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Self-powered Internet-of-Things Nonvolatile Processor and System Exploration and Optimization

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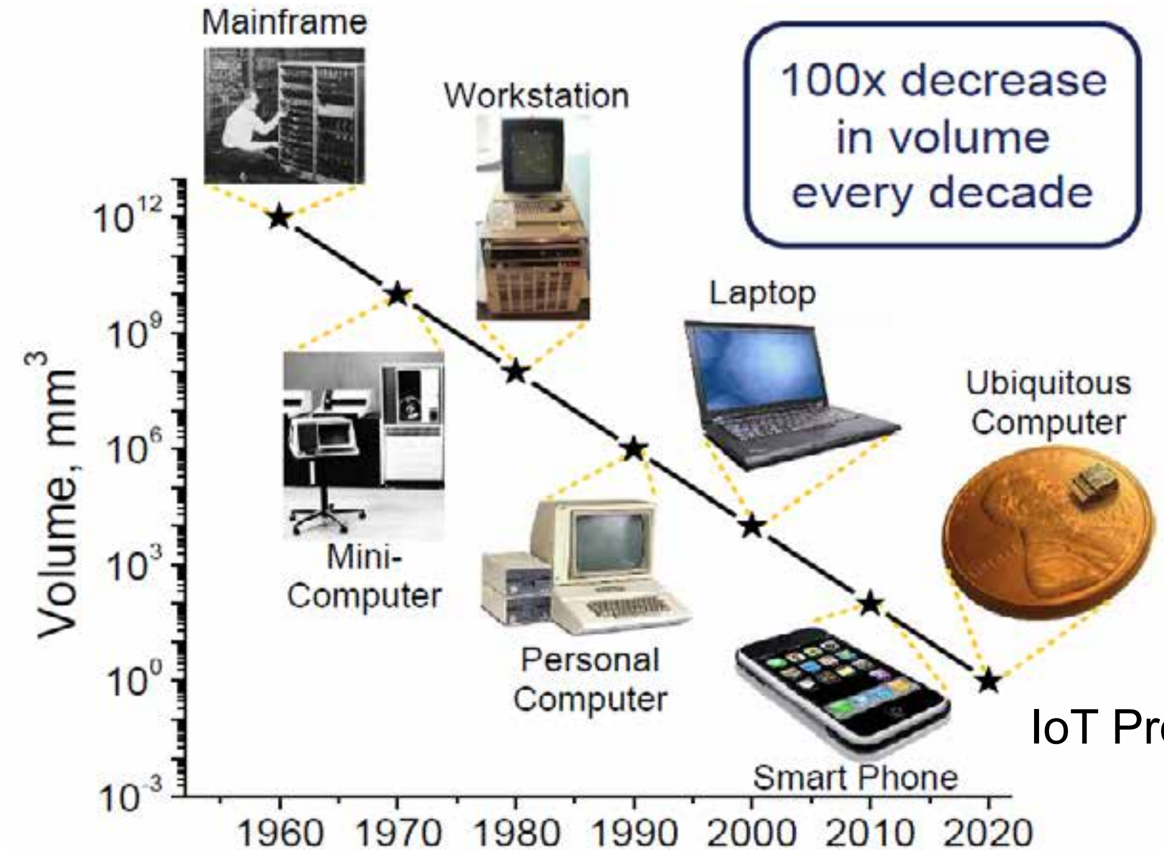
Trend of Internet of Things - Volume Decreases

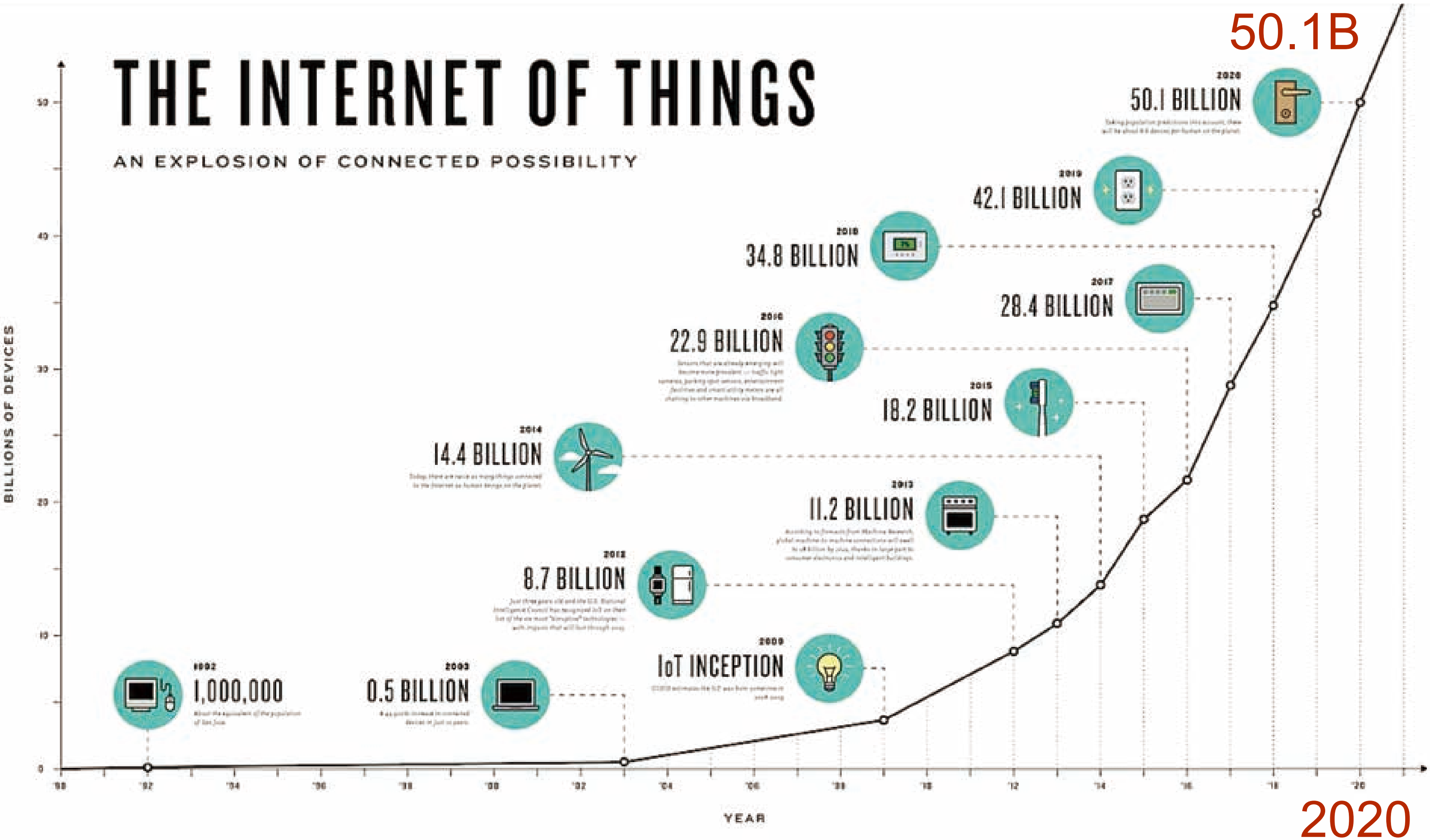


IoT Processors ?

The IoT device is becoming smaller and smaller,
it can be so small that there is limited space for battery !

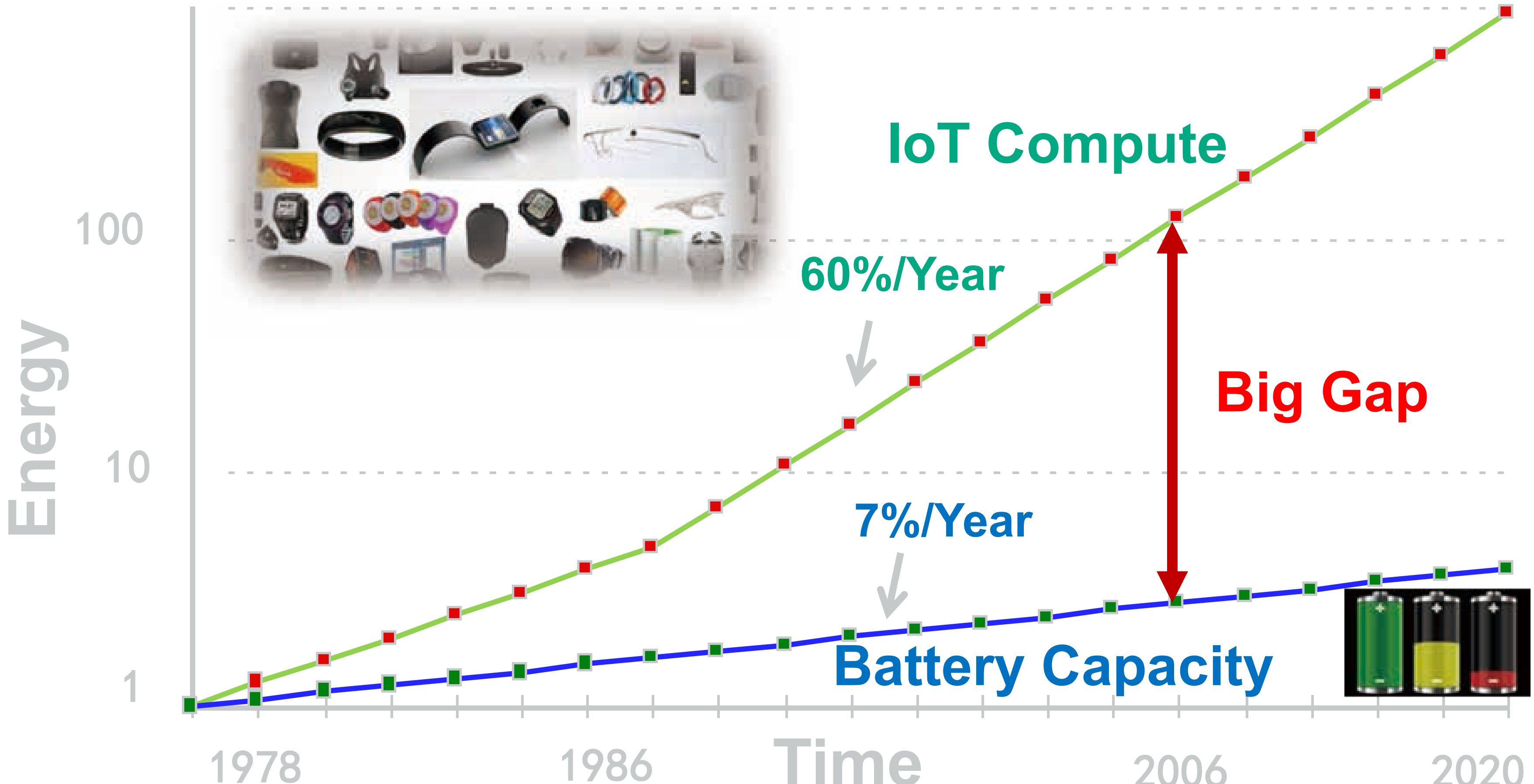
❖Source: ISSCC 2011

Trend of Internet of Things - Device Number Increases



❖Source: Silicon Labs. Thomson Reuters, Morgan Stanley, Goldman Sachs

Power Challenge for IoTs



The development of battery capacity is much slower than energy requirement of IoT devices !

❖Source: ISSCC 2015 Technology Trend

Challenges of Battery

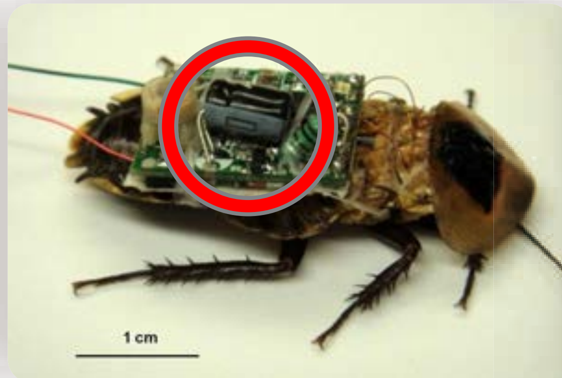
Distributed, limited volume, massive, and safety concerns

- New Challenges for battery from IoT

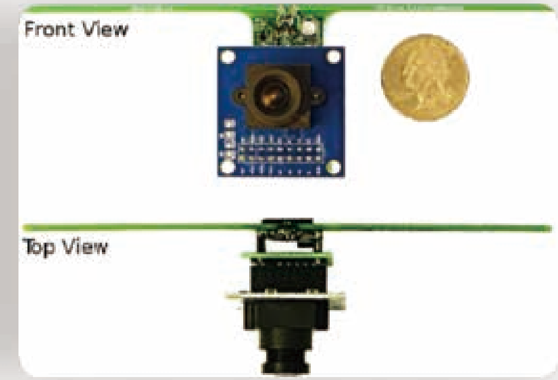
Can some devices survive without charging batteries ?

Promising Energy Harvesting Solutions

Dragonfly Tracking –
University of Washington (UW)

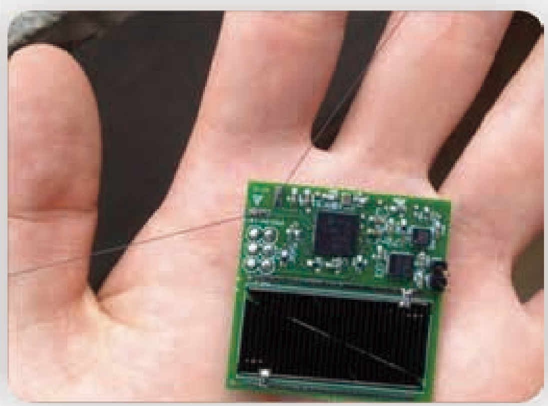


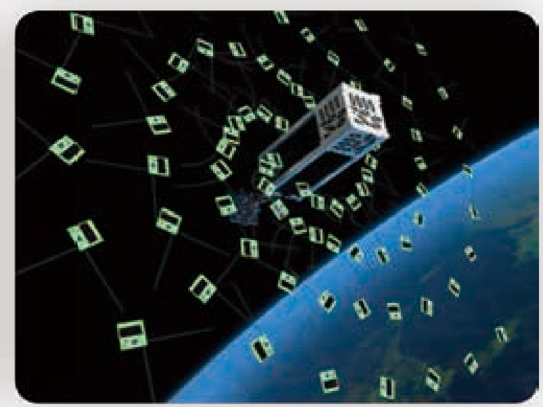
DARPA, N66001-07-1-2006.



WispCam UW Seattle.

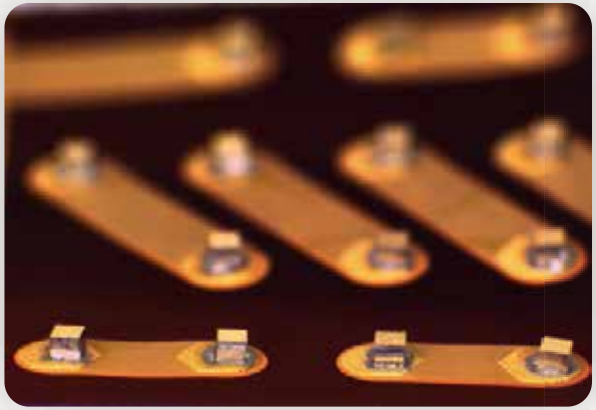
Google Contact Lense

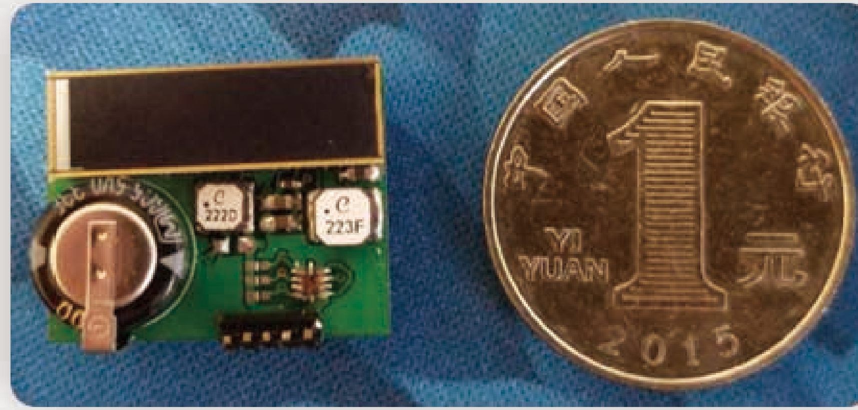




Smallest-Ever Working Satellites and Status in Orbit

Ambient Energy Harvesting Sources

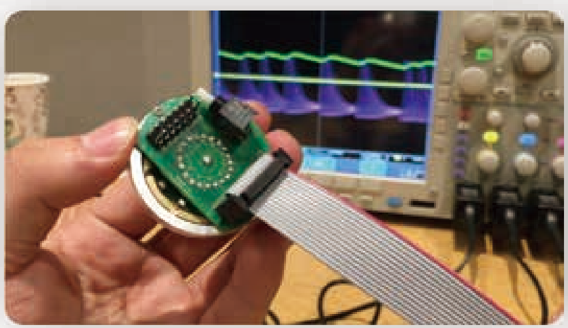


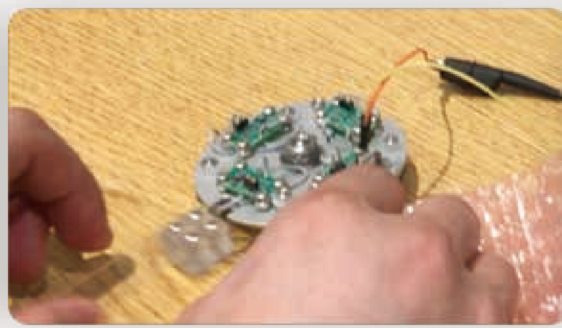


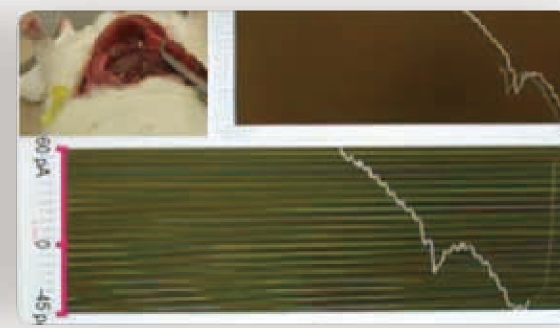
RF Energy
(PSU)

Thermal Energy
(ASSIT@NCSU)

Solar Energy
(PSU)

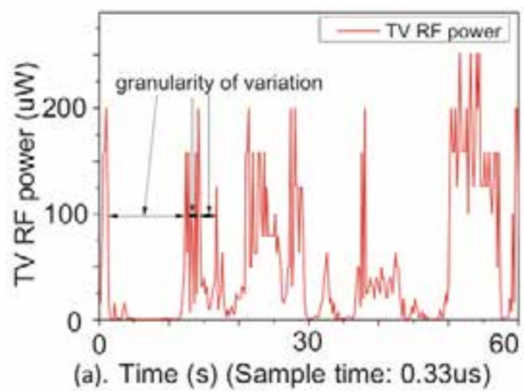


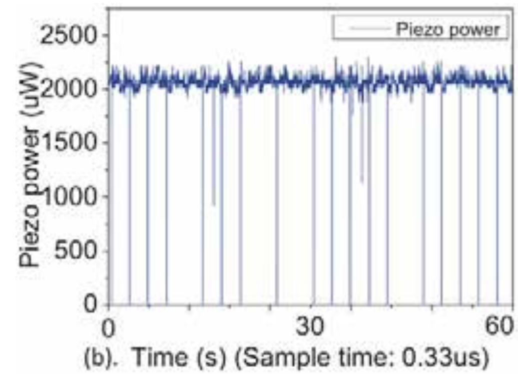




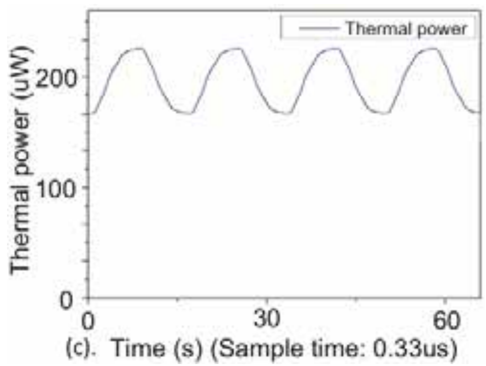
Piezoelectric/Vibration Energy (ASSIT@Utah / Georgia Tech.)

