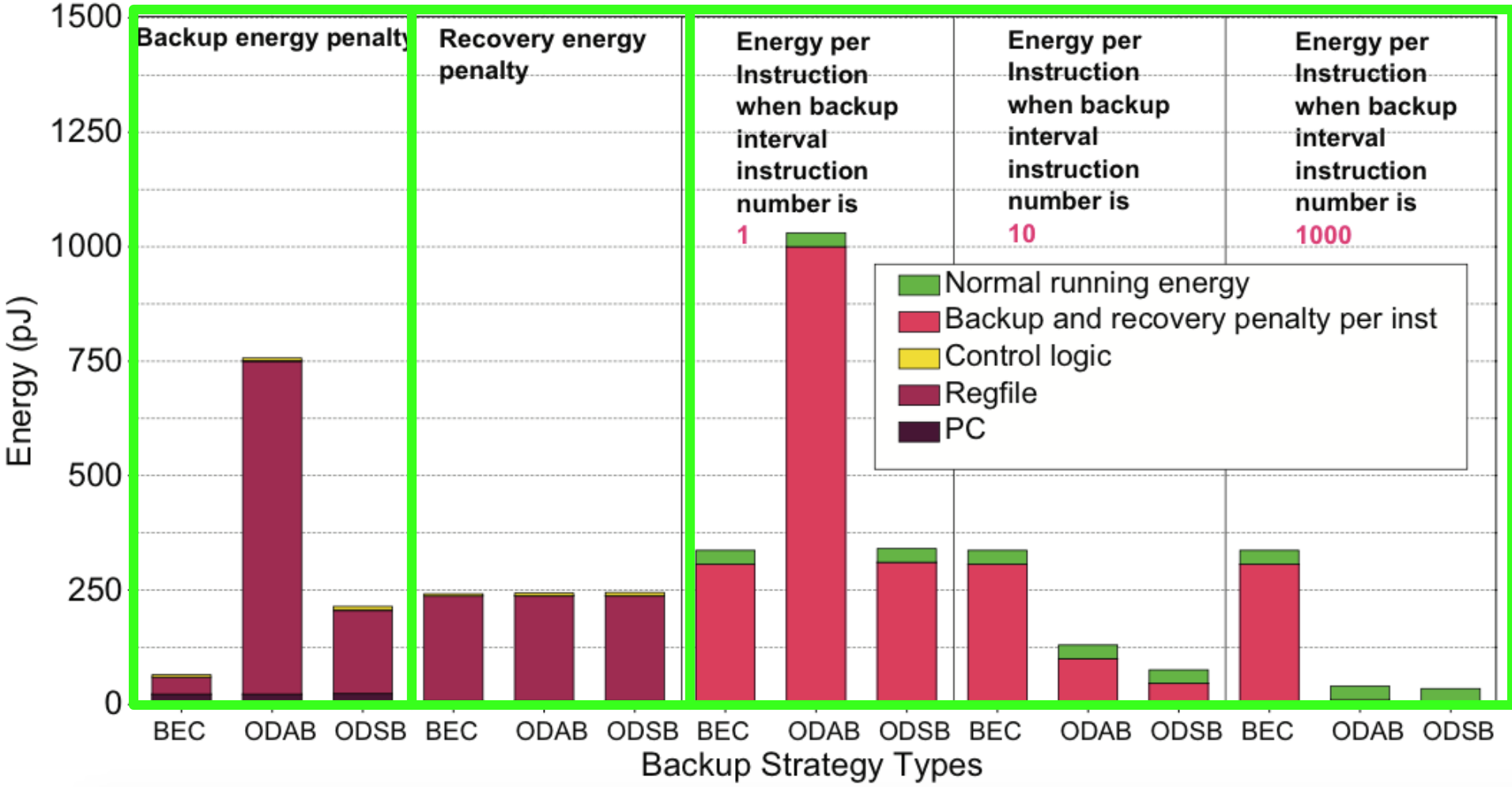
On Demand All Backup (ODAB)



On Demand Selective Backup (ODSB)



Non-Pipelined - Results & Comparison



Non-Pipelined - Conclusion

- ODSB works better with serial backup to reduce the peak power;

- ODSB works >69% more power-efficiently than ODAB with stable power source with negligible overhead (0.002%);

- BEC works better with extremely intermittent power sources like 10~kHz frequency vibration.

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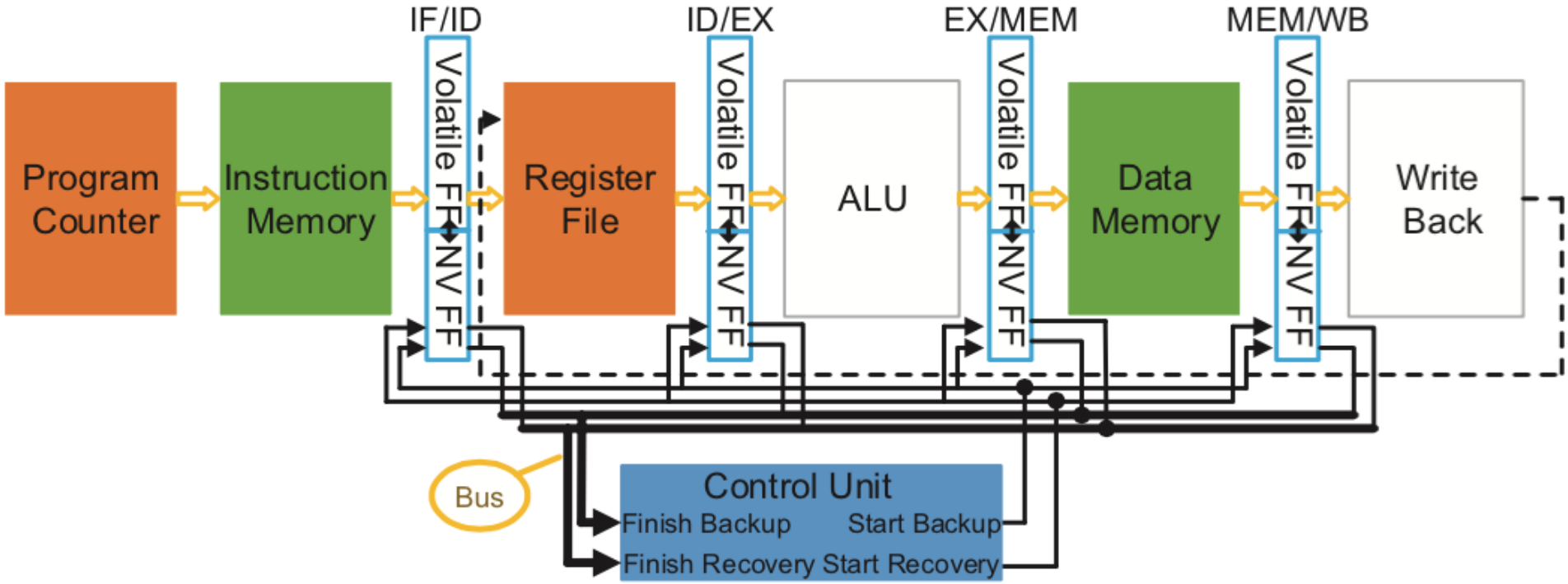
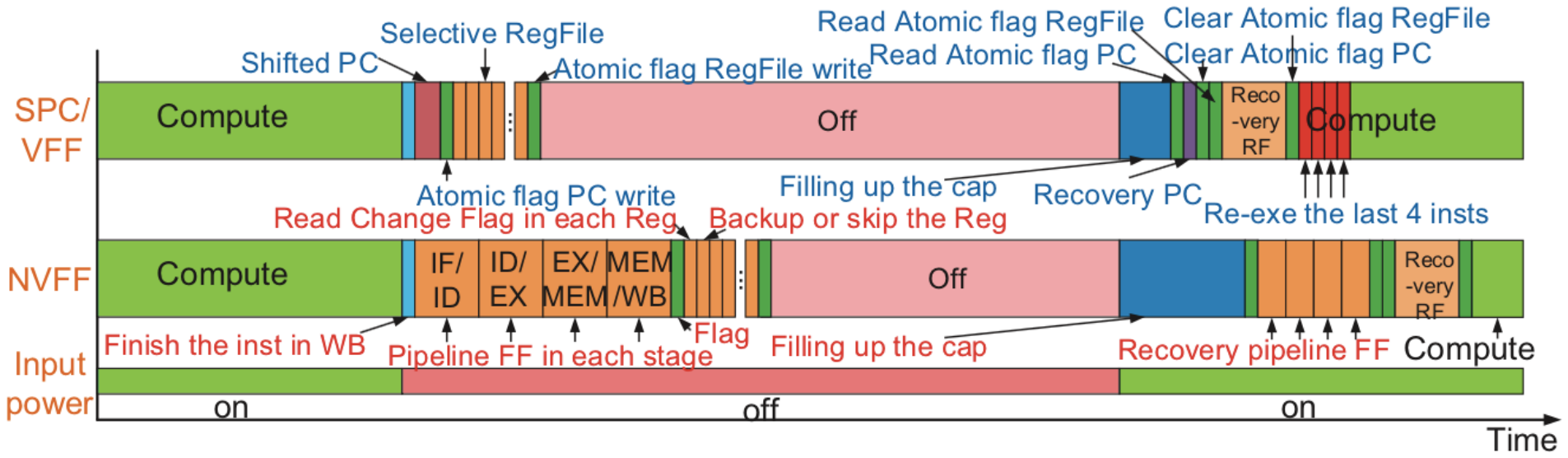
Stage-Pipeline (5SP) with Nonvolatile Flip-flops (NVFF)