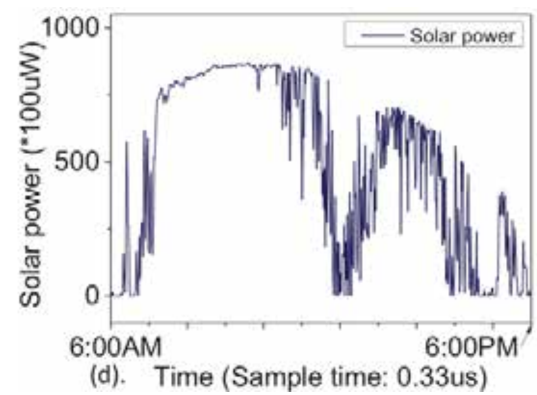
Challenge: Unstable Power with Different Signal Magnitude, Variability and Granularity





TV RF: **Unstable & large variation** **Piezo:** **Periodical**





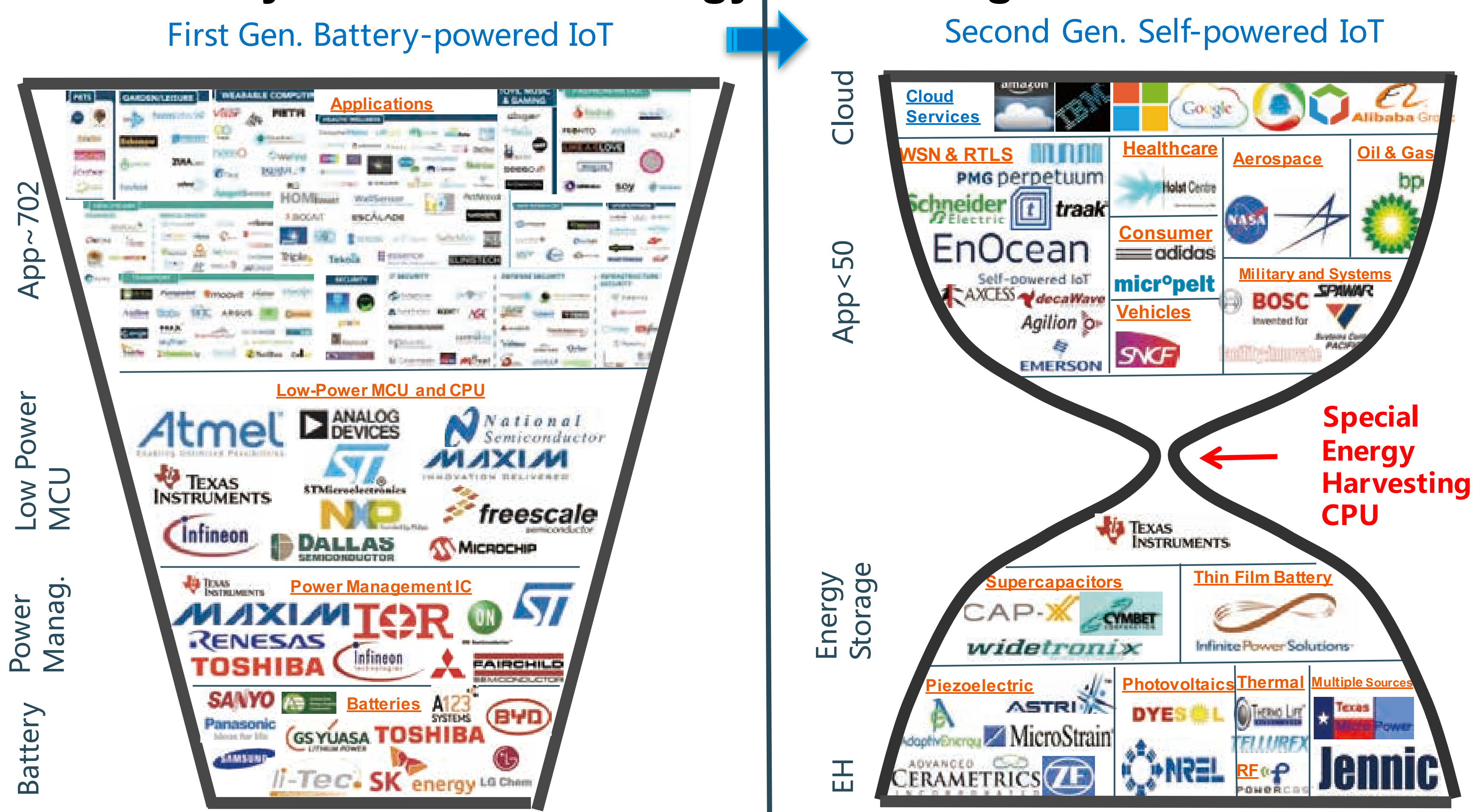
Thermal: **Relatively stable** **Solar:** **Environment dependent**

From Energy Harvesting Source Directly to Load? Free Lunch?

All the energy sources are unstable!

❖Ref: Ma et al. HPCA 2015

The Industry Situation for Energy Harvesting

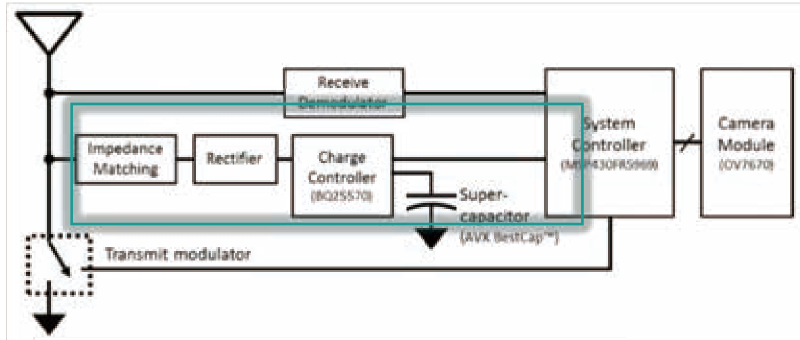


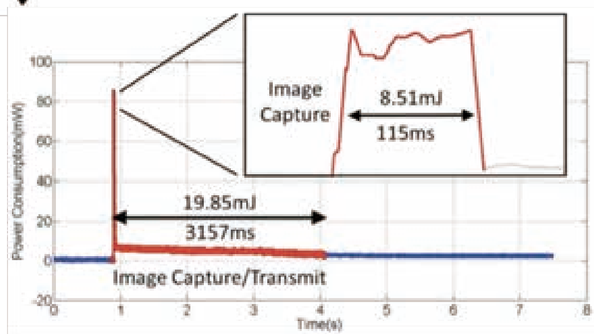
Because of the bottleneck in special EH CPU, currently system have to be designed with low power MCUs.

A Typical Wait-compute System - WispCam by UW Seattle

Application Level

System Design Details





"When 5m away from energy source, it captures and transmits an image approximately **every 15 minutes**." The capacitor is leaking in the 15 minutes.

~min-~hours

Accumulating Energy >50% Energy
(Charging Cap with Low Efficiency, and Capacitor is leaking)

~ms-~s

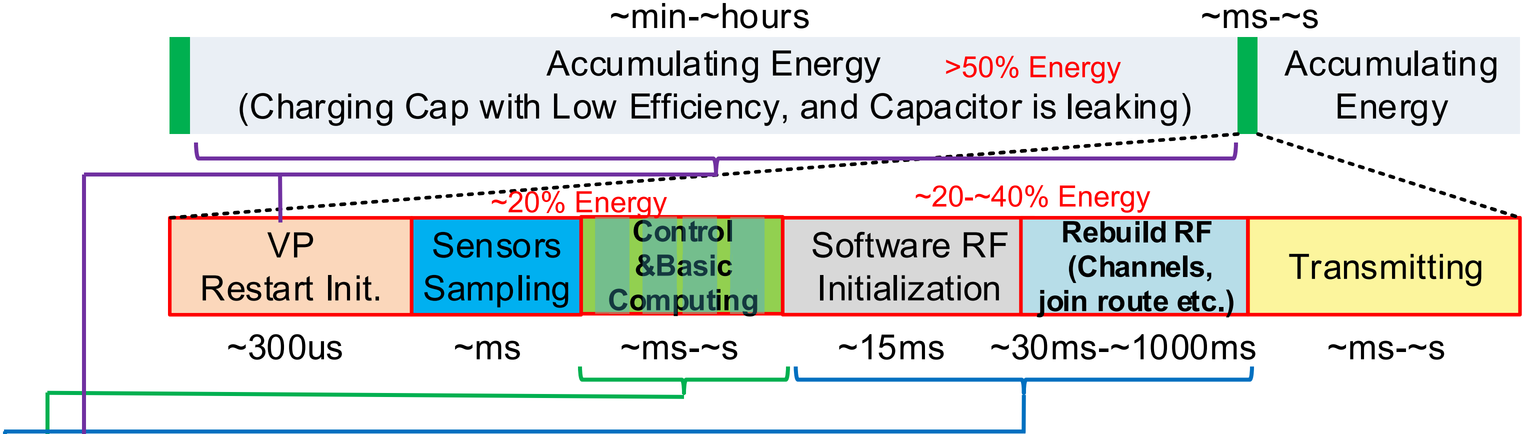
Accumulating Energy

~20% Energy ~20-~40% Energy

VP Restart Init. (~300us) | Sensors Sampling (~ms) | **Control &Basic Computing** (~ms-~s) | Software RF Initialization (~15ms) | **Rebuild RF (Channels, join route etc.)** (~30ms-~1000ms) | Transmitting (~ms-~s)

❖Source: Joshua Smith et al. WispCam: A battery-free RFID camera.

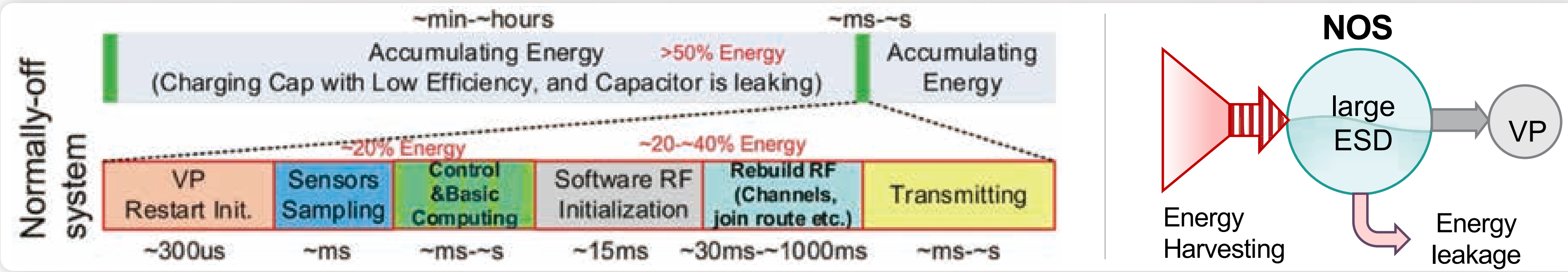
Content

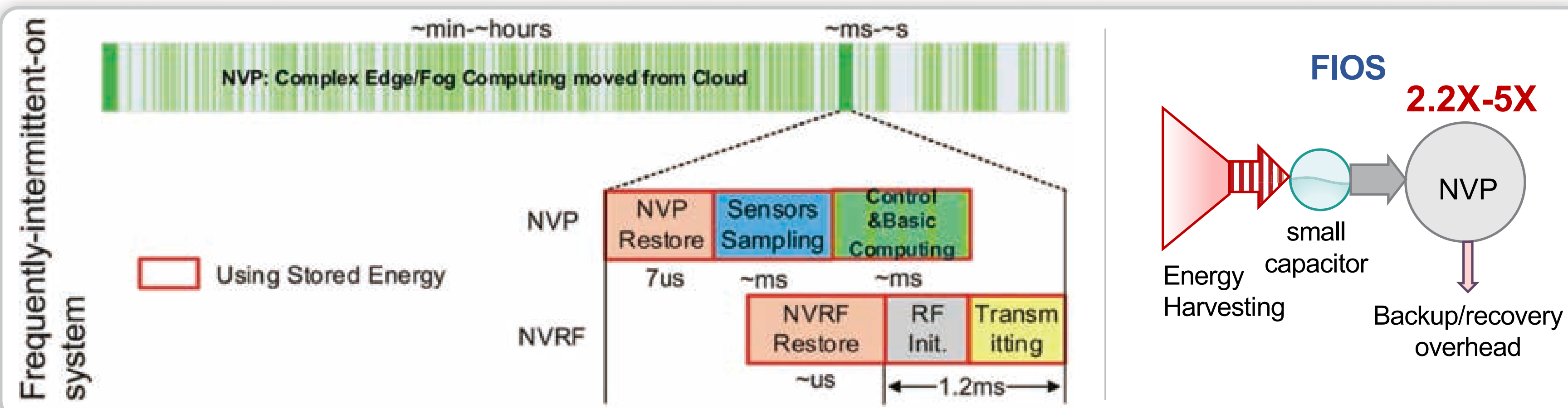


- Motivation and Background
- Nonvolatile Processor Architecture Exploration
  - HPCA 2015 Best Paper Award, Top Picks 2016, IEEE Micro Special Issue 2016.
- Dynamic Intelligent Frequency and Resource Allocation
  - TECS 2016, ASP-DAC 2017 Best Paper Award.
- Incidental Approximate Computing
  - Micro 2017, IEEE Micro Special Issue on Approximate Computing 2018.
- NEOFog: Nonvolatility-Exploiting Optimization in Fog Computing
  - ASPLOS 2018, SenSys 2018(Under Review).
- Conclusion

Energy Harvesting System Optimization Target

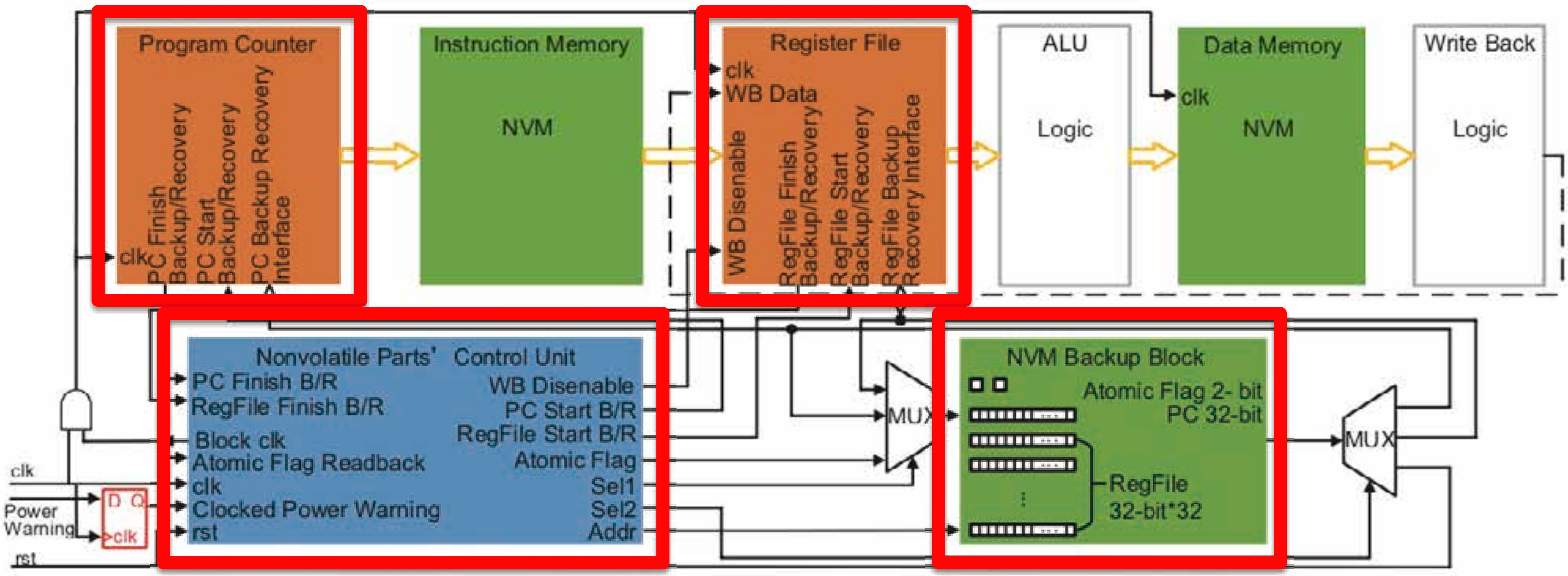
NOS (Normally-off system) → **FIOS** (frequently-intermittent-on system)





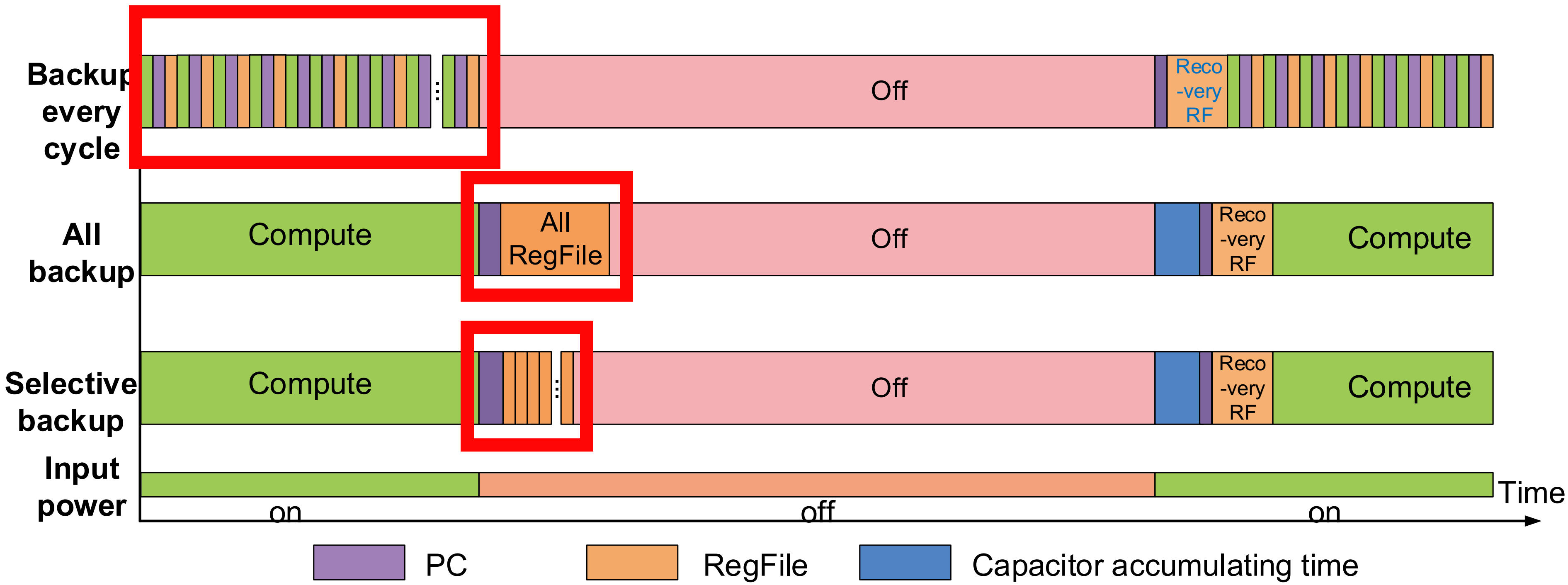
How to design architectures to achieve reliable and continuous computing under unstable power supply ?

From Volatile to Nonvolatile



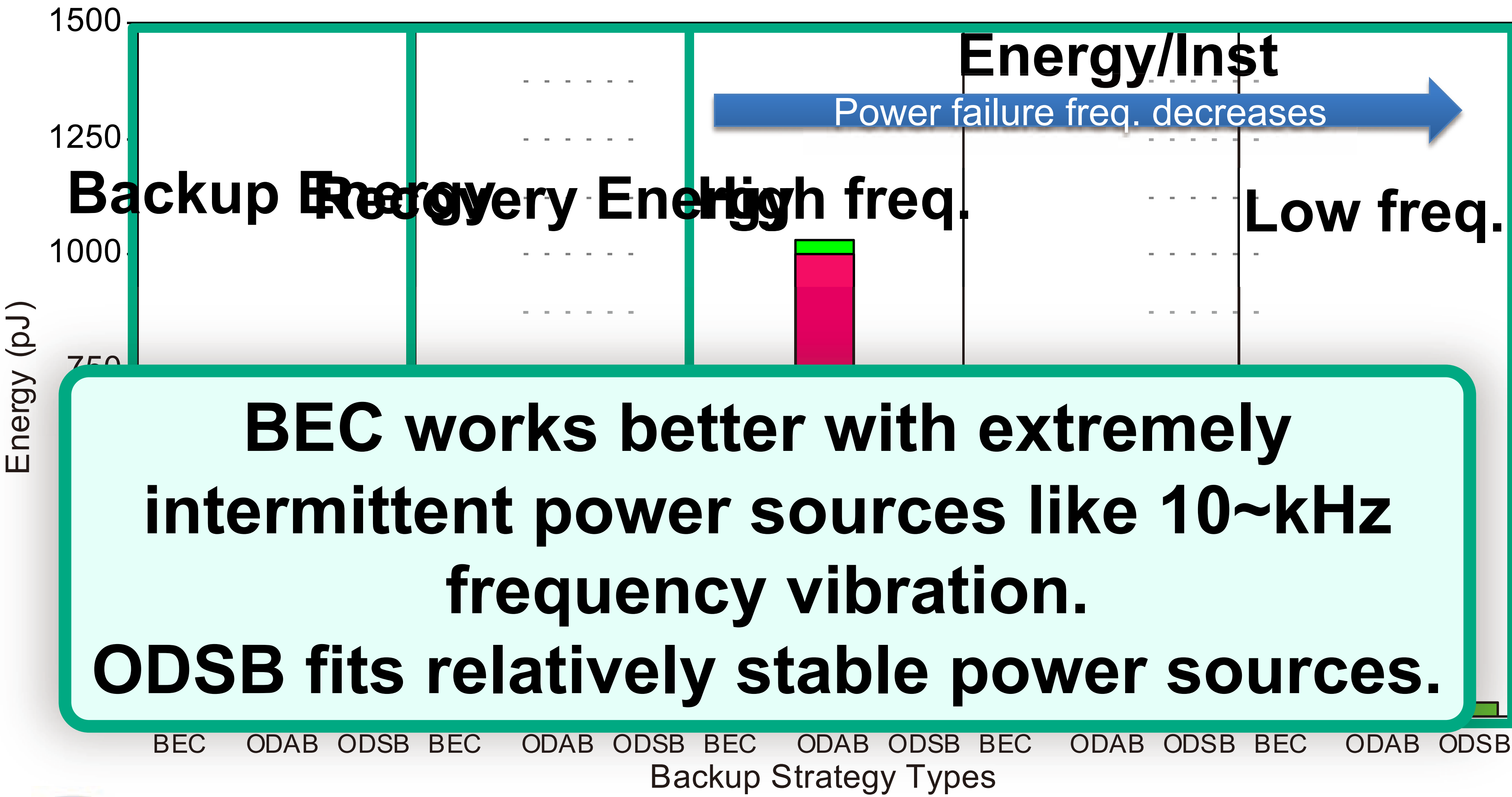
Non-Pipelined (NP)

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



❖Source: Ma et al. HPCA 2015, Selective backup solution has been fabricated and verified by our collaborators in Tsinghua Univ., at ISSCC 2016.

Non-Pipelined - Results & Comparison

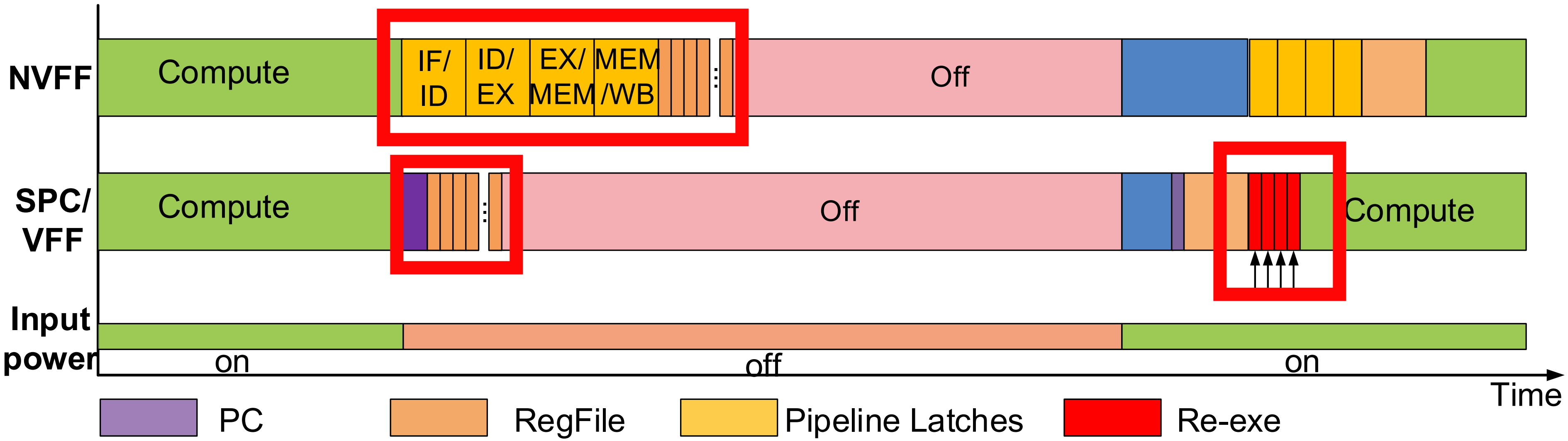


BEC works better with extremely intermittent power sources like 10~kHz frequency vibration.
ODSB fits relatively stable power sources.

N-Stage-Pipeline (5SP)

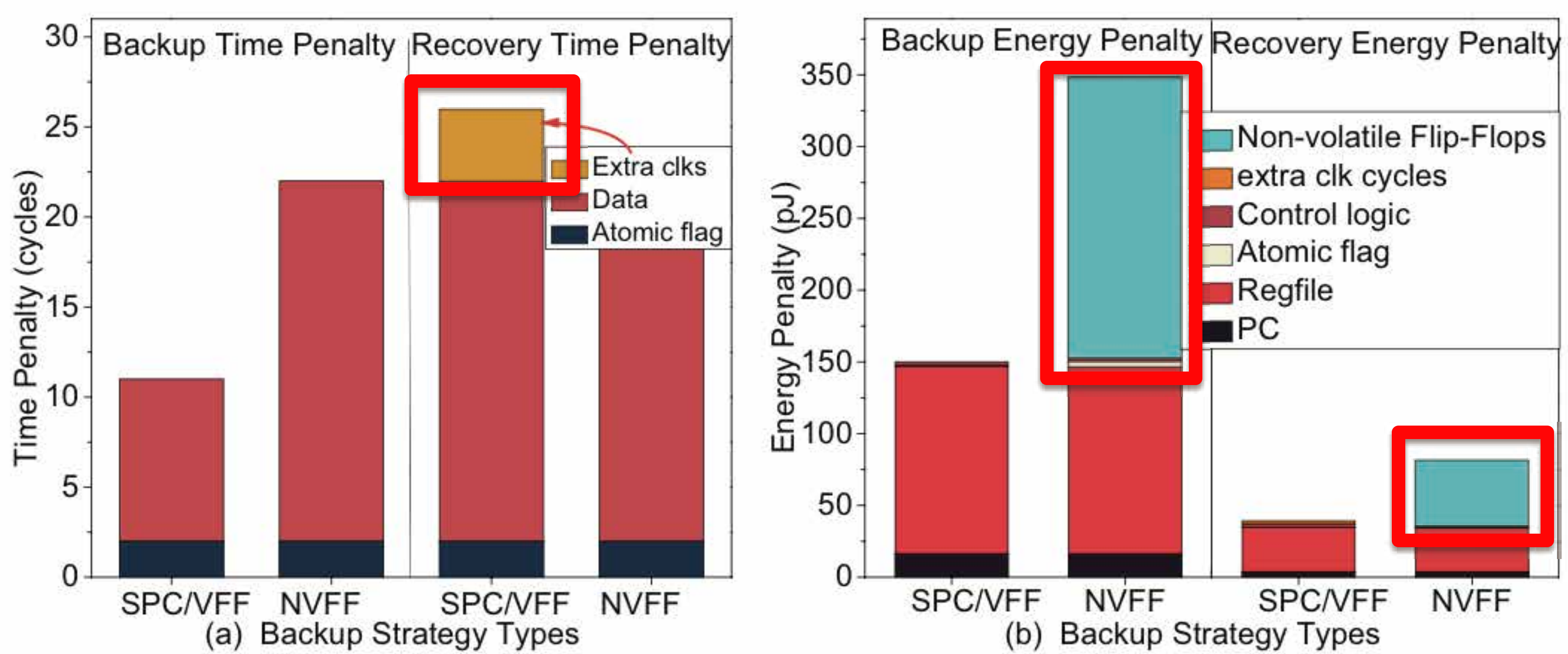
✓Nonvolatile Flip-flops (NVFF) .

✓Shifted PC & Volatile Flip-flops (SPC)



A trade-off between more things to be backed up and fewer backups with re-execution

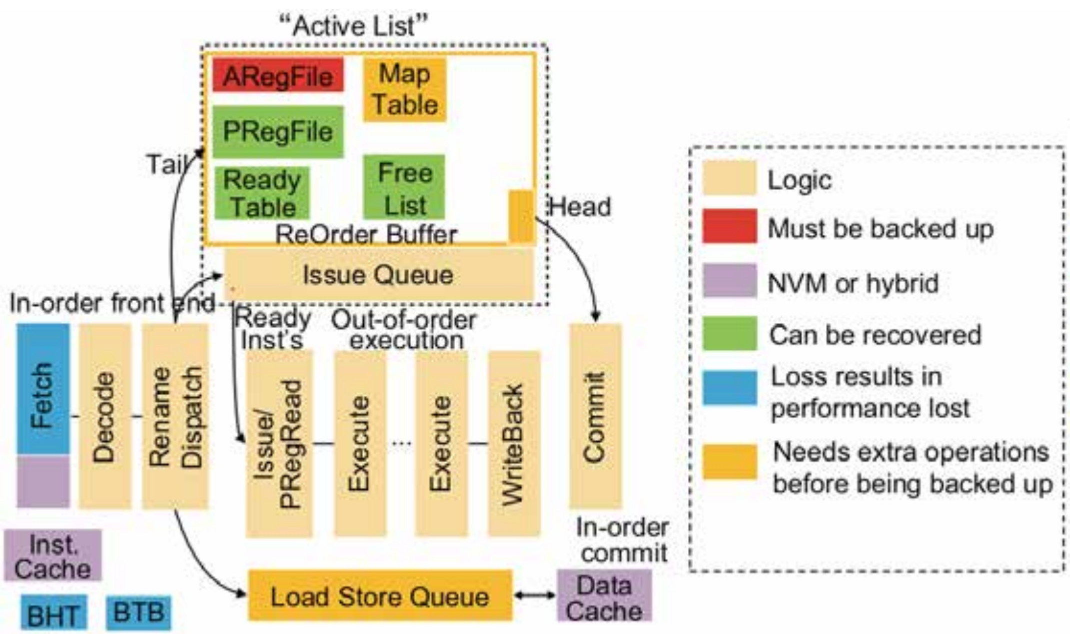
Less is More!



SPC is more energy-efficient than NVFF

Out-of-order: An Even Larger Policy Space

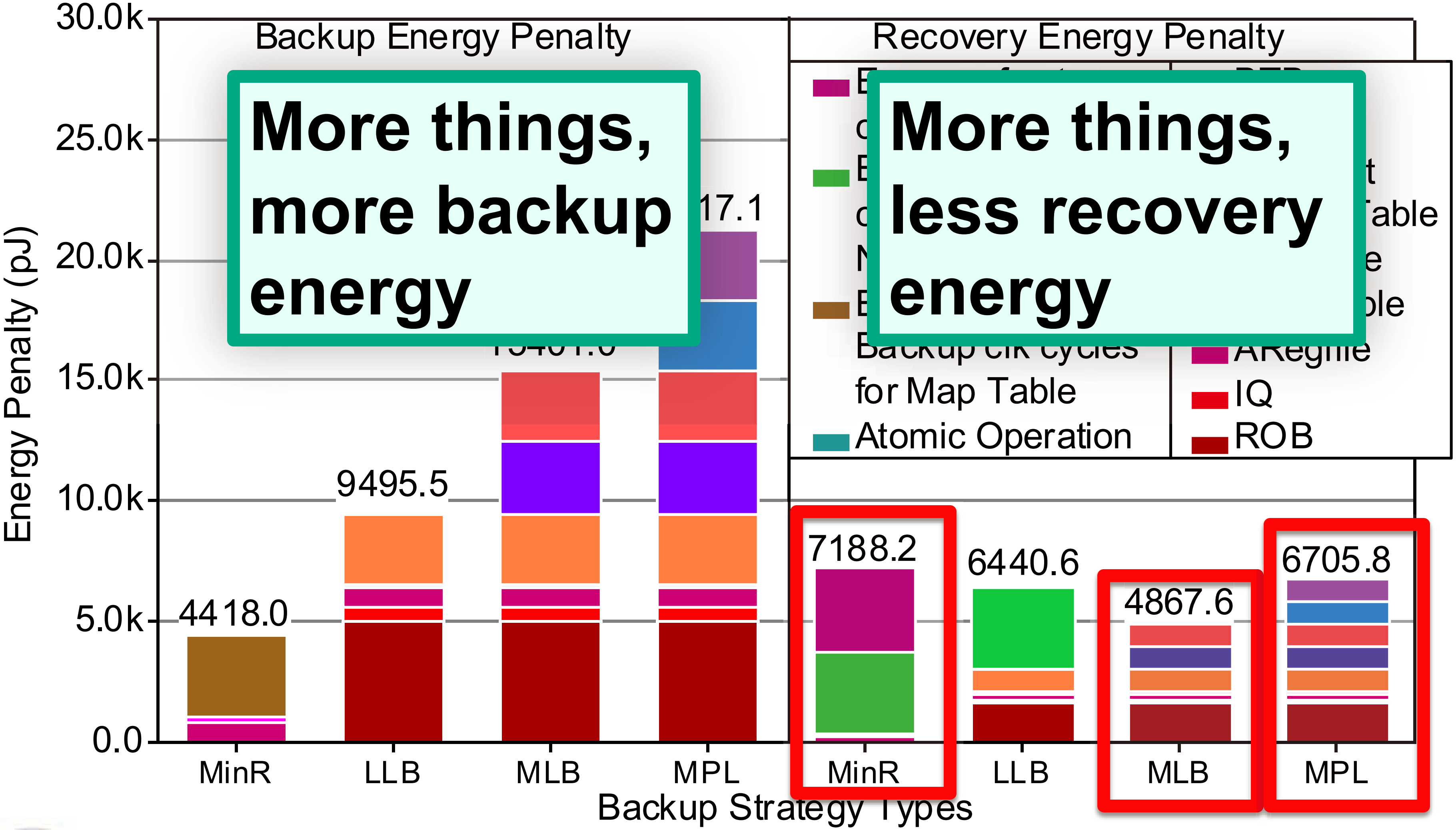
- ✓Minimum State Resource backup solution (MinR)
- ✓Low-latency backup solution (LLB)
- ✓Middle-level backup solution (MLB)
- ✓Min-state-lost backup solution (MPL)



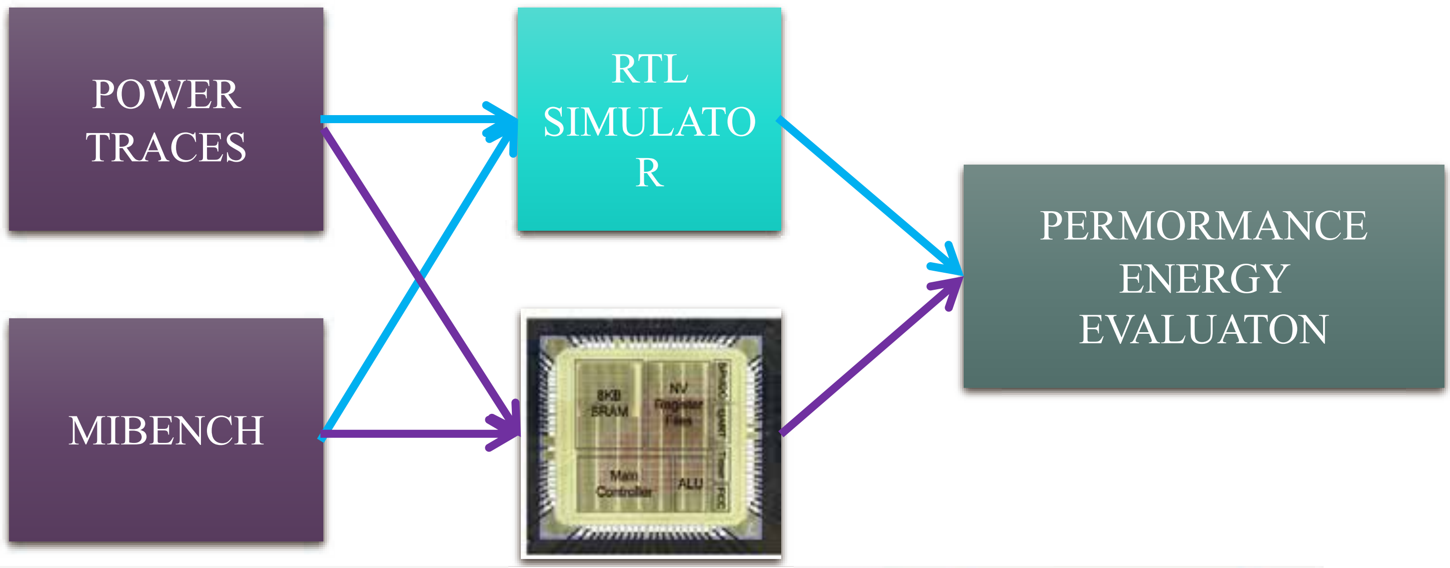
OoO solutions	ROB	IQ	AReg File	Map Table	PReg File	Ready Table	Free List	BHT	BTB
MinR	★		☆	✩					
LLB	☆	☆	☆	☆	☆				
MLB	☆	☆	☆	☆	☆	☆	☆		
MPL	☆	☆	☆	☆	☆	☆	☆	☆	☆

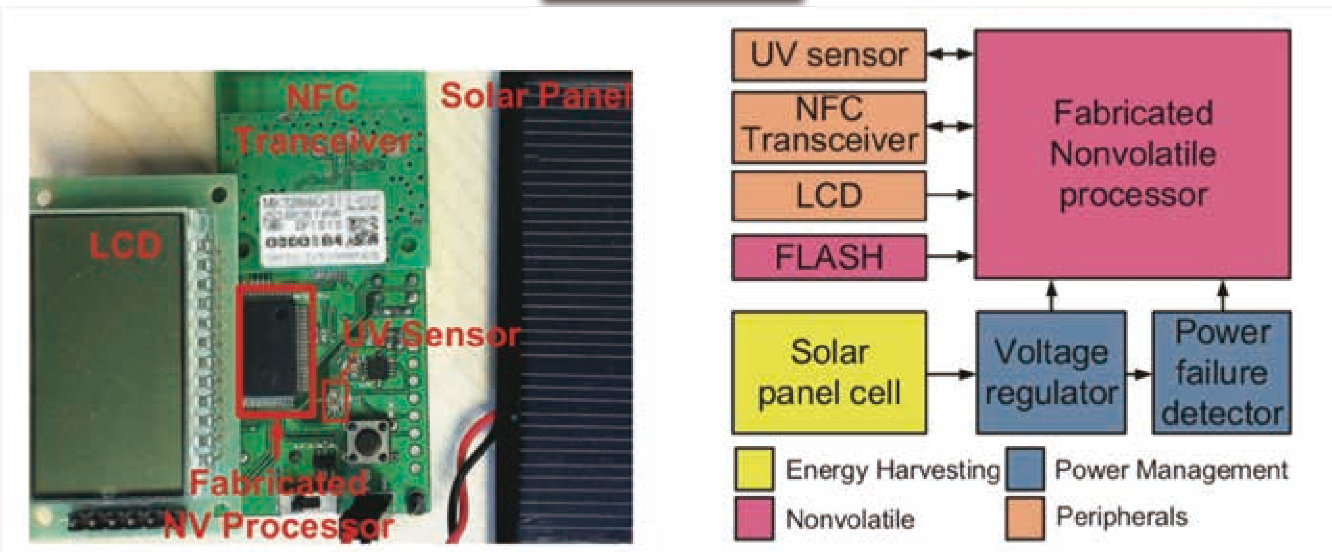
☆ Back up ★ Last uncommitted PC ✩ Pseudo-misprediction

Backup and Recovery Energy Costs

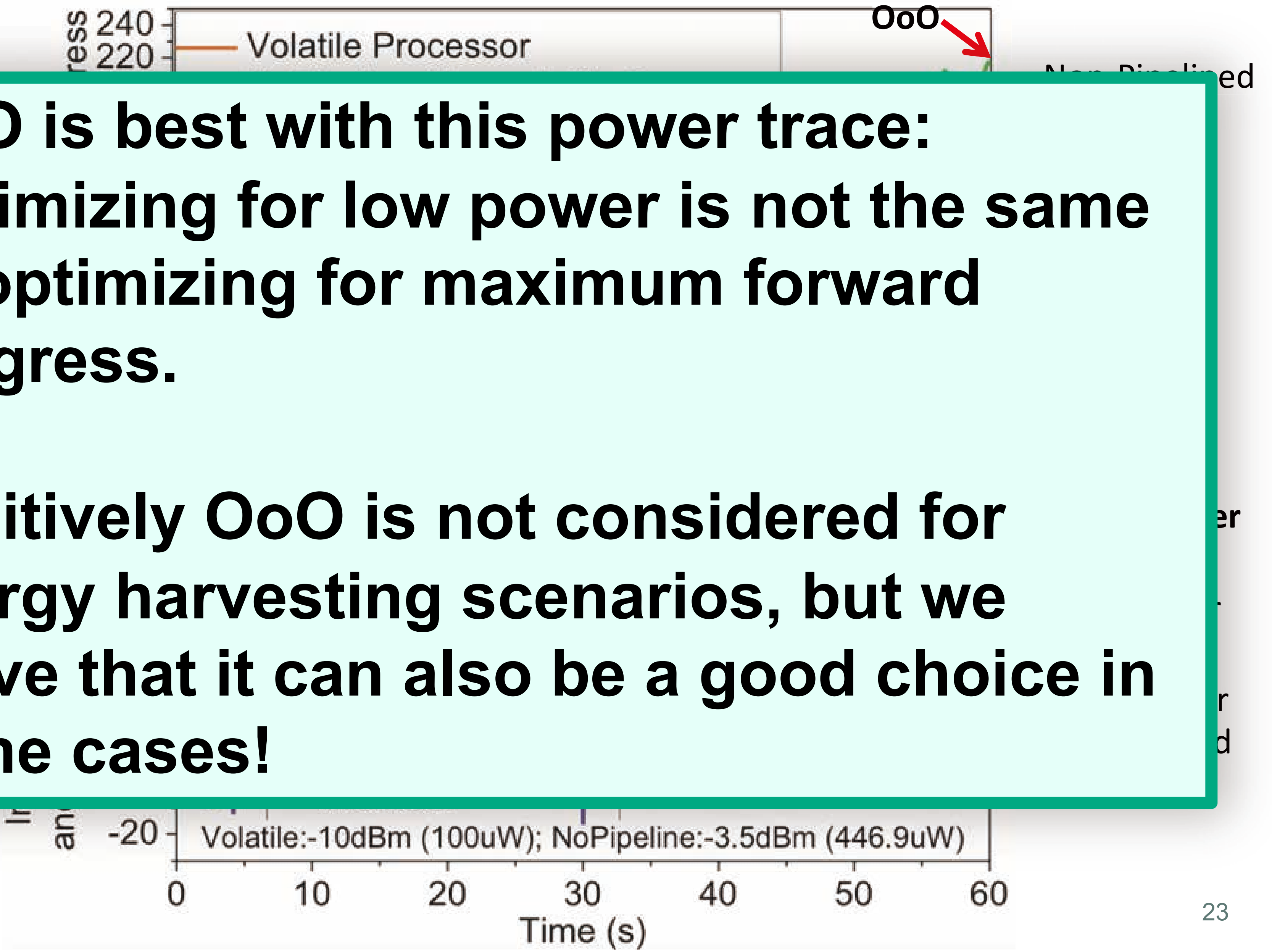


Validation Methodology





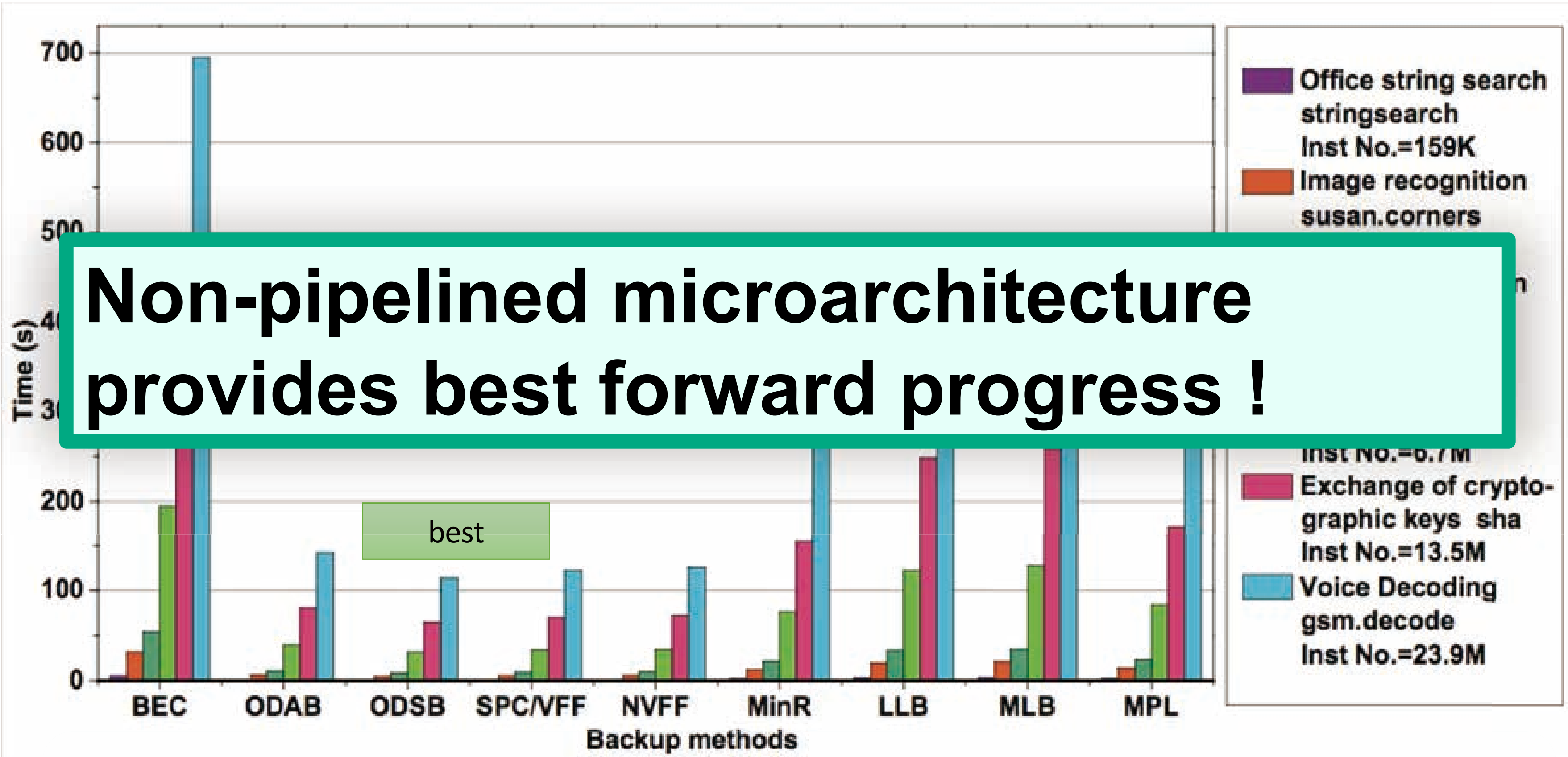
Architecture Exploration Results



OoO is best with this power trace: Optimizing for low power is not the same as optimizing for maximum forward progress.