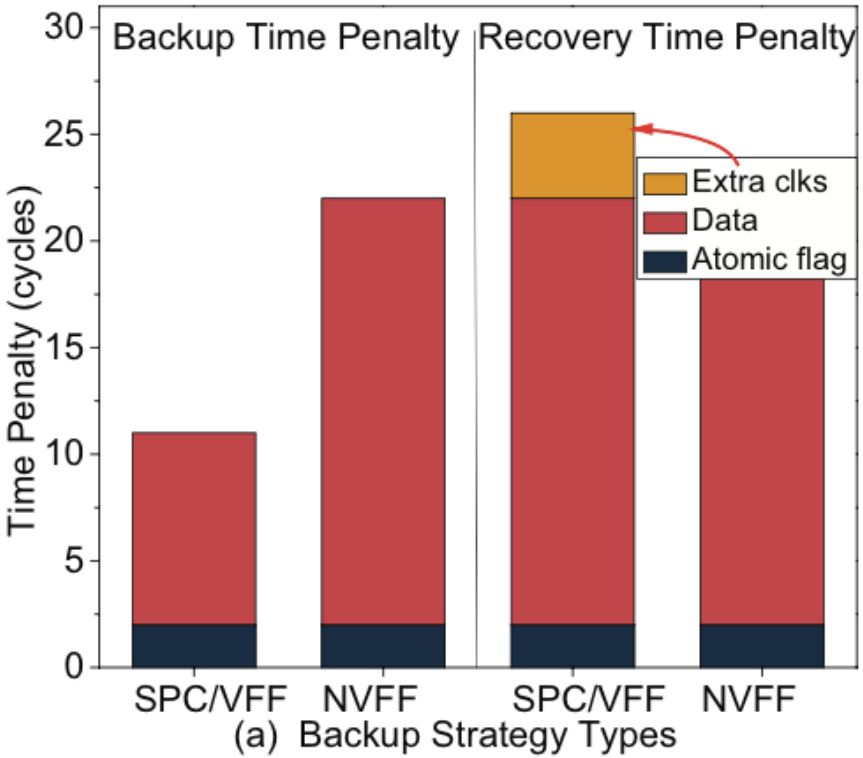
- Higher power threshold than the non-pipelined architecture.
- Better stored energy extrication efficiency

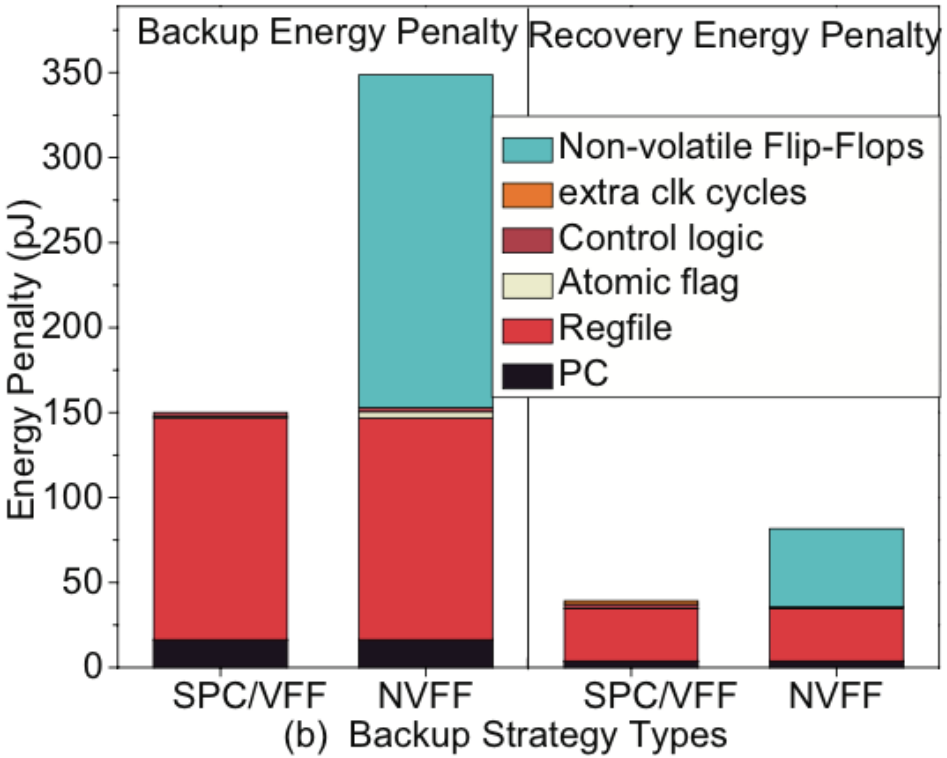
5SP : Shifted PC & Volatile Flip-flops (SPC/VFF)



Pipeline	IF	RF	EX	MEM	WB
InstQue1	LW	ADD	SUB	SW	ADD
Shifter	PC	PC-4	PC-8	PC-12	
InstQue2	LW	J	SUB	SW	ADD
Shifter	PC2	PC1	PC1-4	PC1-8	

N-Stage-Pipeline (5SP) - Discussion





- SPC/VFF is more energy-efficient than NVFF

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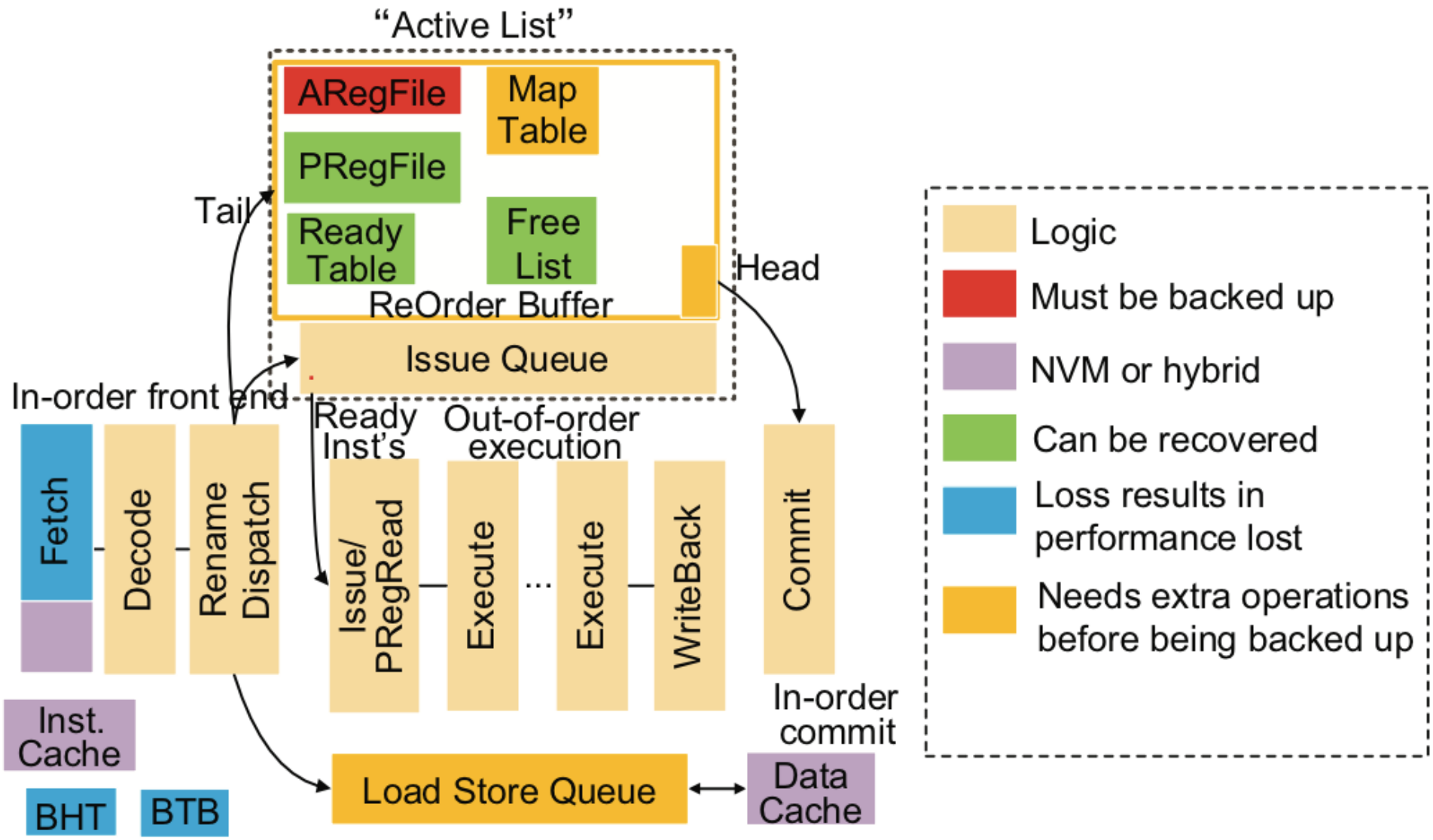
Out-of-Order