Intuitively OoO is not considered for energy harvesting scenarios, but we prove that it can also be a good choice in some cases!

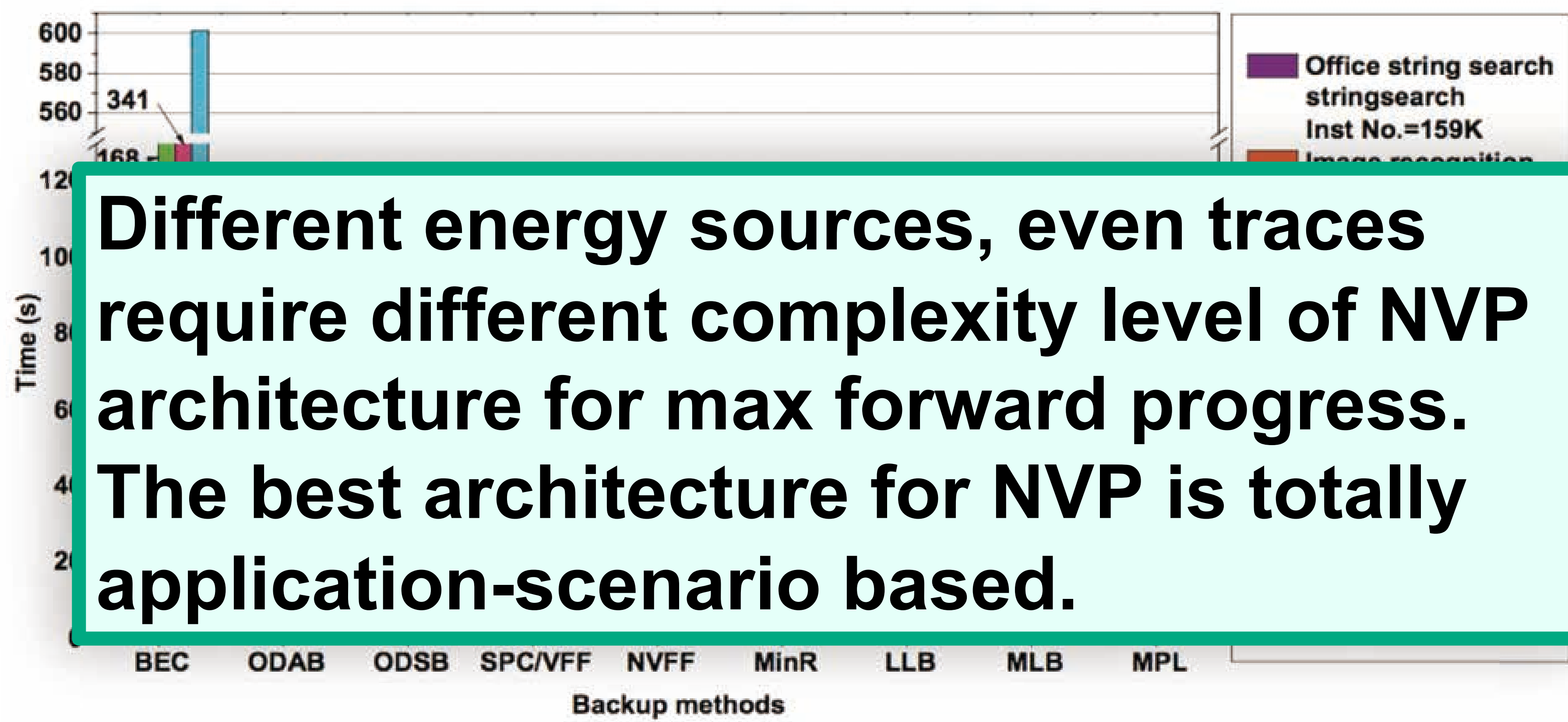
Execution time with energy scavenged from WiFi Home environment



Non-pipelined microarchitecture provides best forward progress !

NP architecture with OnDemand Selective Backup (ODSB) architecture has the best forward progress.

Execution time with energy scavenged from WiFi Office environment



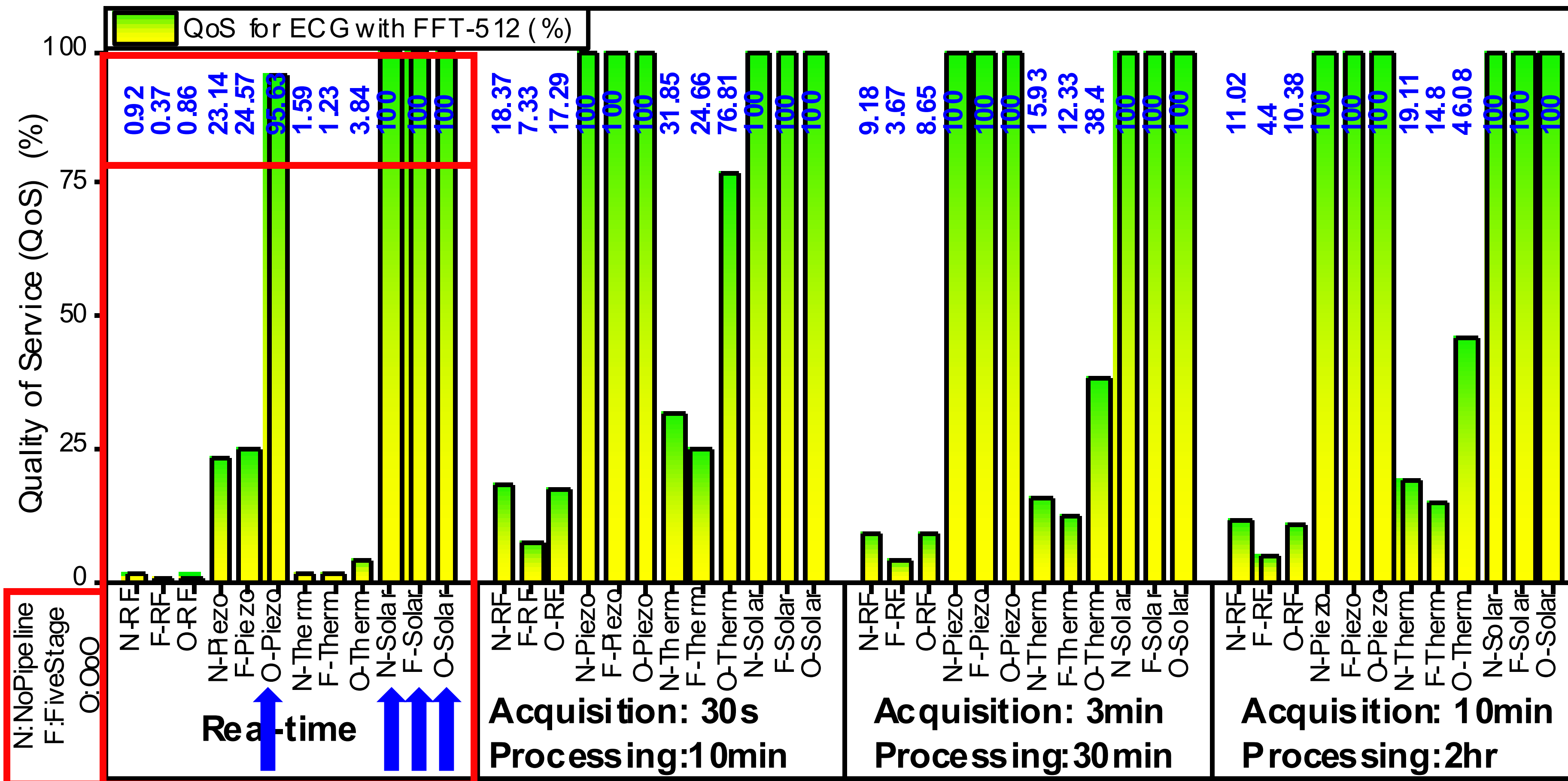
Different energy sources, even traces require different complexity level of NVP architecture for max forward progress. The best architecture for NVP is totally application-scenario based.

OoO architecture with Min-Performance-Lost (MPL) architecture has the best forward progress.

Design Guidelines

- How possible is an ECG watch powered by thermoelectrics?

Design Guidelines – Quality of Service (QoS)



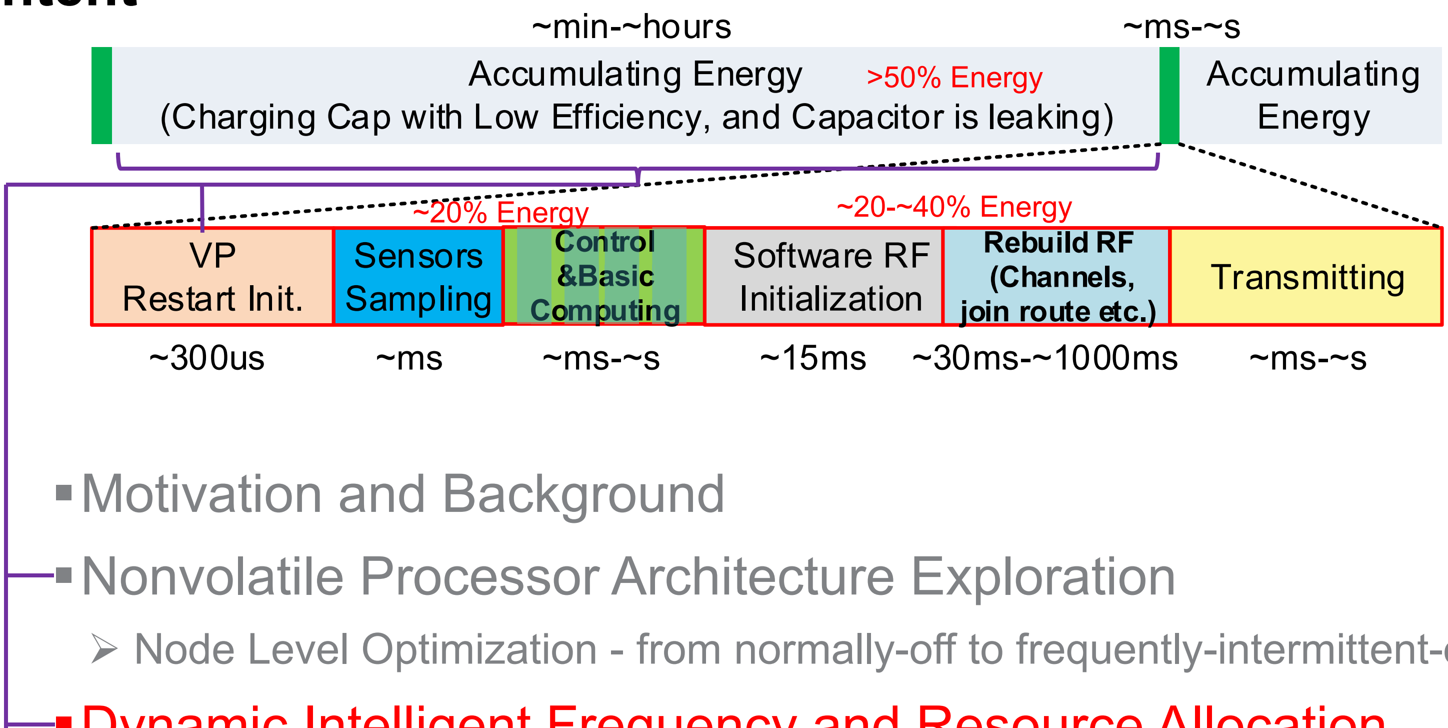
(a), QoS for different architectures/energy sources/acquisition&processing strategies in ECG

Design Guidelines – Make it Possible !

Baseline parameters and relationship with QoS

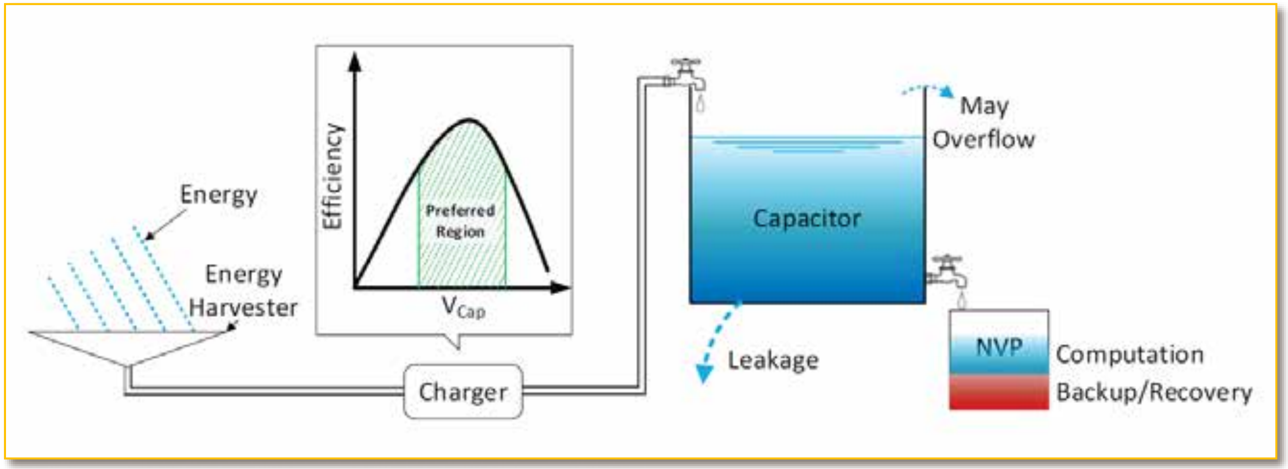
Source	Parameter	QoS Baseline	Relation to Efficiency
RF	Antenna gain	6dBi	α
	Bandwith	539M	α
	Distance	10km	$1/\alpha^2$
Therm	Area	$1cm^2$	α
	ΔT	$20\ ^{\circ}C$	α^2
Piezo	Volume	$1cm^3$	α
Solar	Area	$4cm^2$	α
	Efficiency	28%	α
Circuit	IP matching, AC-DC, DC-DC, LDO, Cap		
Tech.	Shink Tech.	130nm	α^2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

Content



- Motivation and Background
- Nonvolatile Processor Architecture Exploration
  - Node Level Optimization - from normally-off to frequently-intermittent-on
- Dynamic Intelligent Frequency and Resource Allocation
  - Node Level Optimization for efficiency
- Incidental Approximate Computing
  - QoS Level Optimization
- NEOFog: Nonvolatility-Exploiting Optimization in Fog Computing
  - System Level Optimization - How nonvolatility changes the system
- Conclusion

NVP System Optimization Opportunities



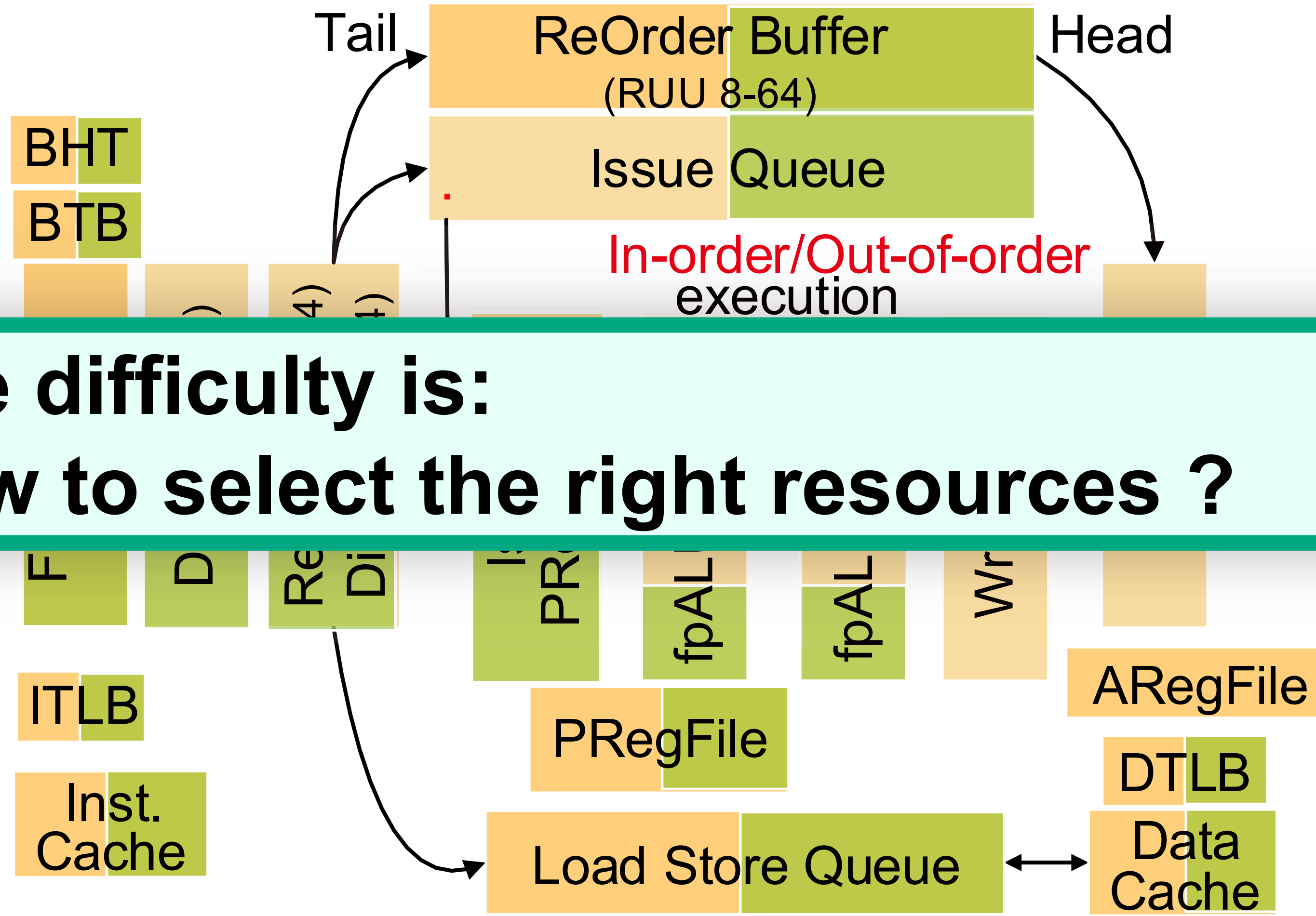
Forward Progress = Energy used for Computation / Energy per Instruction

Energy used for Computation = (Input Energy * Harvester efficiency * Storage Efficiency – Leakage - Overflow) * Ratio of computation/backup&recovery

- Use the energy as aggressively as possible, DFS etc.
- Reduce EPI: Resource allocation for IPC, Approximate computing, Code optimization
- Reduce backup energy: selective backup, approximate backup, compression

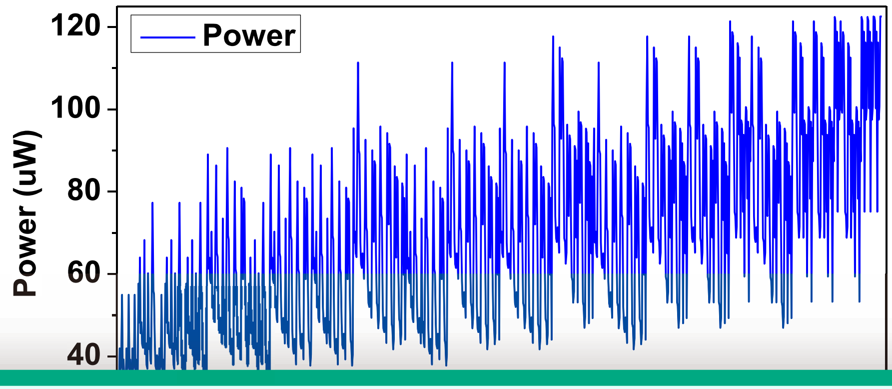
❖Source: Ma et al. IEEE TECS 2017

Dynamic OoO

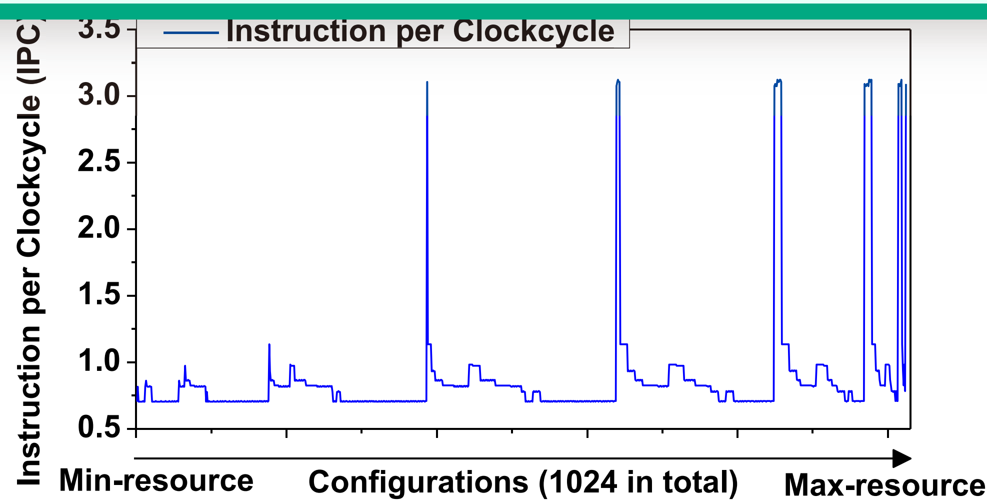


The difficulty is:
How to select the right resources ?