"Active List"
ARegFile
Map Table
PRegFile
Tail
Ready Table
Free List
Head
ReOrder Buffer
Issue Queue
In-order front end
Ready Inst's
Out-of-order execution
Fetch
Decode
Rename Dispatch
Issue/ PRegRead
Execute
...
Execute
WriteBack
Commit
In-order commit
Inst. Cache
BHT
BTB
Load Store Queue
Data Cache
Logic
Must be backed up
NVM or hybrid
Can be recovered
Loss results in performance lost
Needs extra operations before being backed up

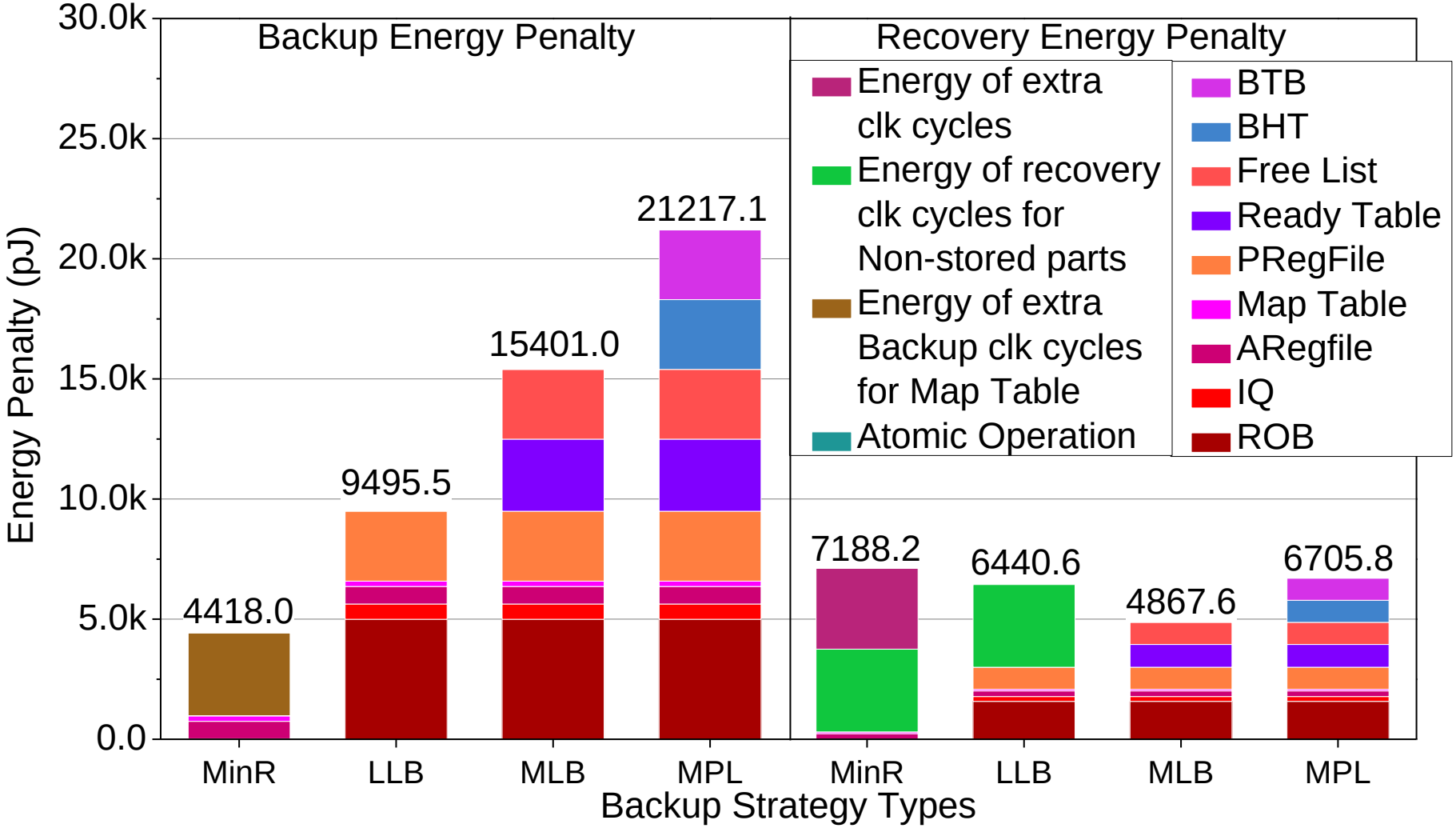
Out-of-Order – Solutions

- Minimum State Resource backup solution (MinR)
- Low-latency backup solution (LLB)
- Middle-level backup solution (MLB)
- Min-state-lost backup solution (MPL)

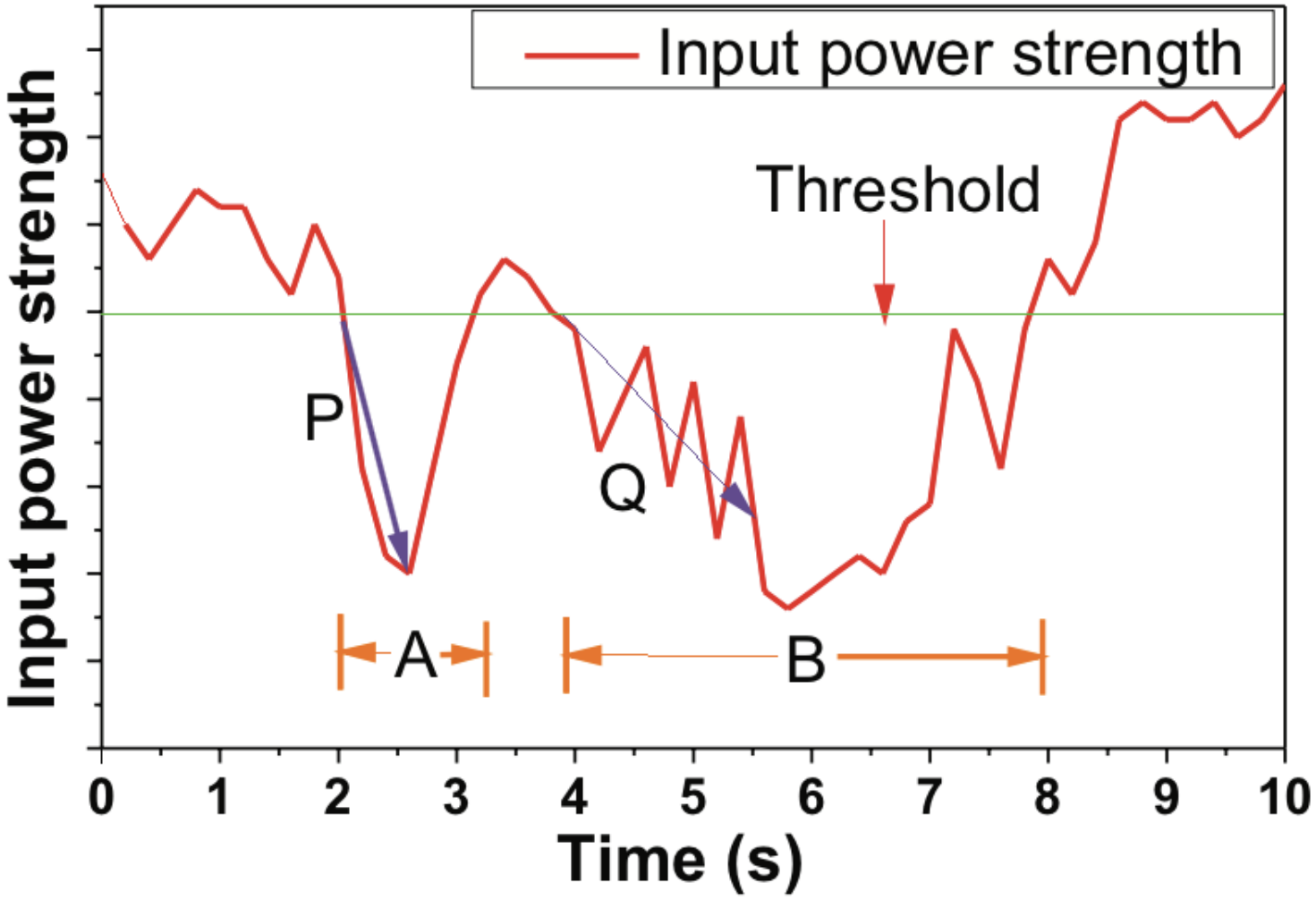
OoO solutions	ROB	IQ	AReg File	Map Table	PReg File	Ready Table	Free List	BHT	BTB
MinR	★		☆	☆					
LLB	☆	☆	☆	☆	☆				
MLB	☆	☆	☆	☆	☆	☆	☆		
MPL	☆	☆	☆	☆	☆	☆	☆	☆	☆