Higher Power is NOT Always Good

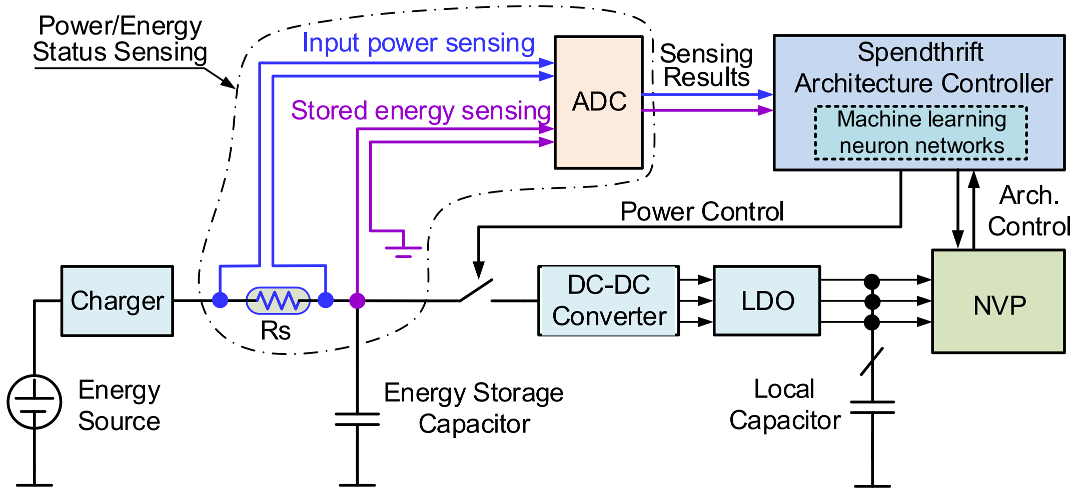


How to intelligently select the proper resource, for each testbench ?

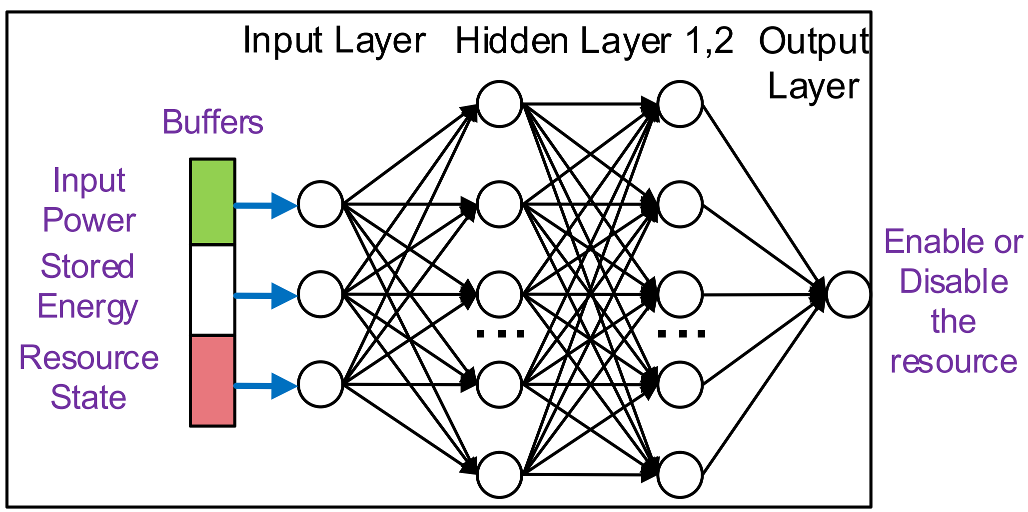


IPC V.S. different resource configurations, testbench “susan_corners”.

Neural Networks Predictor

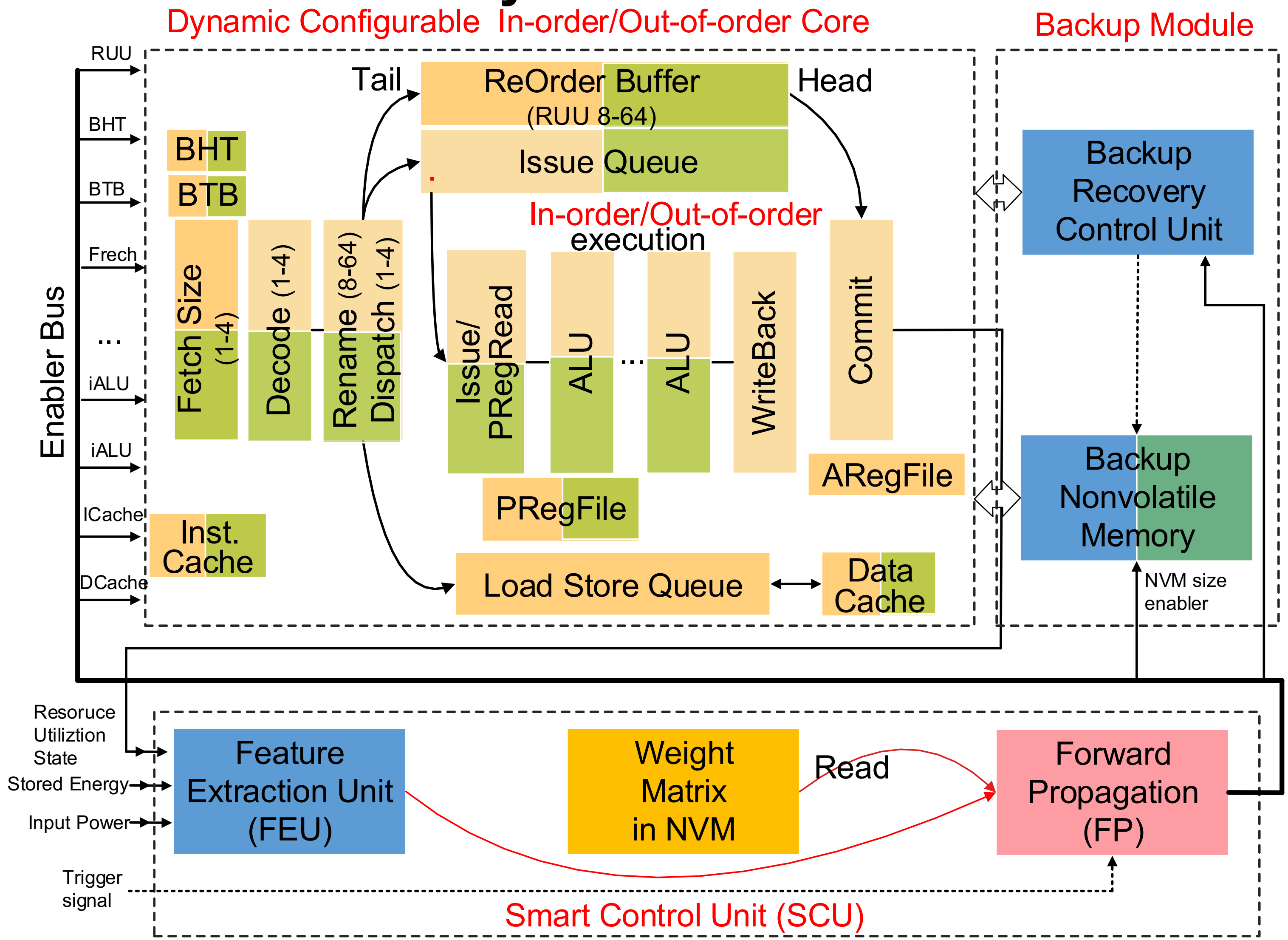


System diagram with feature extraction circuits



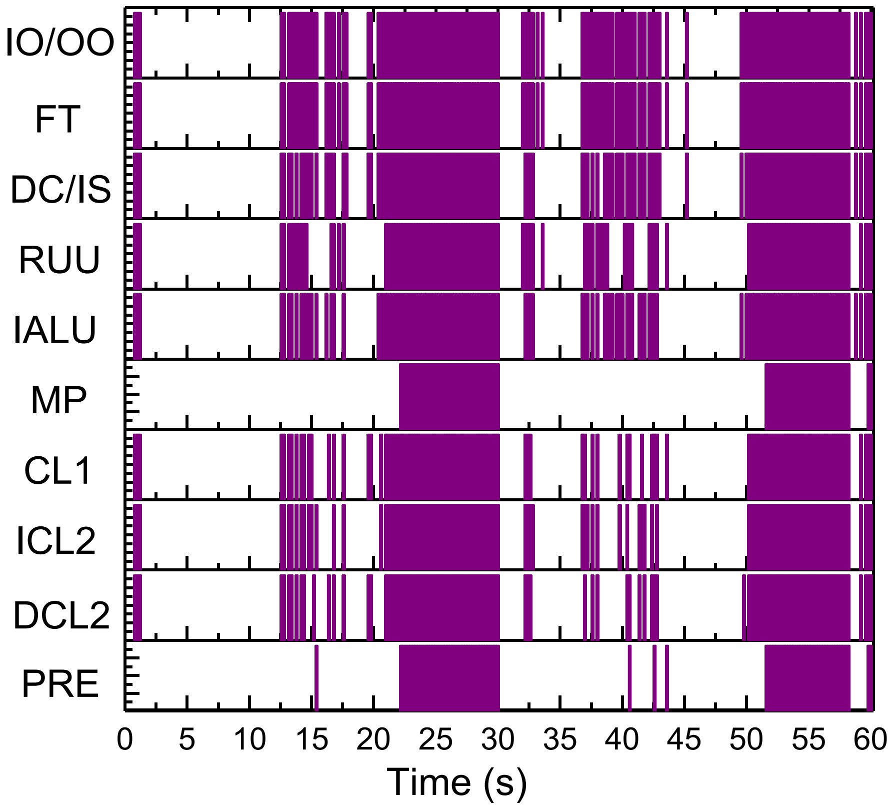
Neural networks for one resource prediction

Resource Allocation System Architecture

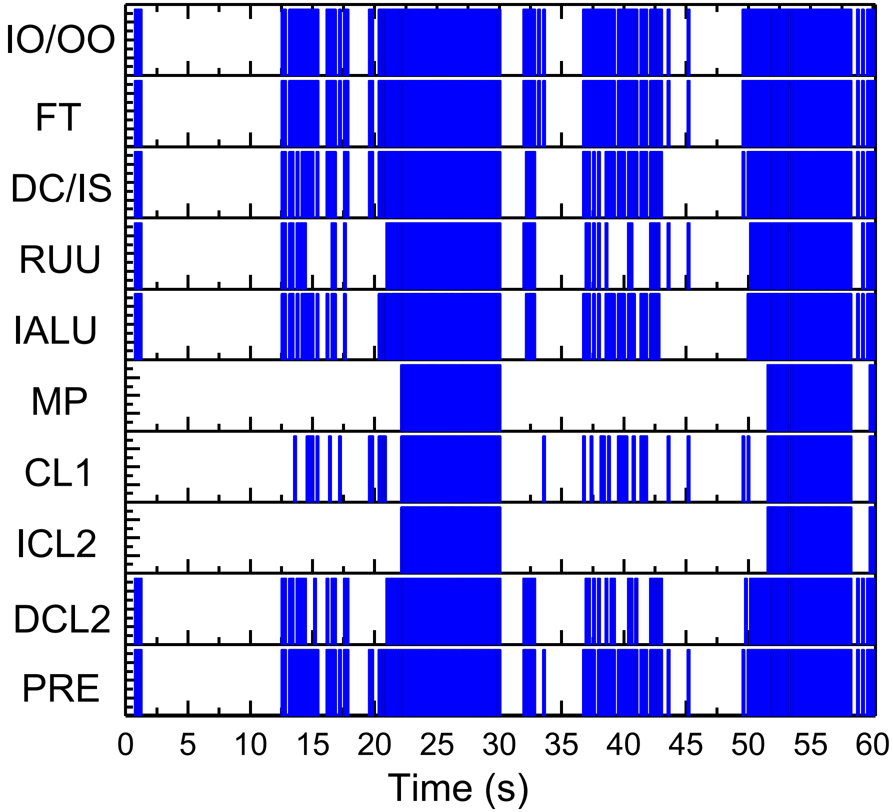


The system diagram of configurable resource allocation architecture. Configurations: IO/OO: InOrder/Out-of-Order, low for In-Order, high for Out-of-Order; FT: Fetch Width, low for 1, high for 4; DC/IS: decoder and issue width, low for 1, high for 4; RUU: low for 8, high for 128; ALU: low for 1, high for 4; MP: memory port, low for 2, high for 8; CL1: Instruction and Data Cache: low for -cache:il1 il1:256:32:1:l, high for -cache:il1 il1:256:32:4:l; ICL2: low for -cache:dl1 dl1:256:32:1:l, high for -cache:dl1 dl1:256:32:4:l; DCL2: low for -cache:dl2 ul2:64:64:4:l, high for -cache:dl2 ul2:256:64:4:l; PRE: low for -bpred:bimod 128, high for -bpred:bimod 1024.

Bottleneck Resource Allocation Results



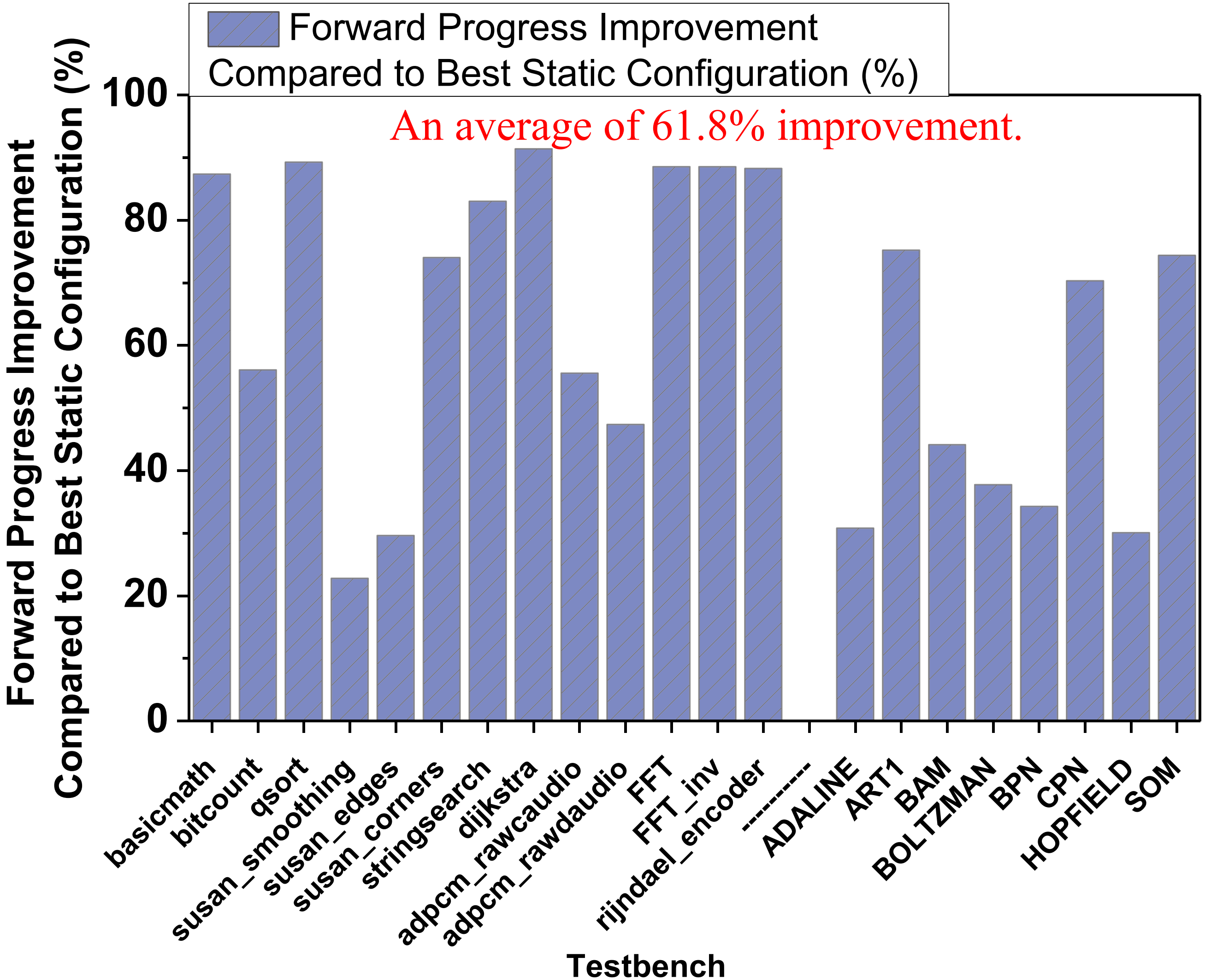
Testbench "susan_corners" resource allocation.



Testbench "rijndael_encoder" resource allocation.

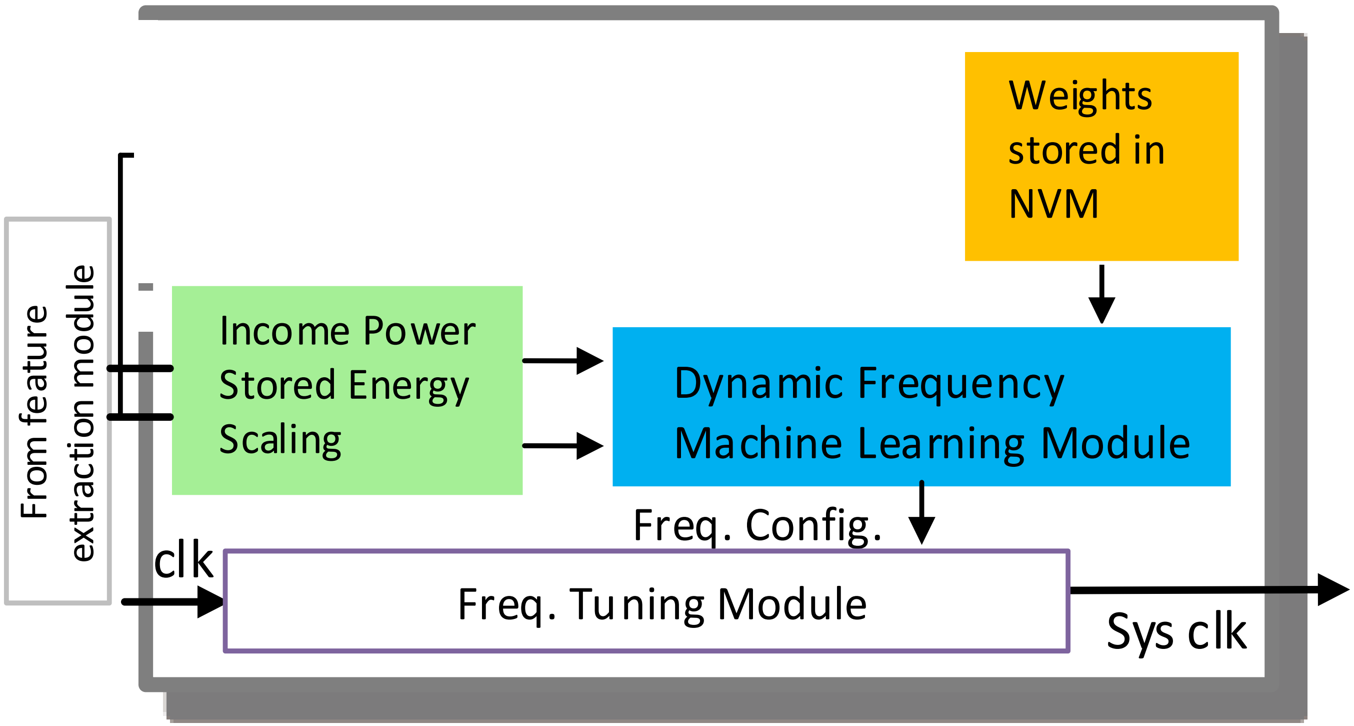
Predictor details: Offline training is used with 10k training set, achieving an accuracy above 90% on Mibench "small inputs".