☆ Back up ★ Last uncommitted PC ☆ Pseudo-misprediction

Out-of-Order – Energy Penalty

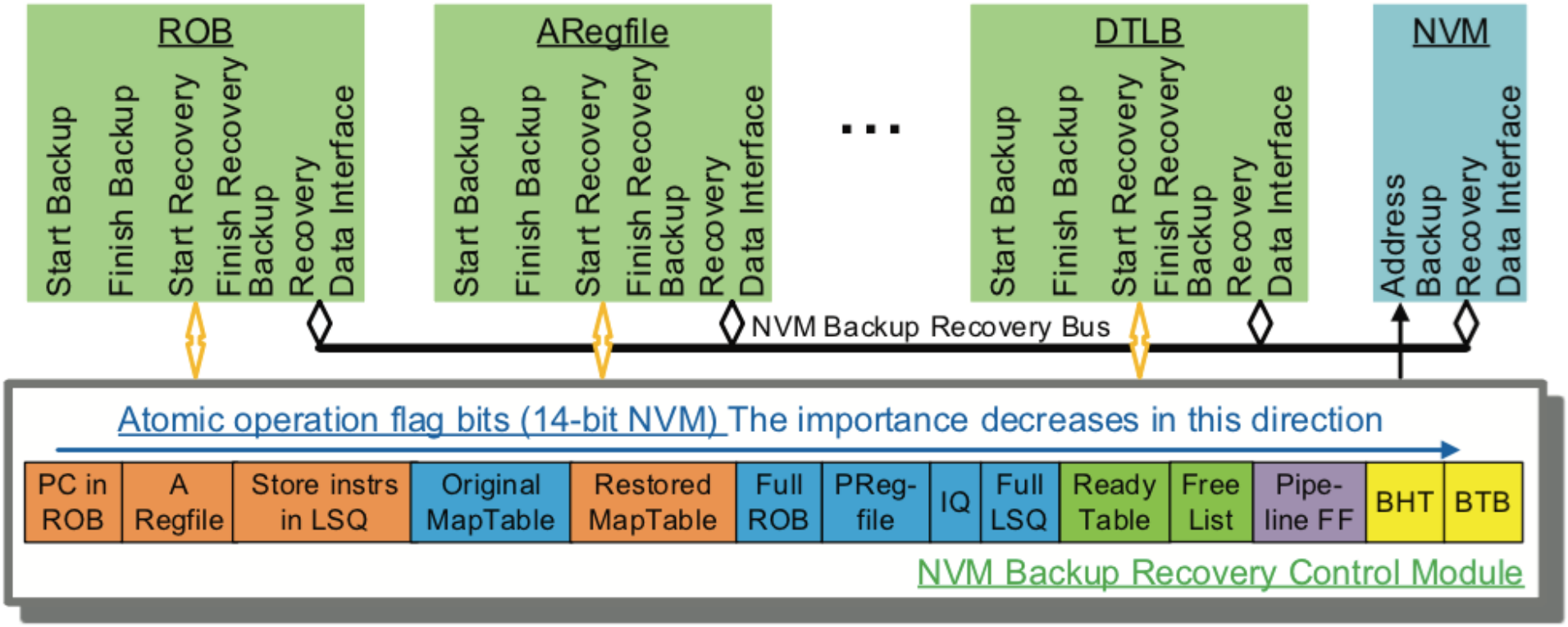


Out-of-Order – Additional Energy Income during Backup



Out-of-Order – Proposed IFA Backup Policy

- Integrated Flexible Atomic Backup Policy (IFA)
- Atomic flag bits !



Out-of-Order - Conclusion

- Prior art: OoO is too complex for such systems!
- Our art: OoO is better in some scenarios with occasional high input power!
  - When it runs, it runs faster

- Prior art: backup of the minimum states has the least energy penalty
- Our art: MLB has the least recovery energy penalty!

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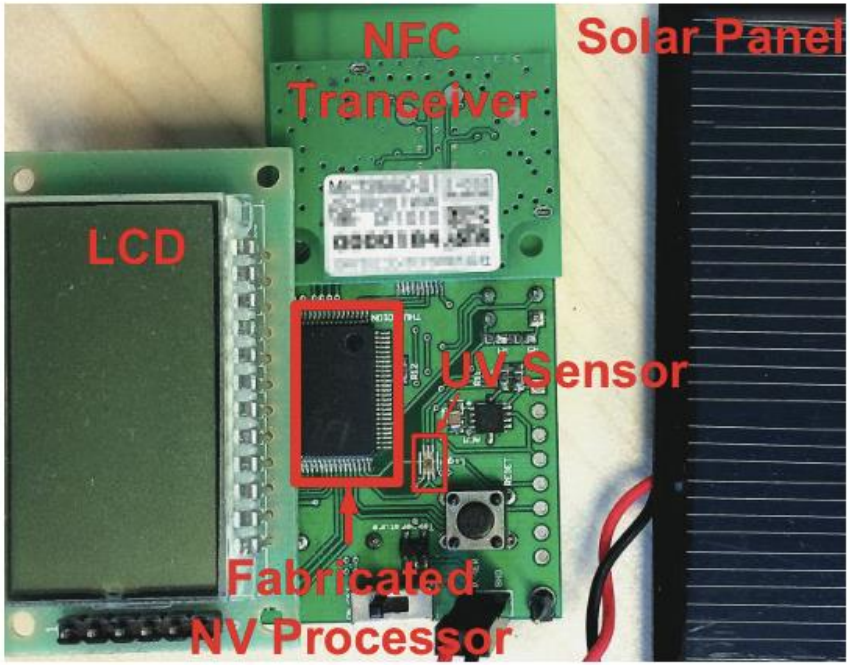
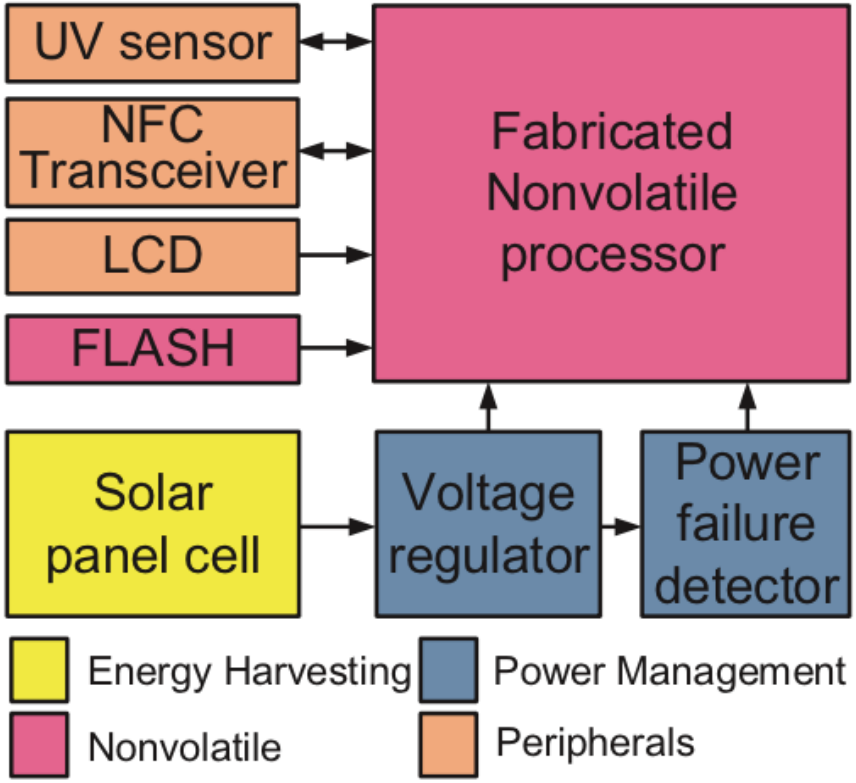
Simulation Overview

- RTL level model
- Logic area and critical path delay - Synopsys Design Compiler using a 45 nm TSMC LP Library.
- The nonvolatile technology is based on STT-RAM block – NVSim.
- Testbenches - MiBench suite, along with some real-world applications.
- The power trace is WiFi at home and office.
- 8kHz clock frequency.

Validation Platform

- UV sensor – a fabricated NVP
- ODAB solution





Validation Platform

Testbench	Stable/ms	Interrupted/ms *		error
	Measured	Measured	Model	
FIR-11	0.626	1.260	1.209	-1.59%
Sqrt	2.620	5.280	5.190	0.81%
KMP	3.573	7.184	7.059	0.77%
FFT-8	4.207	8.460	8.238	-0.13%
Matrix	5.826	11.740	12.021	2.39%
Bubble sort	27.23	54.705	57.236	4.63%

* 1 kHz square waveform power input

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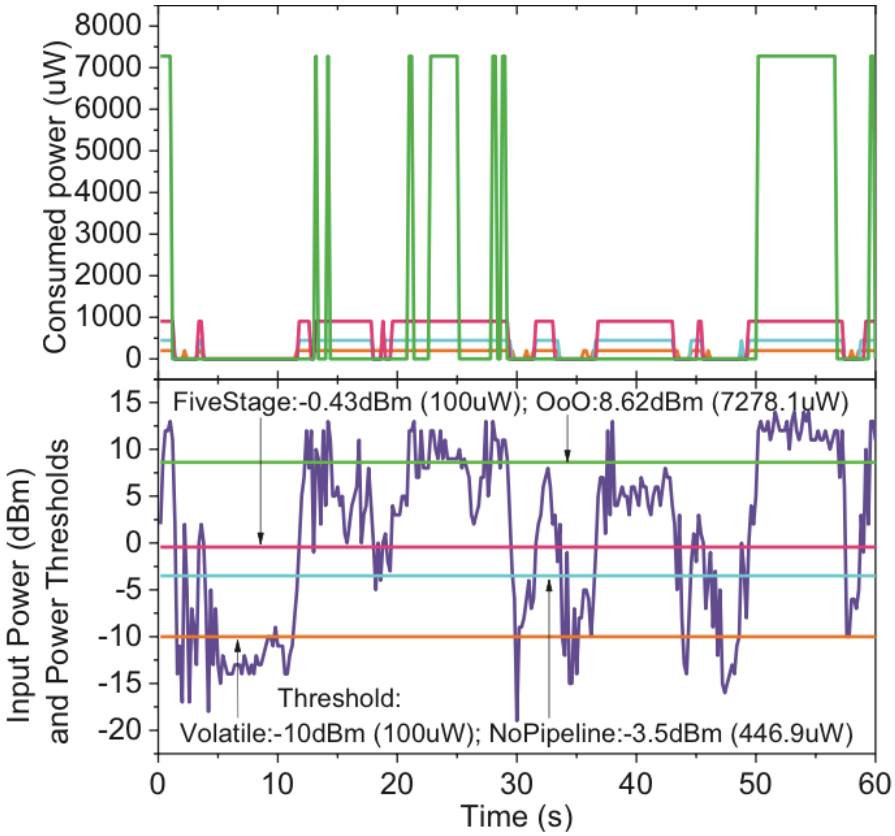
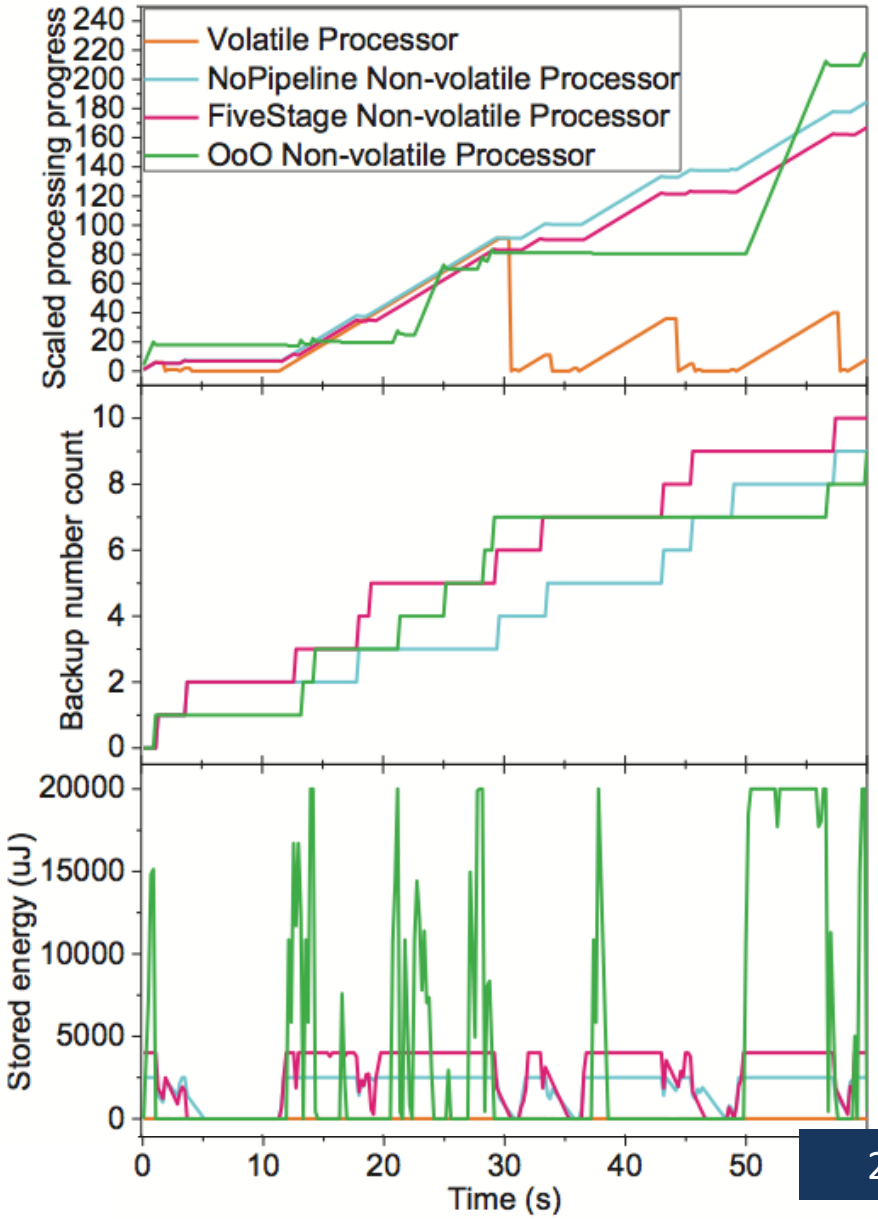
Simulation Results

- NVP versus MSP430;
- Independent add operations as workload;
- Powered by RF signals.