Bottleneck Resource Allocation - Improvement



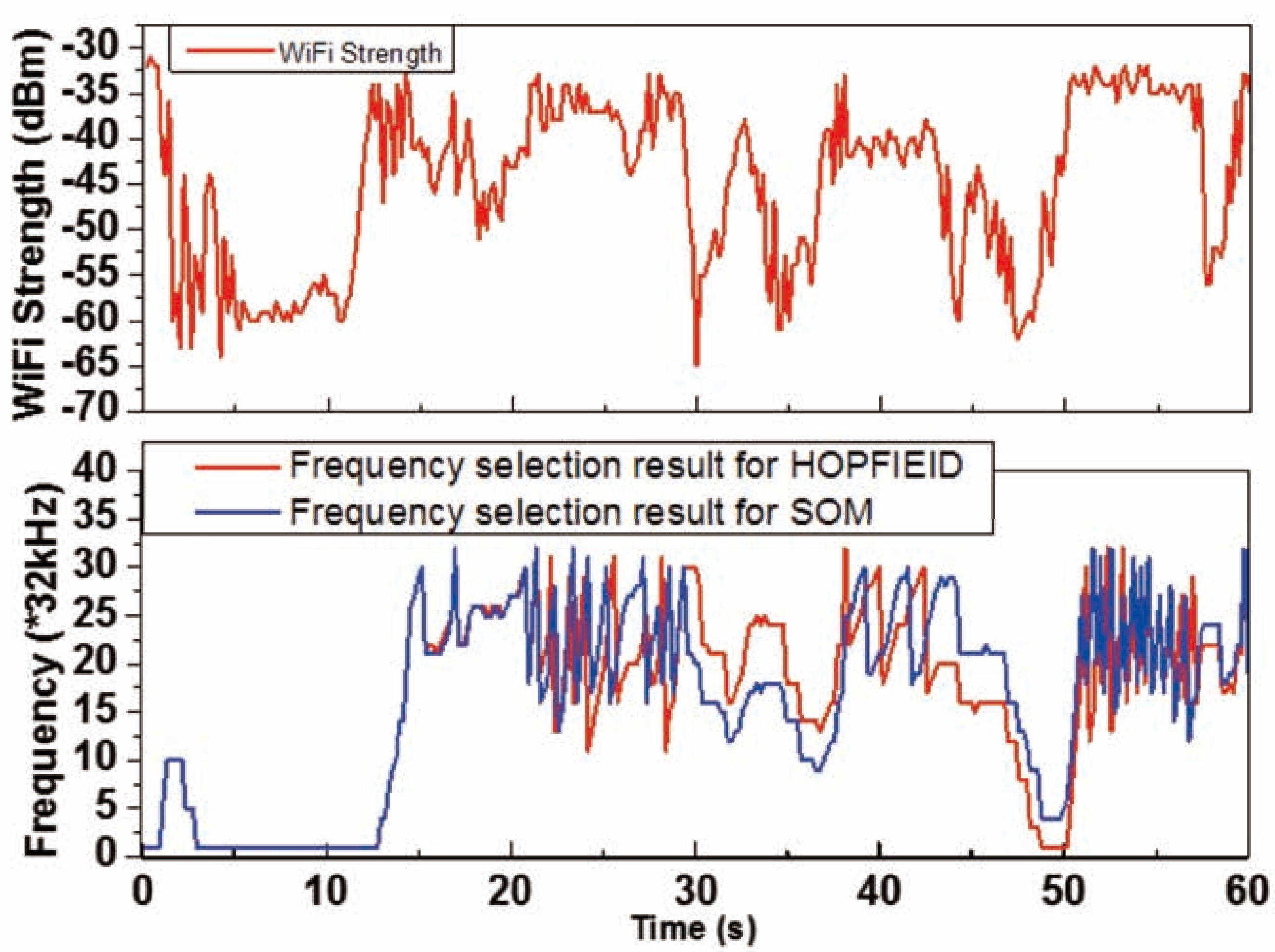
Bottleneck resource prediction: An average of 61.8% forward progress improvement.

Smart Frequency Prediction Module



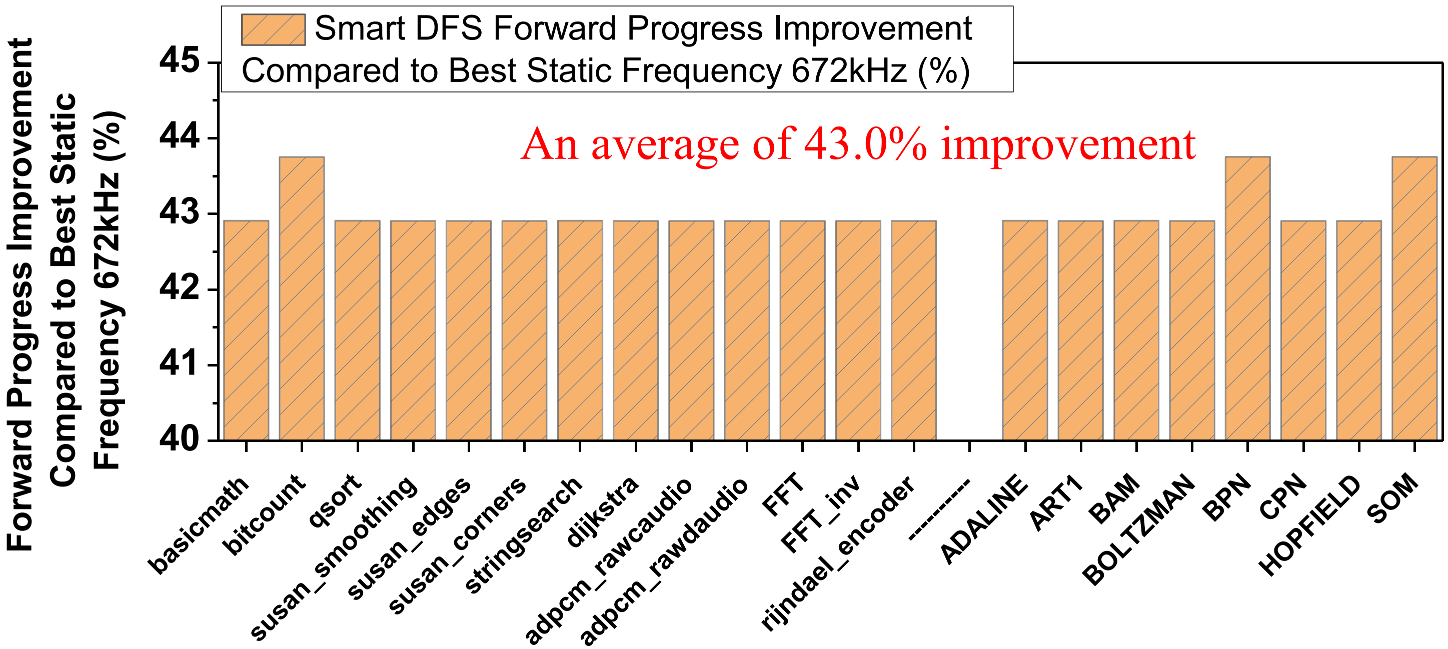
Predictor details: It has 2 entries: power income level and stored energy level. There are two hidden layers for 32*2 hidden neurons, and 32 outputs as the predicted possibility to select the frequency. The frequency with the largest possibility will then be selected (Simplified Softmax layer). The initial neural networks achieve above 98% accuracy with <10k training set.

Smart Frequency Prediction Results



DFS frequency selection results.

Smart Frequency Prediction Results



DFS frequency forward progress improvement compared to the best static frequency 672kHz

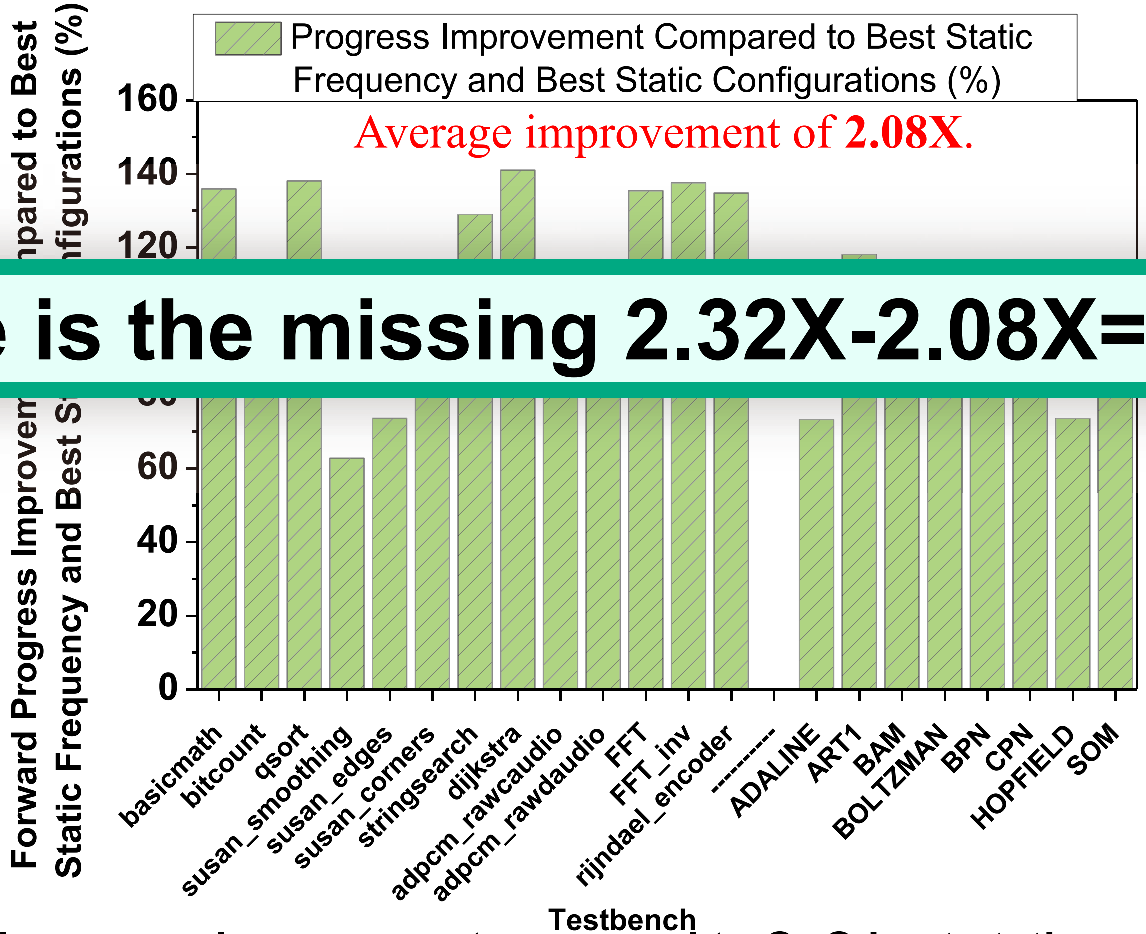
$$\text{Forward Progress Improvement} = \frac{\text{FP of Smart DFS}}{\text{FP of best static frequency}}$$

$$= \frac{\dfrac{\text{Energy for Computation of Smart DFS}}{\text{EPI for Specific Testbench}}}{\dfrac{\text{Energy for Computation of Fixed Frequency}}{\text{EPI for Specific Testbench}}}$$

Bottleneck Resource + Smart Frequency Prediction

$$\text{Forward Progress} = \frac{\text{Energy used for computation}}{\text{Energy per Instruction (EPI)}}$$

1.43X / 1.62X → 2.32X



Where is the missing 2.32X-2.08X= 0.24X ?

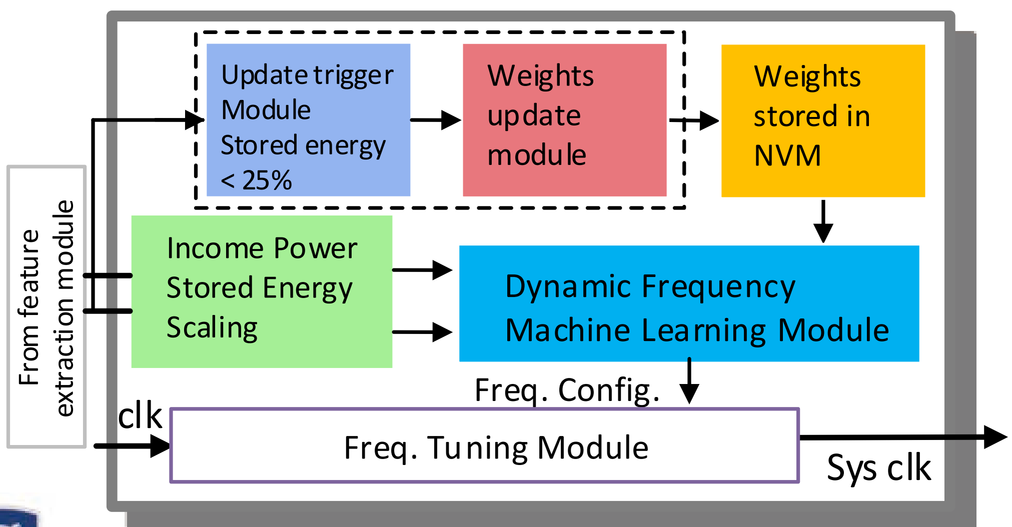
Forward progress improvement compared to OoO best static configuration and best static frequency. Average improvement of 2.08X.

Bottleneck Resource + Smart Frequency Prediction

$$\text{Forward Progress} = \frac{\text{Energy used for computation}}{\text{Energy per Instruction (EPI)}}$$

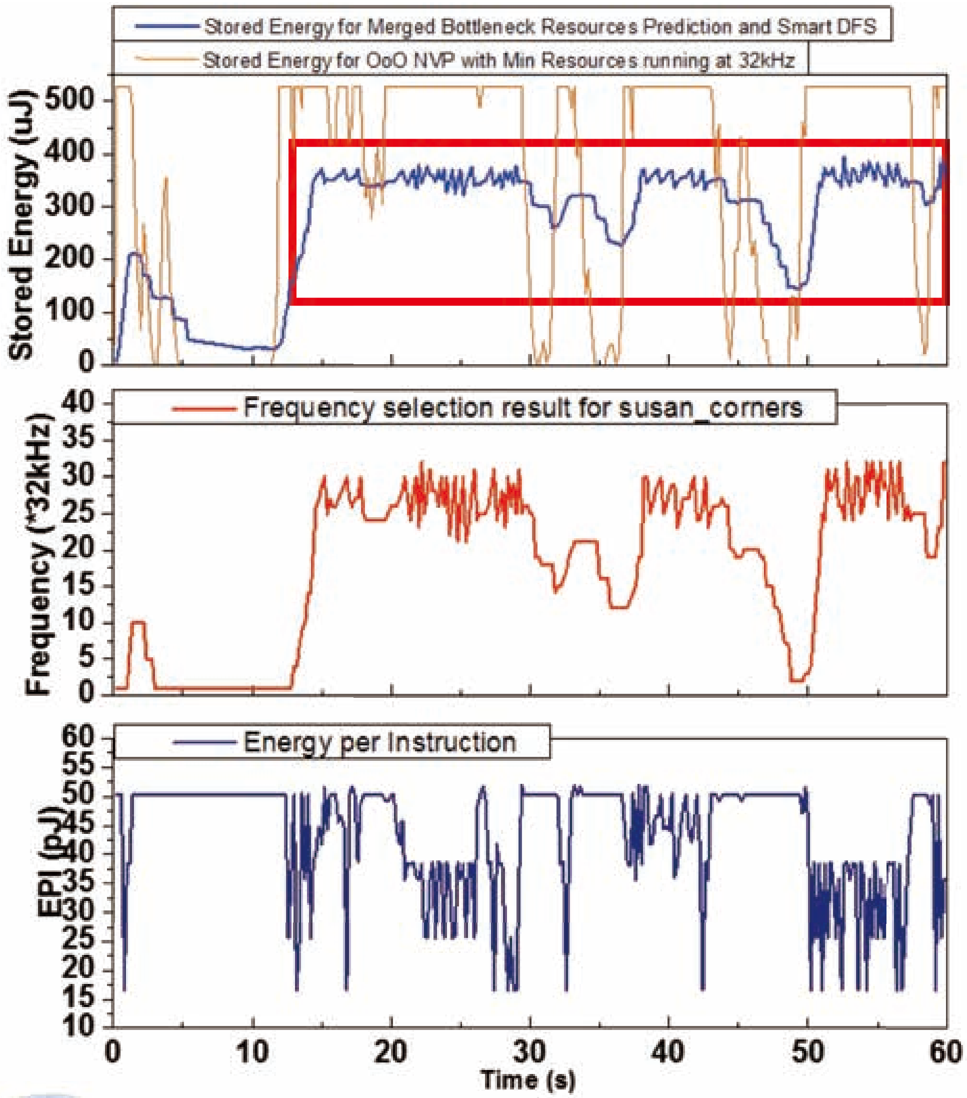
- Smart DFS -> energy used for computation; bottleneck resource prediction -> EPI.
- However, both approaches **compete for the same income power** to affect their benefits.

- Powering on all resources is rarely the most energy efficient way to use income energy.
  - **Good policy for only bottleneck resource prediction**
  - **Bottleneck Resource + Smart FS**: **Targeting the best EPI point while bursting the frequency.**



To avoid increased backups, once the stored energy level is less than 25%, the training module is triggered to compute the new weights, and update the weight in NVM, using one step lower frequency.

Bottleneck Resource + Smart Frequency Prediction

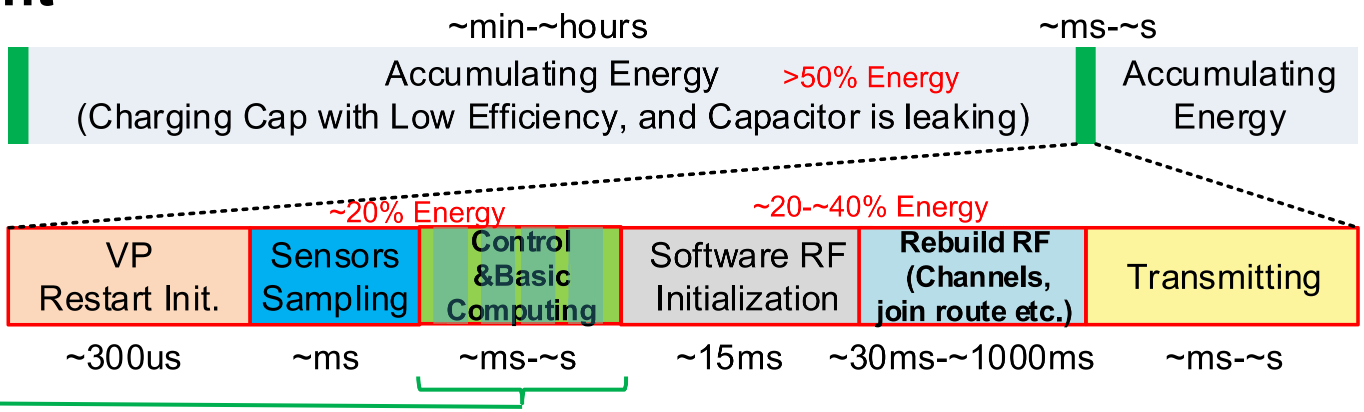


Fine-grained simulation results for merged bottleneck resources predictor and smart DFS.

If the stored energy level is not full, the bottleneck resources predictor is unlikely to predict powering on all resources, and will continue at a more EPI-efficient point.

In contrast, when the input power is very small, the predictor generates minimum resource configurations with higher EPI to ensure the NVP continues running but avoids backup operations.

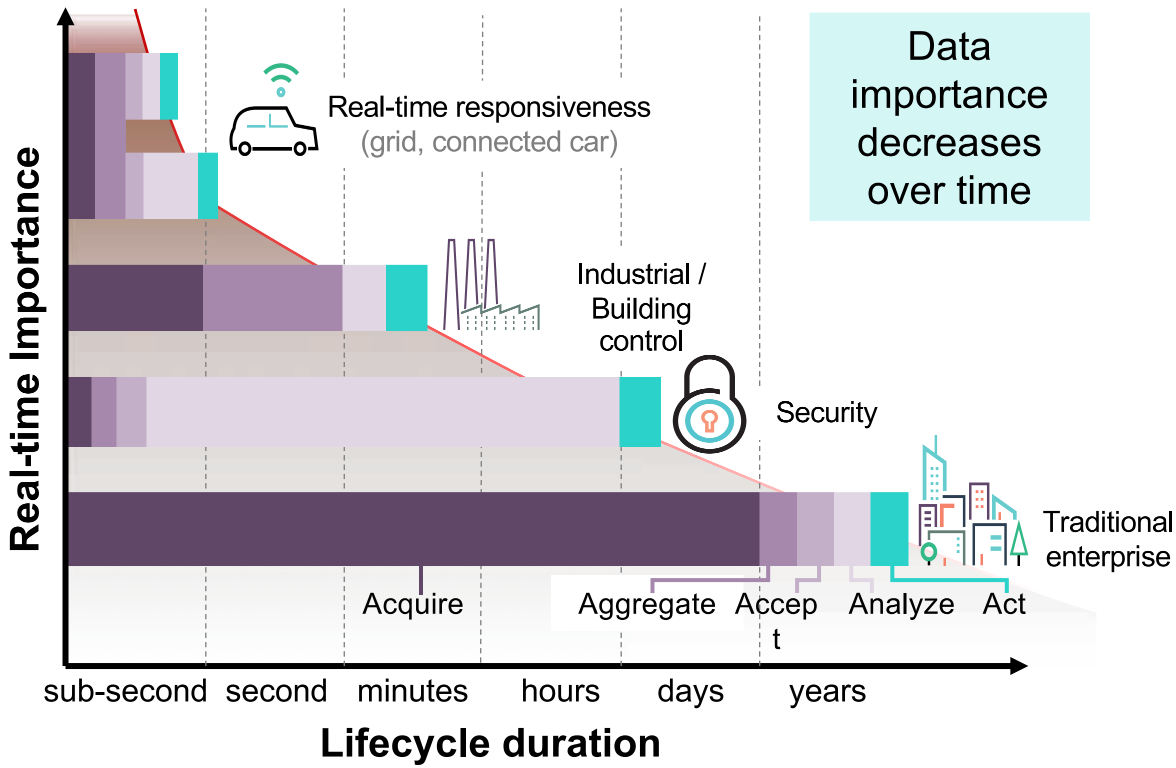
Content



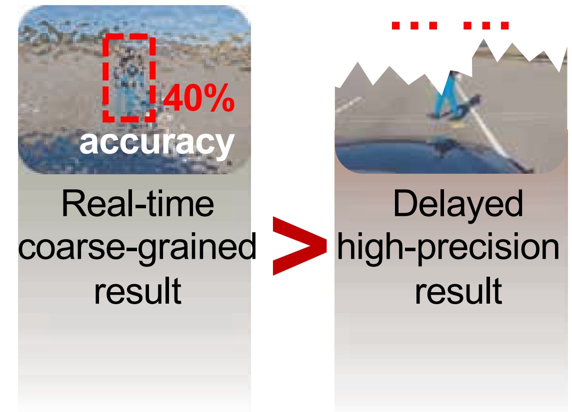
- Motivation and Background
- Nonvolatile Processor Architecture Exploration
  - Node Level Optimization - from normally-off to frequently-intermittent-on
- Dynamic Intelligent Frequency and Resource Allocation
  - Node Level Optimization for efficiency
- Incidental Approximate Computing
  - QoS Level Optimization
- NEOFog: Nonvolatility-Exploiting Optimization in Fog Computing
  - System Level Optimization - How nonvolatility changes the system
- Conclusion

Quality of Service in IoT Nonvolatile Processors

Best Forward Progress = Best Quality of Service ?