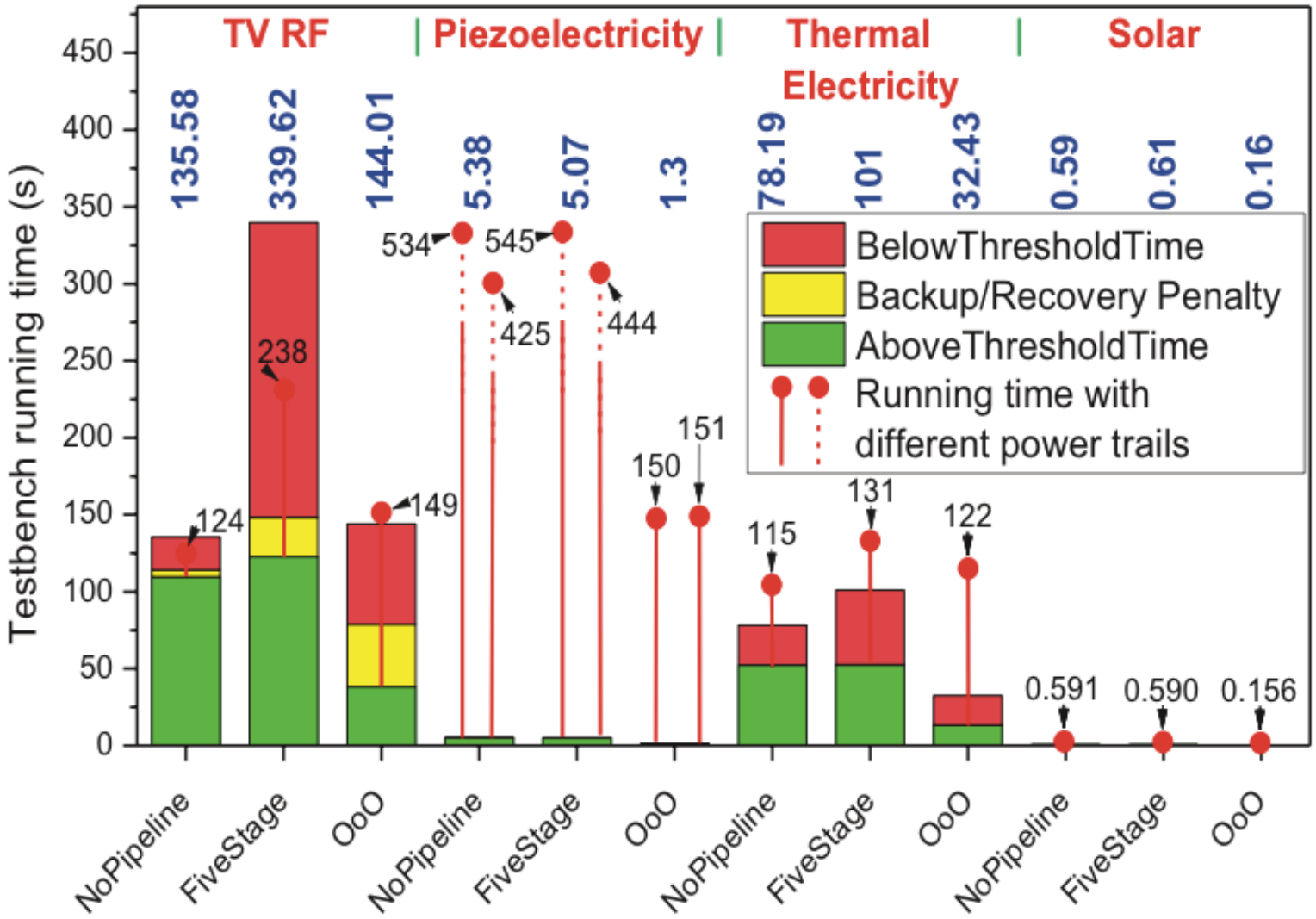


Simulation - Conclusion

- Optimizing for low power is not the same as optimizing for maximum forward progress.

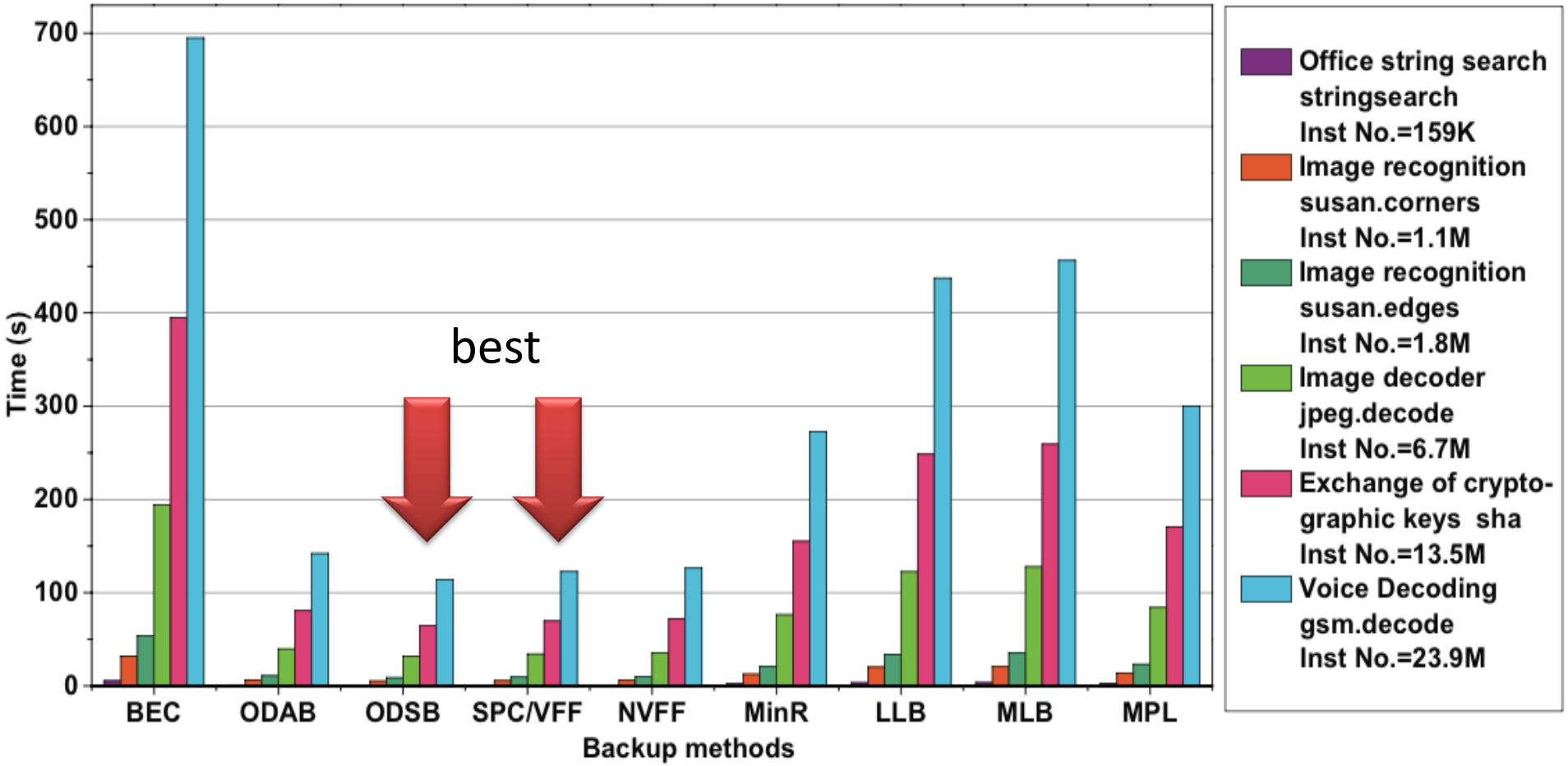
- Significant energy is wasted if processor is not powerful enough in batteryless system.

Execution Time for Different Energy Sources



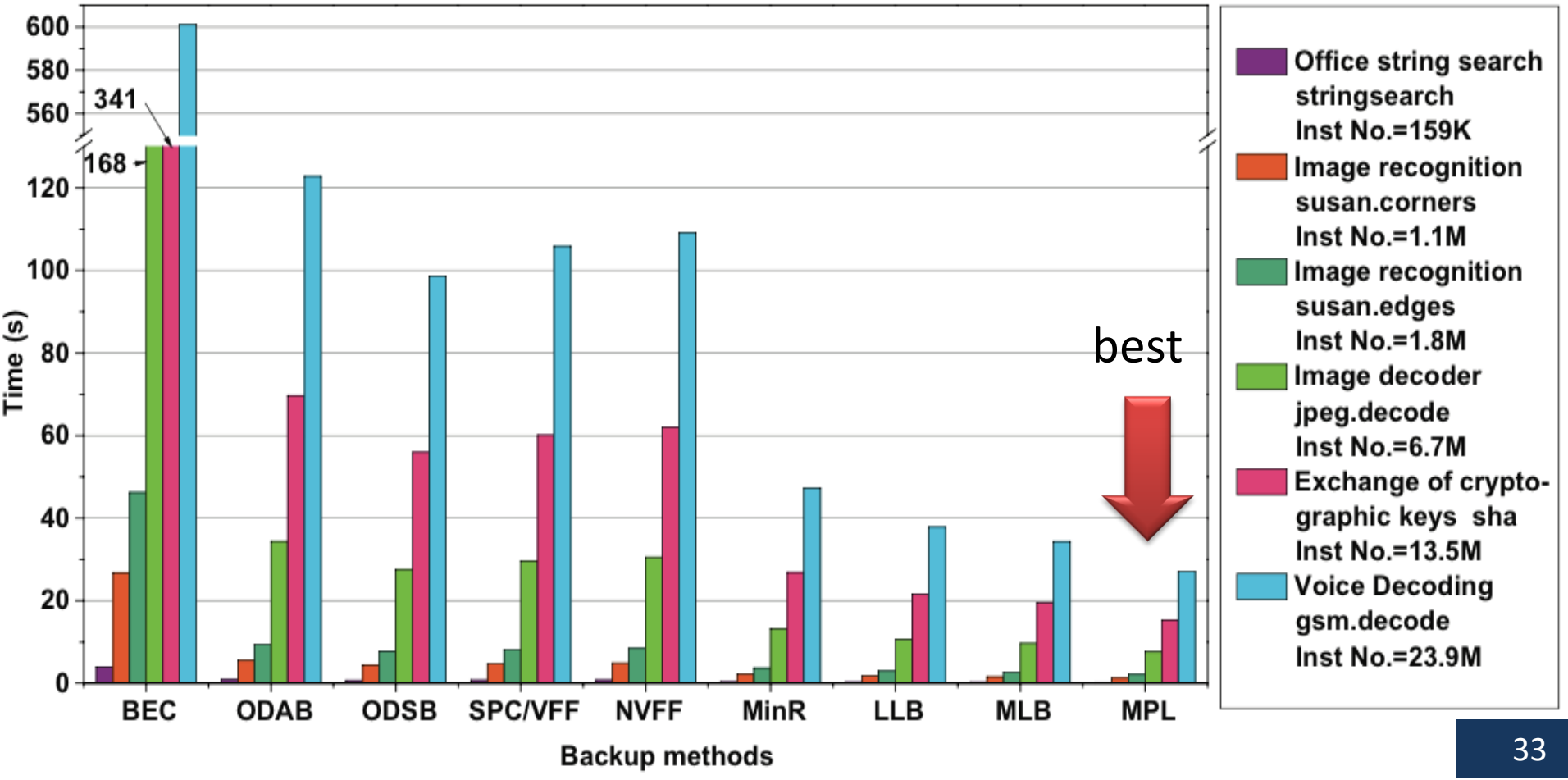
Testbench: Loop and basicmath, Inst.No.=65.5M

WiFi Home Environment



WiFi Office Environment

- Additional office WiFi routers enable more complex architectures

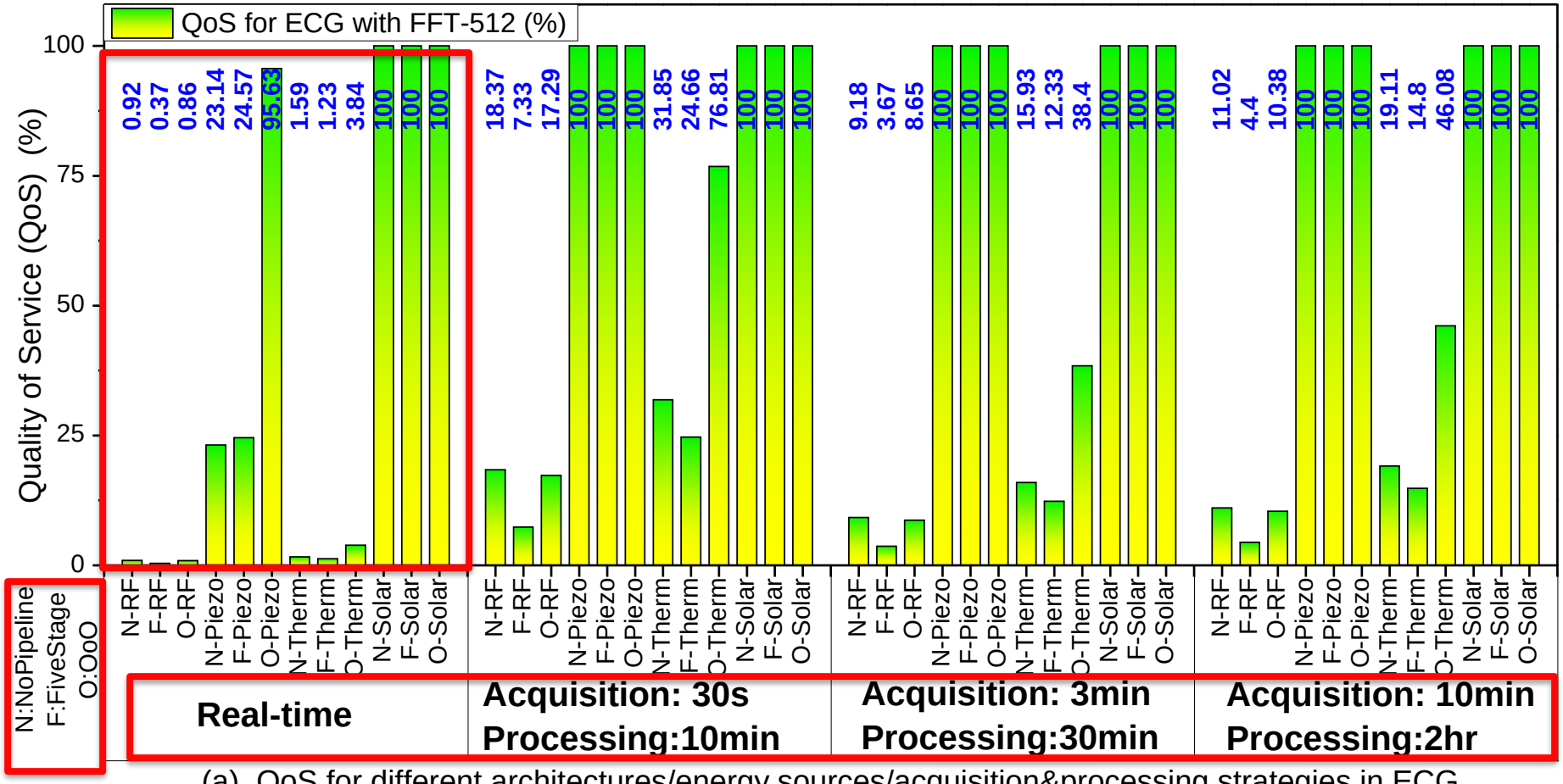


Design Guidelines

- Is it possible to power an ECG watch by thermoelectric?

- How about RF/Solar-powered real-time Augmented-reality contact lenses?

Design Guidelines – Quality of Service (QoS)



(a), QoS for different architectures/energy sources/acquisition&processing strategies in ECG

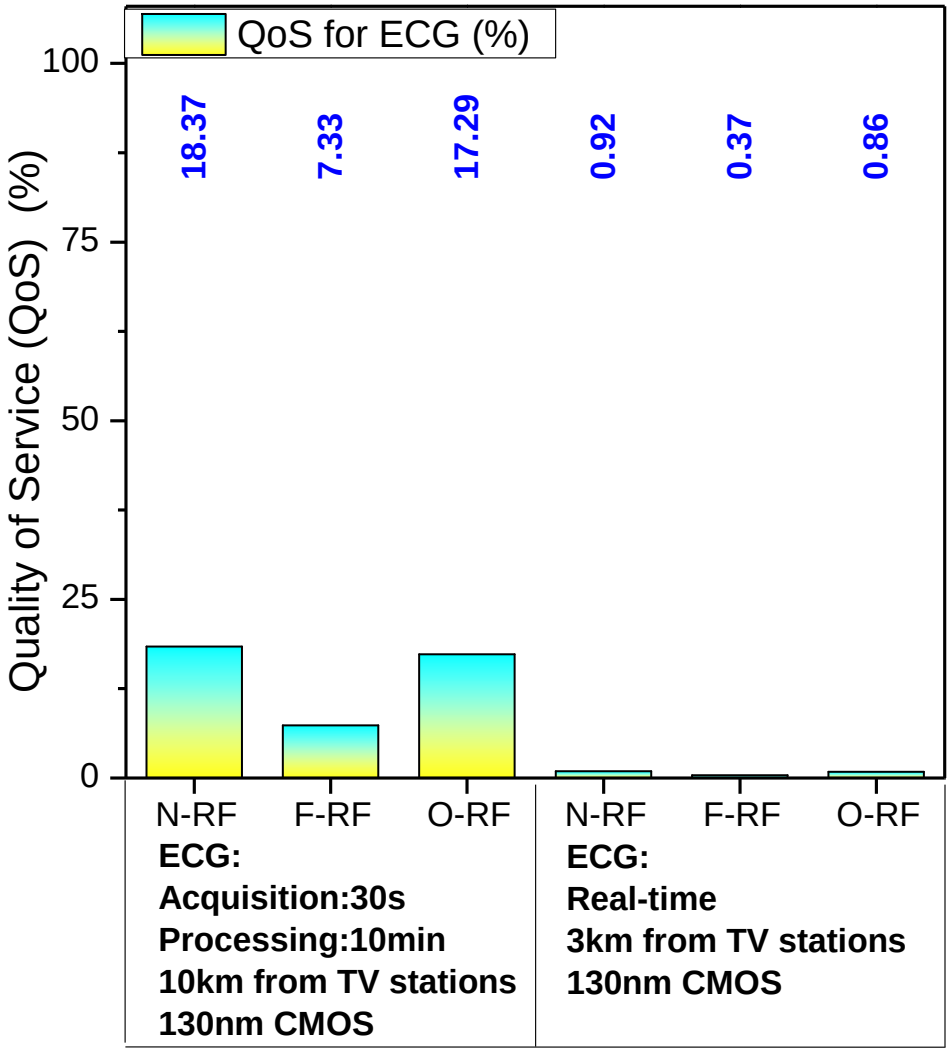
Design Guidelines – Make it Possible !