❖ Source: Hewlett Packard Enterprise



Quality metrics of NVP

Forward Progress

+

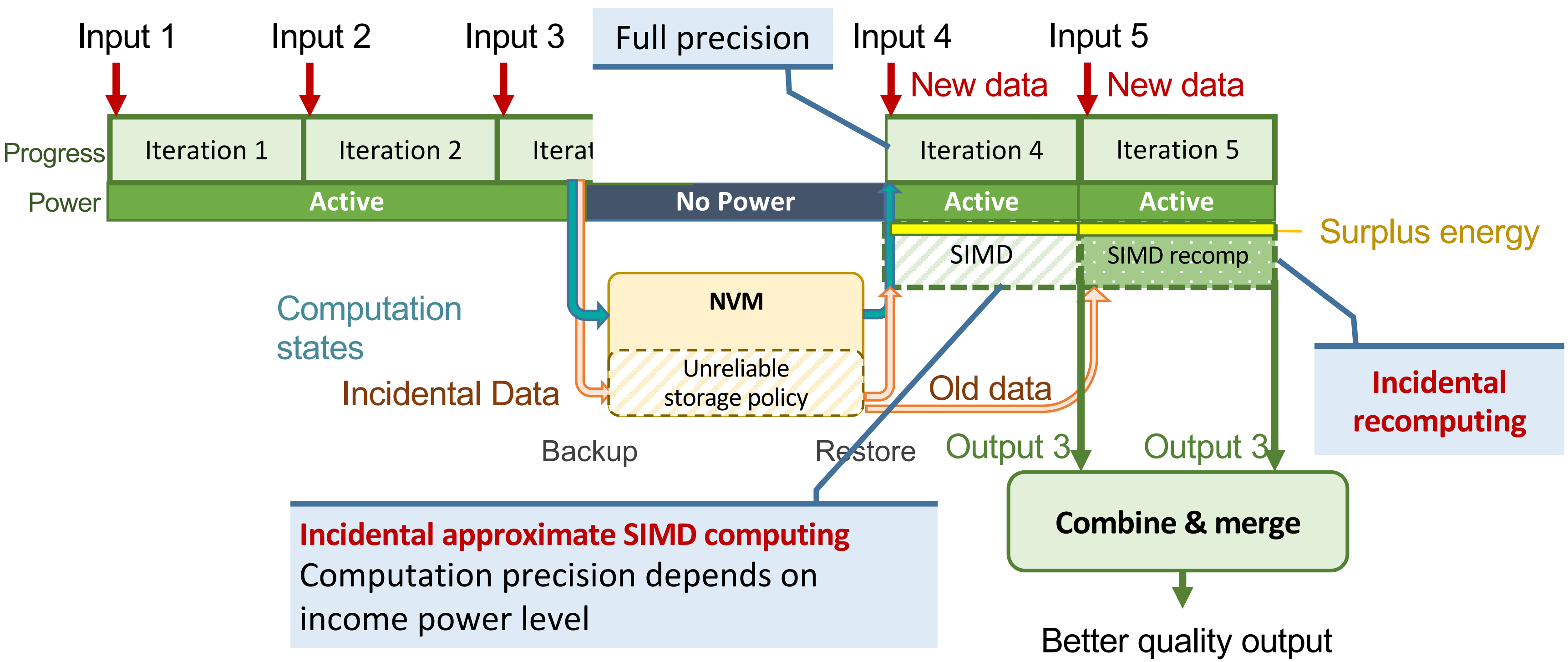
QoS

(response time)

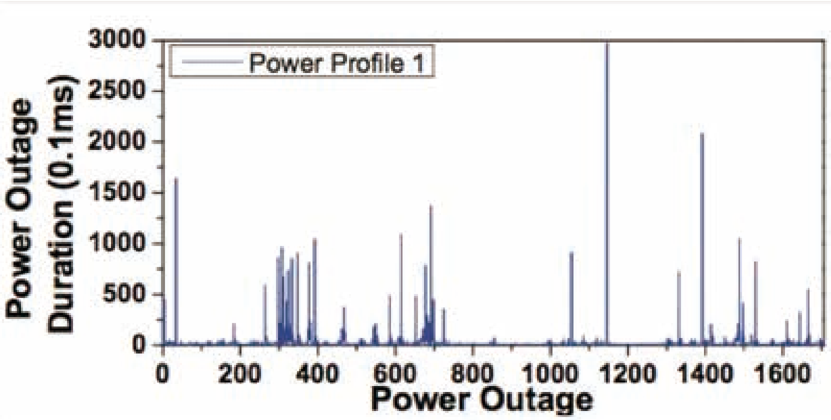
Incidental Approximate Computing Concept

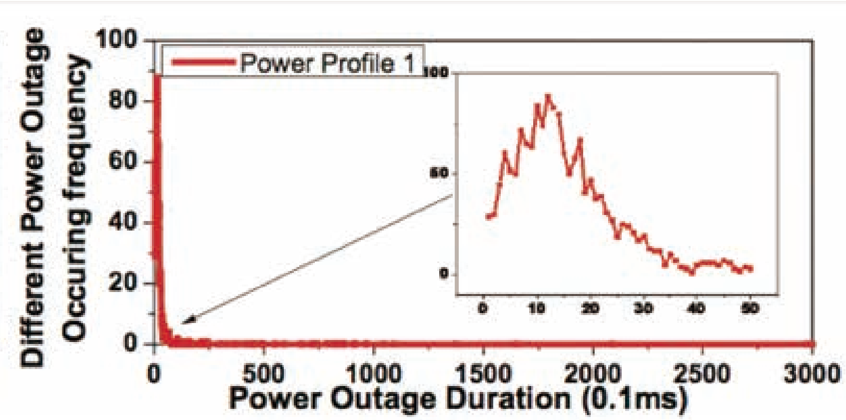
Incidental computing, wherein older computation is carried out in a best-effort fashion during the execution of newer computations.

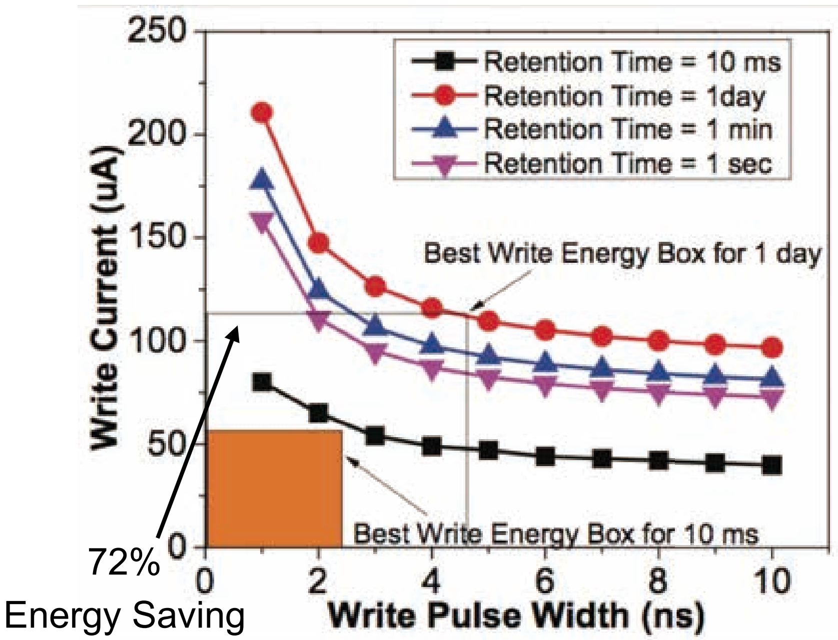
Roll-forward Instead of Roll-back **Recompute and Combine (RAC)**

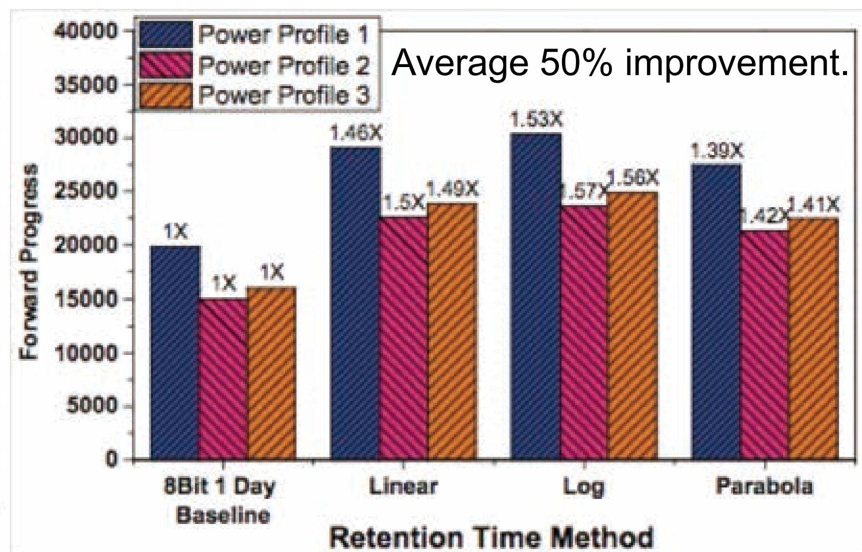


Incidental Approximate Backup - 50% more FP benefit



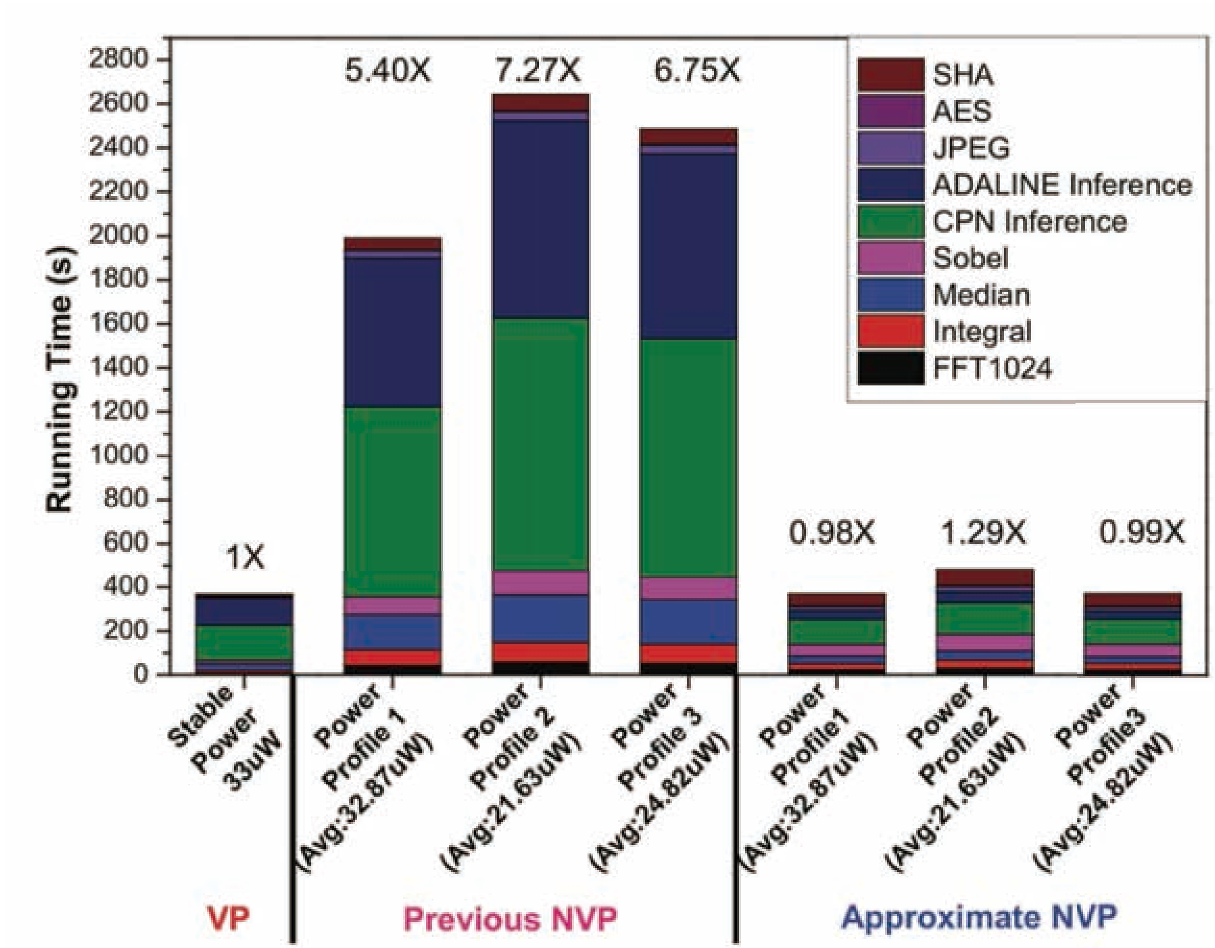






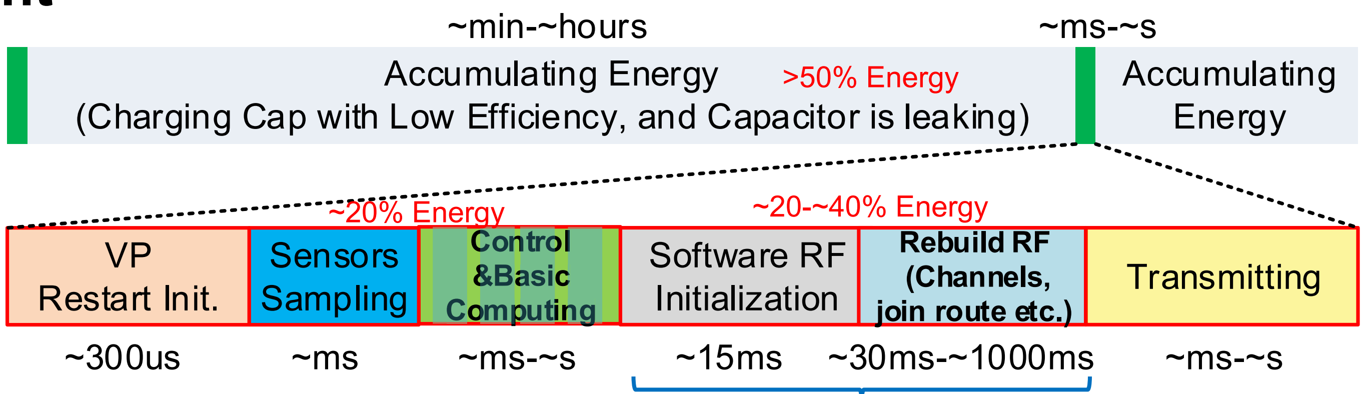
❖Source: Ma et al. MICRO 2017, Ma et al. NVMTS 2015

Incidental Approximate Computing Results



Approximate NVPs are able to buy back much of what was lost due to power instability with approximation efficiency.

Content



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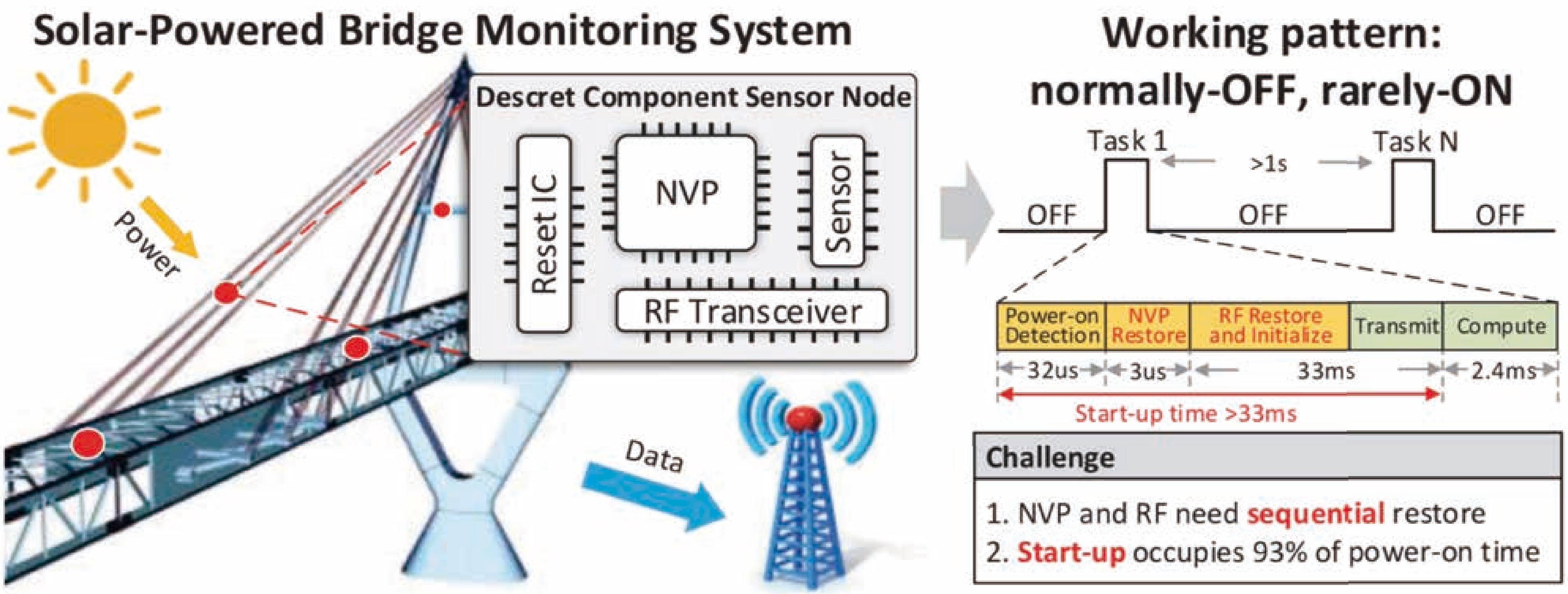
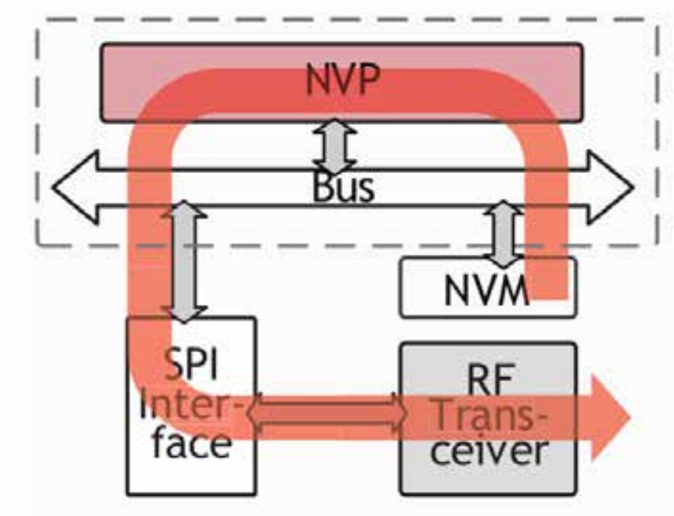
NEOFog - Background of NVRF



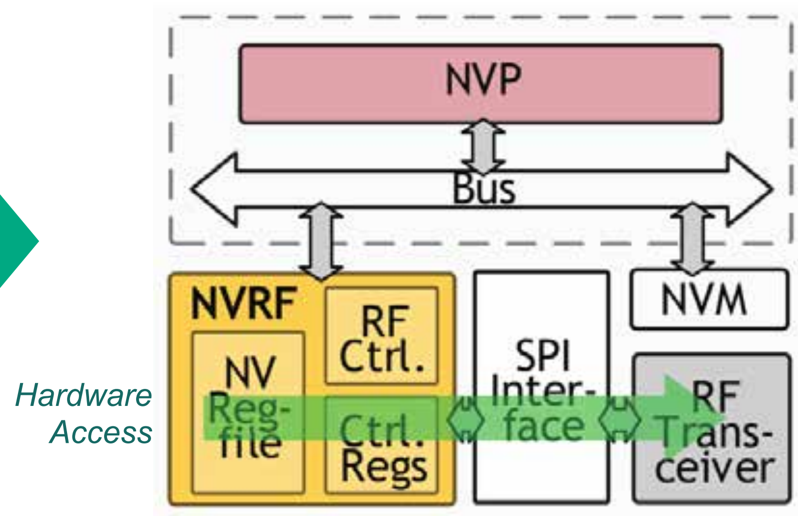
Nonvolatile Radio Frequency Controllers (NVRF)

Software RF based Architecture

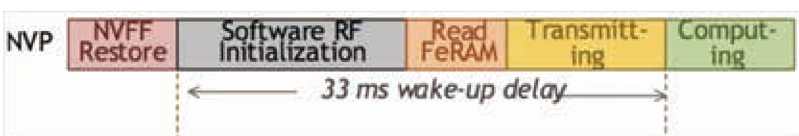


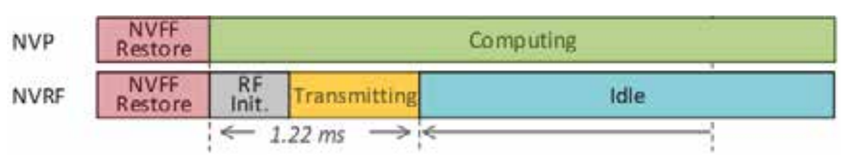
Long and Slow Data Path

NVRF based Architecture



Direct and Fast RF Configuration



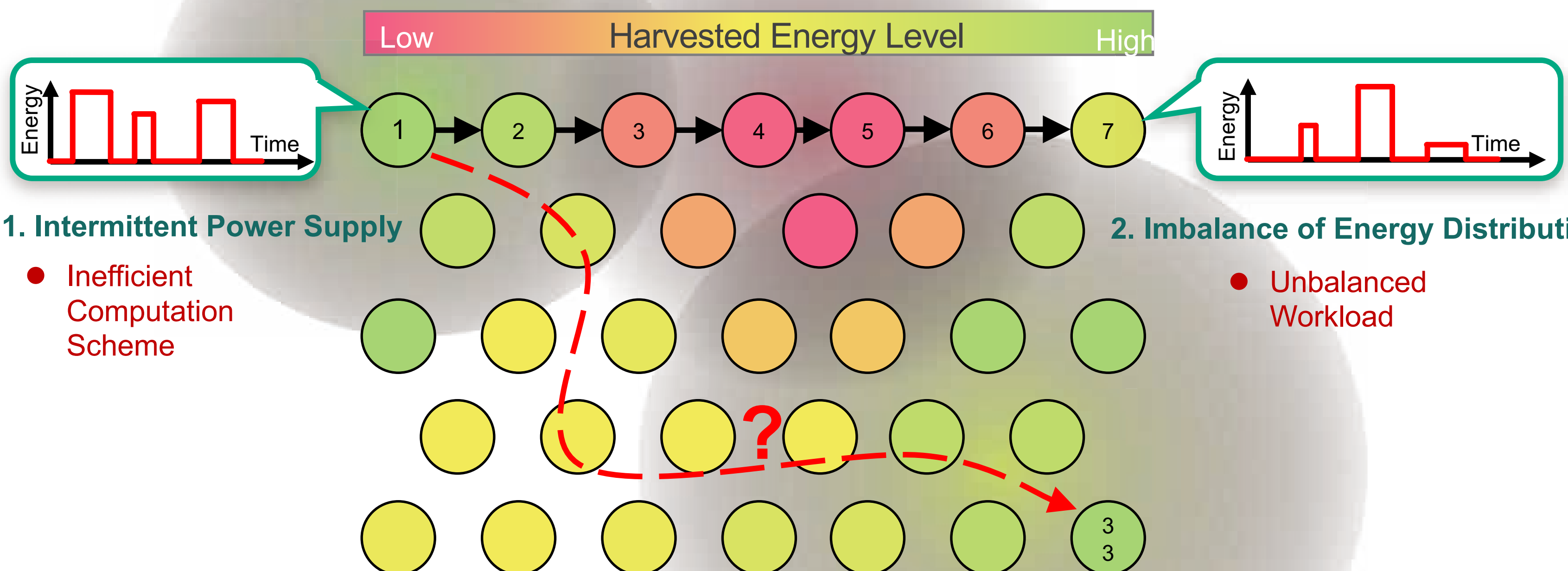


27x faster NVRF wakeup

❖ Source: Wang et al. Symp. VLSI, 2017.