- From Input Power view.
- From Circuits and Tech view.

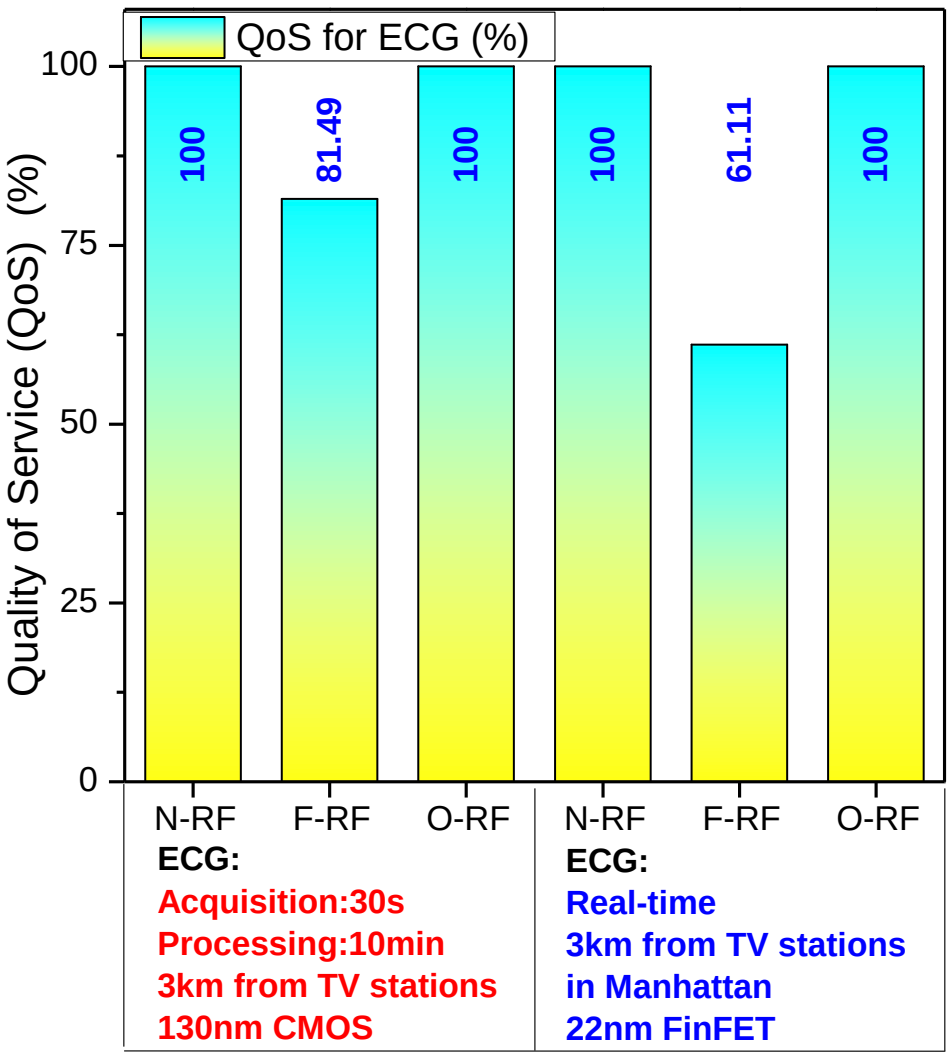
Baseline parameters and relationship with QoS

Source	Parameter	QoS Baseline	Relation to Efficiency
RF	Antenna gain	6dBi	α
	Bandwith	539M	α
	Distance	10km	$1/\alpha^2$
Therm	Area	$1cm^2$	α
	ΔT	$20\ ^\circ C$	α^2
Piezo	Volume	$1cm^3$	α
Solar	Area	$4cm^2$	α
	Efficiency	28%	α
Circuit	IP matching, AC-DC, DC-DC, LDO, Cap		
Tech.	Shink Tech.	130nm	α^2
	FinFET, IG-FinFET, TFET, NC-FET	CMOS	
	DVFS, DATS	Fixed frequency	
	Voltage	0.95V	$1/\alpha^2$

Design Guidelines – Make it Possible !!



(a), Original QoS

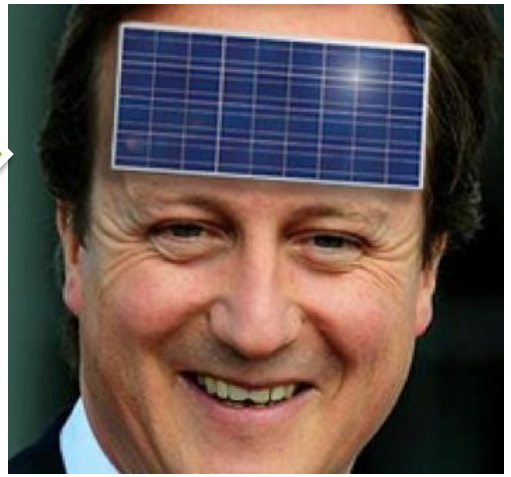


(b), Optimized QoS

Answers to the questions.

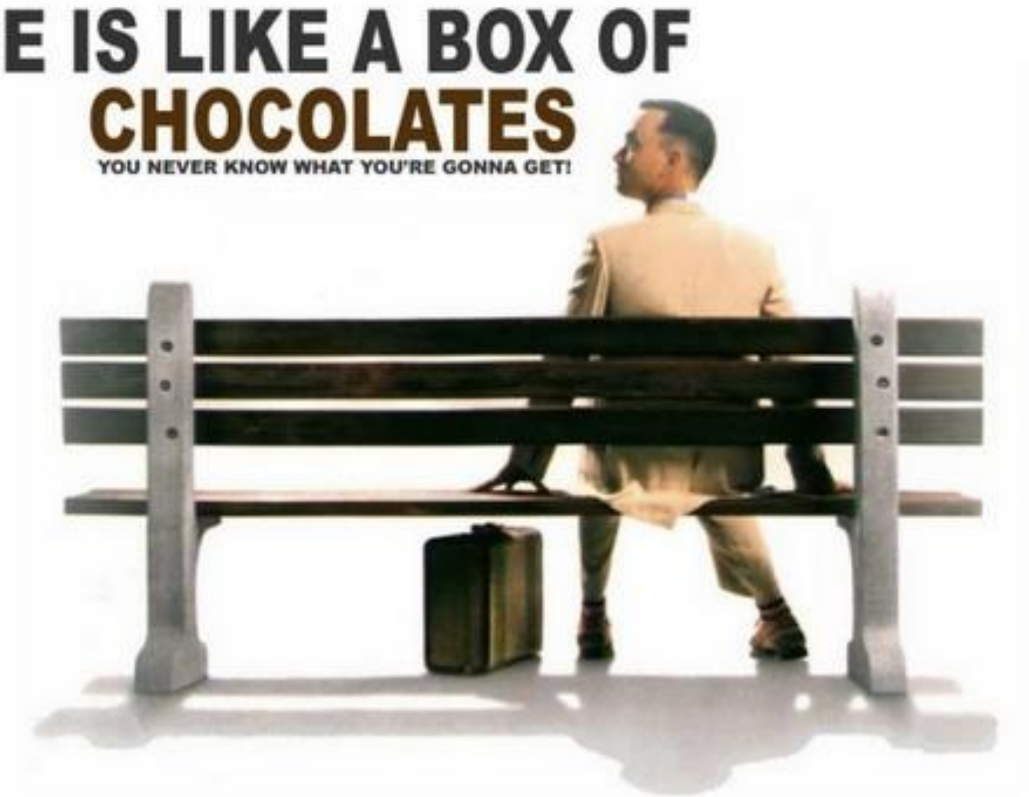
- Is it possible to power an ECG watch by thermoelectric?
- You need at least a wristband (26.04 cm^2)to collect thermal energy.
- Asian girls.

- How about RF/Solar-powered real-time Augmented-reality contact lenses?
- TV RF : 218.2m^2 antenna
- Solar ?
- Fashion: LV, Prada…



Conclusion

- Optimizing for low power is not the same as optimizing for maximum forward progress.
- Significant energy is wasted if processor is not powerful enough in battery-less system.
- Backing up min states doesn’t guarantee fastest system recovery.



But this work tells you what you're gonna get in wearable devices, and what you need to pay !

QUESTIONS?