Challenges and Opportunities in Energy Harvesting WSNs

Challenges of energy harvesting WSNs



1. Intermittent Power Supply

- Inefficient Computation Scheme

2. Imbalance of Energy Distribution

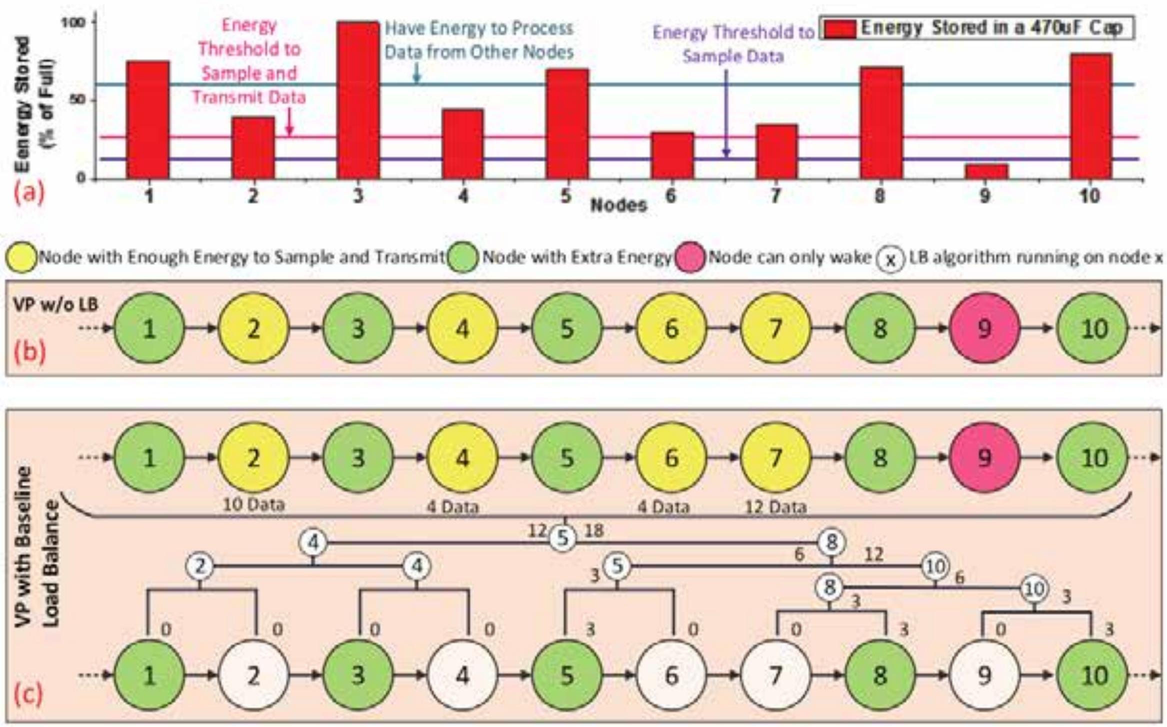
- Unbalanced Workload

3. Spatial Differentiation & Time Variation of Harvested Energy

- Unreliable Network Topology

Intra-chain Level - Load Balancing in FIOS

Traditional top-down multi-level tree load balancing algorithm



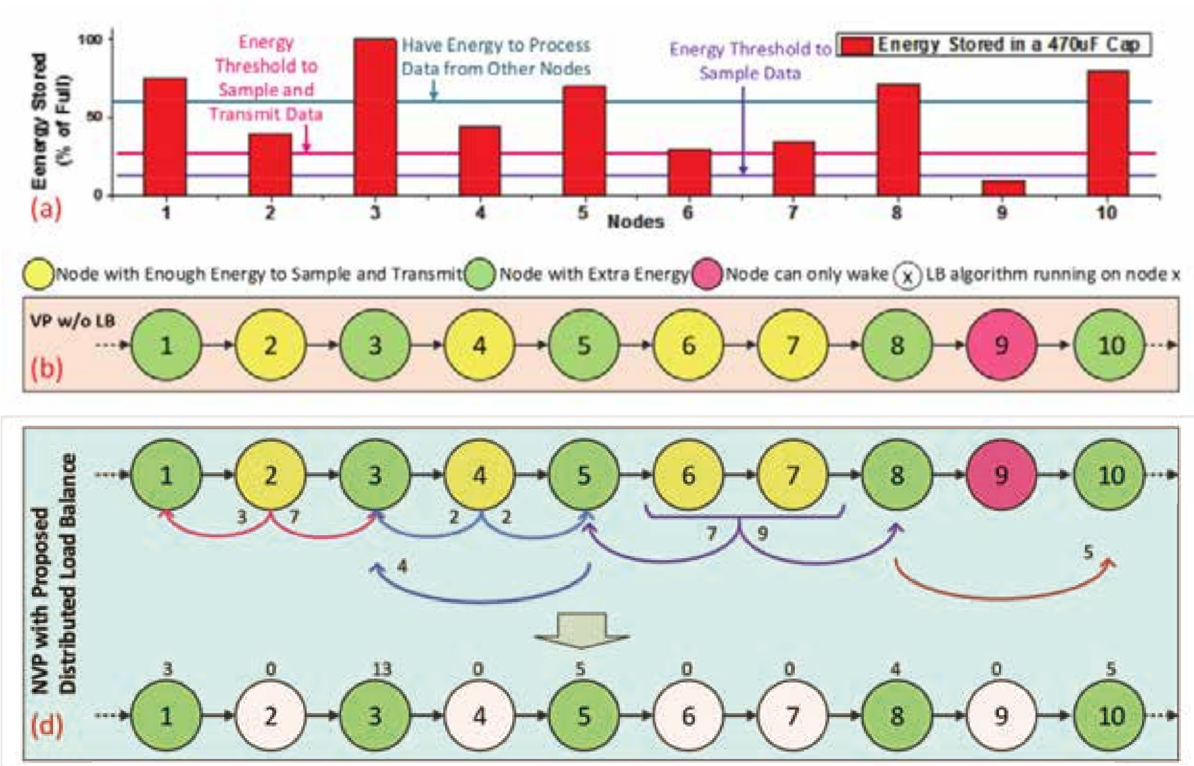
May not fully alleviate energy imbalances

Purpose:
Make the nodes that harvest ample energy do more computation than nodes with limited energy

Principle:
allocate the tasks to the most efficient rather than inefficient nodes

Intra-chain Level - Load Balancing in FIOS

Proposed Distributed load balance algorithm



Available energy &
NVP configuration
are shared with nearby nodes

INPUT:

Time cost
if n task running on the left nodes
$$\langle a_1, a_2, \ldots, a_n \rangle$$
if n task running on the right nodes
$$\langle b_1, b_2, \ldots, b_n \rangle$$

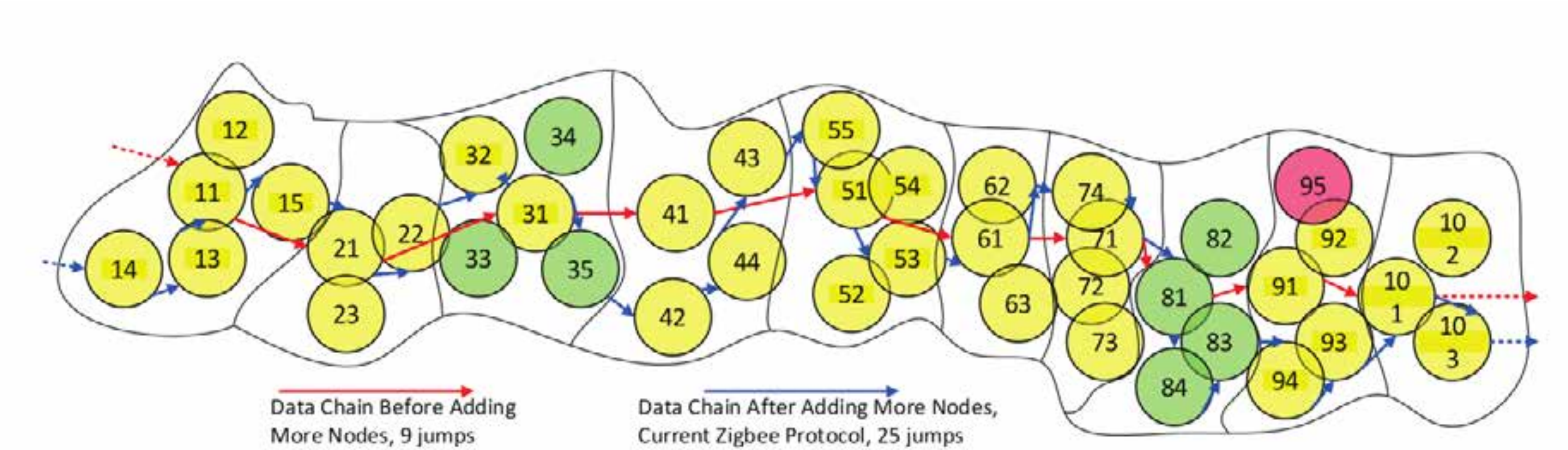
***MAXTIME*:**
load balance call interval

OUTPUT:

Assignment result
Assign task to left or right ?
$$\langle o_1, o_2, \ldots, o_n \rangle$$

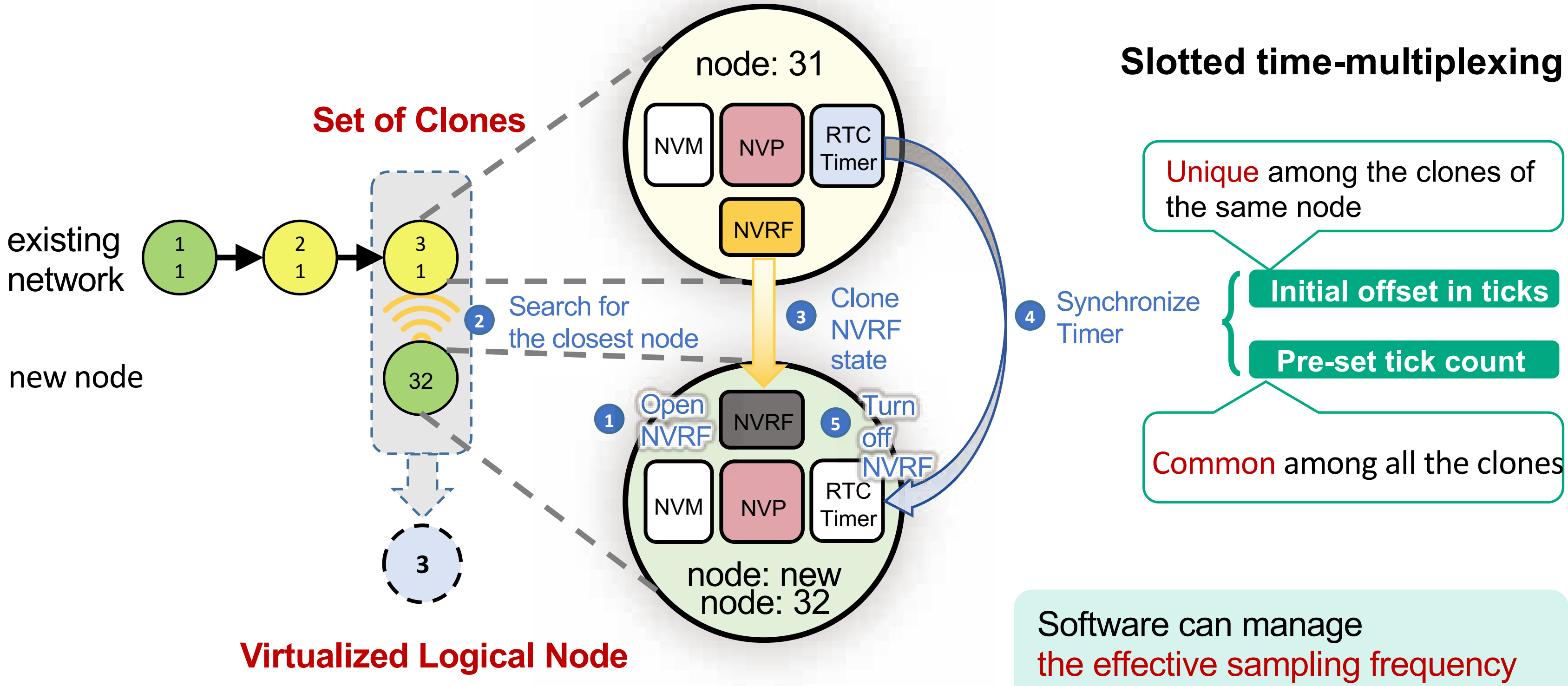
Inter-chain Level - Node Virtualization for Enhanced QoS (NVD4Q)

Naive density increase does not boost Zigbee QoS



Inter-chain Level - Node Virtualization for Enhanced QoS (NVD4Q)

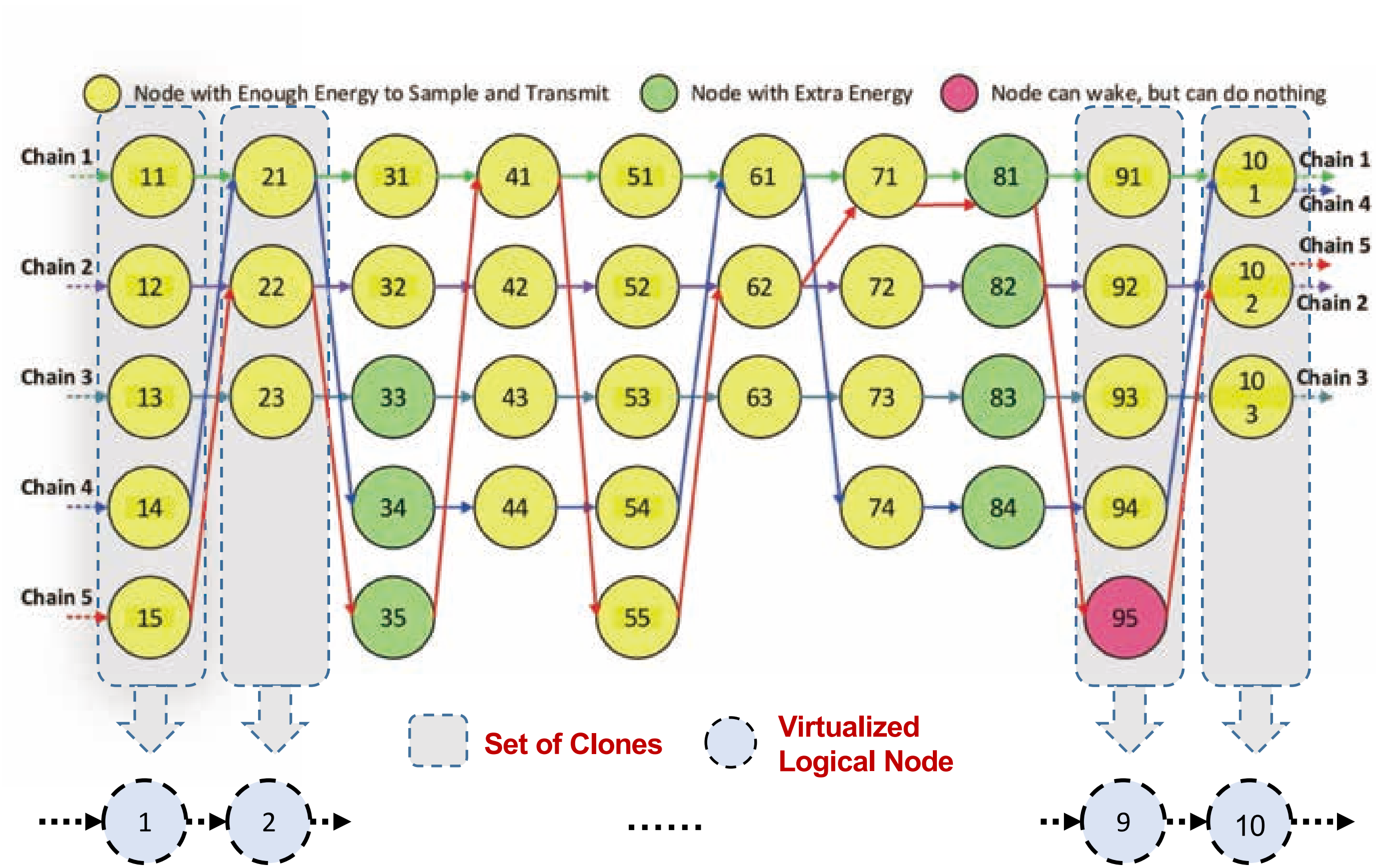
Slotted time-multiplexing node virtualization for QoS algorithm (NVD4Q)



Software can manage the effective sampling frequency of the logical node by updating these two parameters

Inter-chain Level - Node Virtualization for Enhanced QoS (NVD4Q)

NVD4Q Node virtualization for QoS expected effects



Nodes with a common phase compose one chain

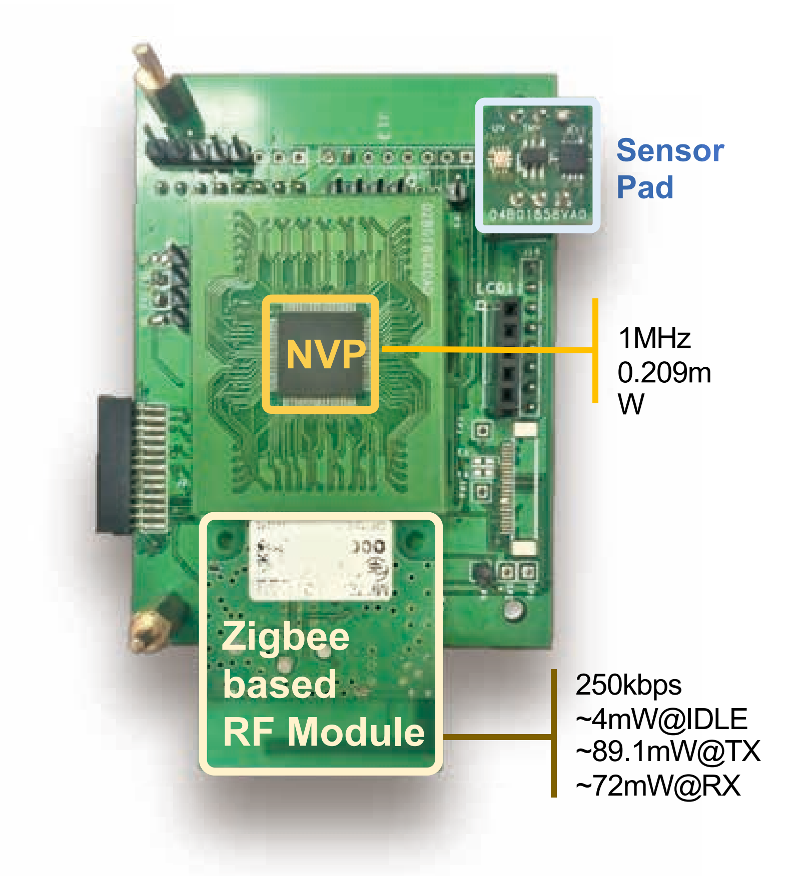
Only one chain wake up at each wake-up period

From the network's perspective, the network structure and information does not change during power off period

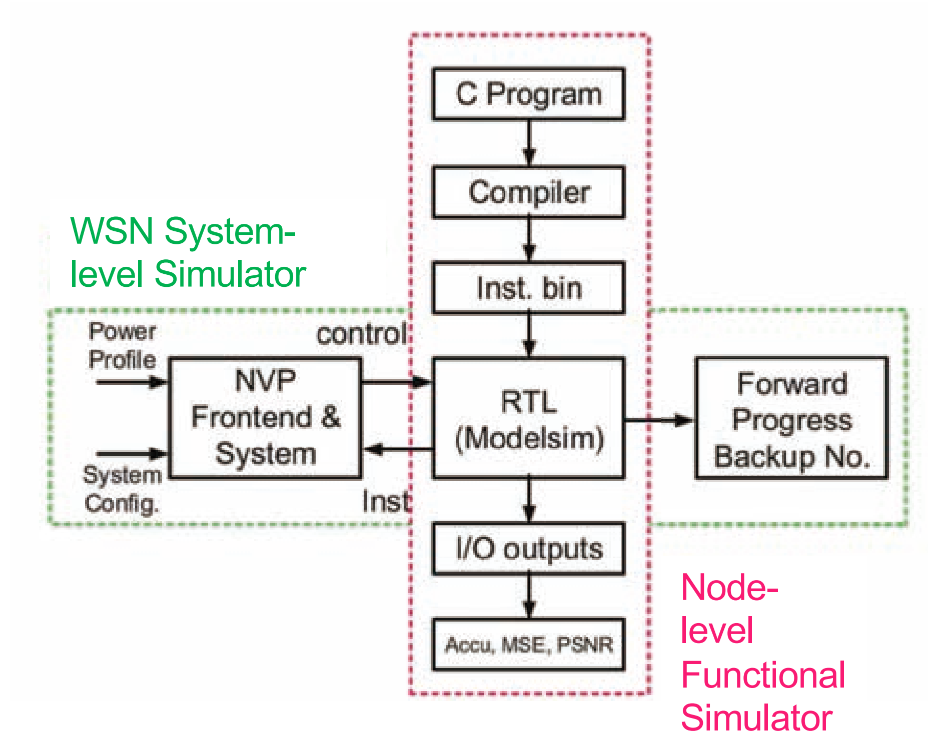
No reconstruction penalty

Simulation Methodology

NVP-based WSN prototype platform



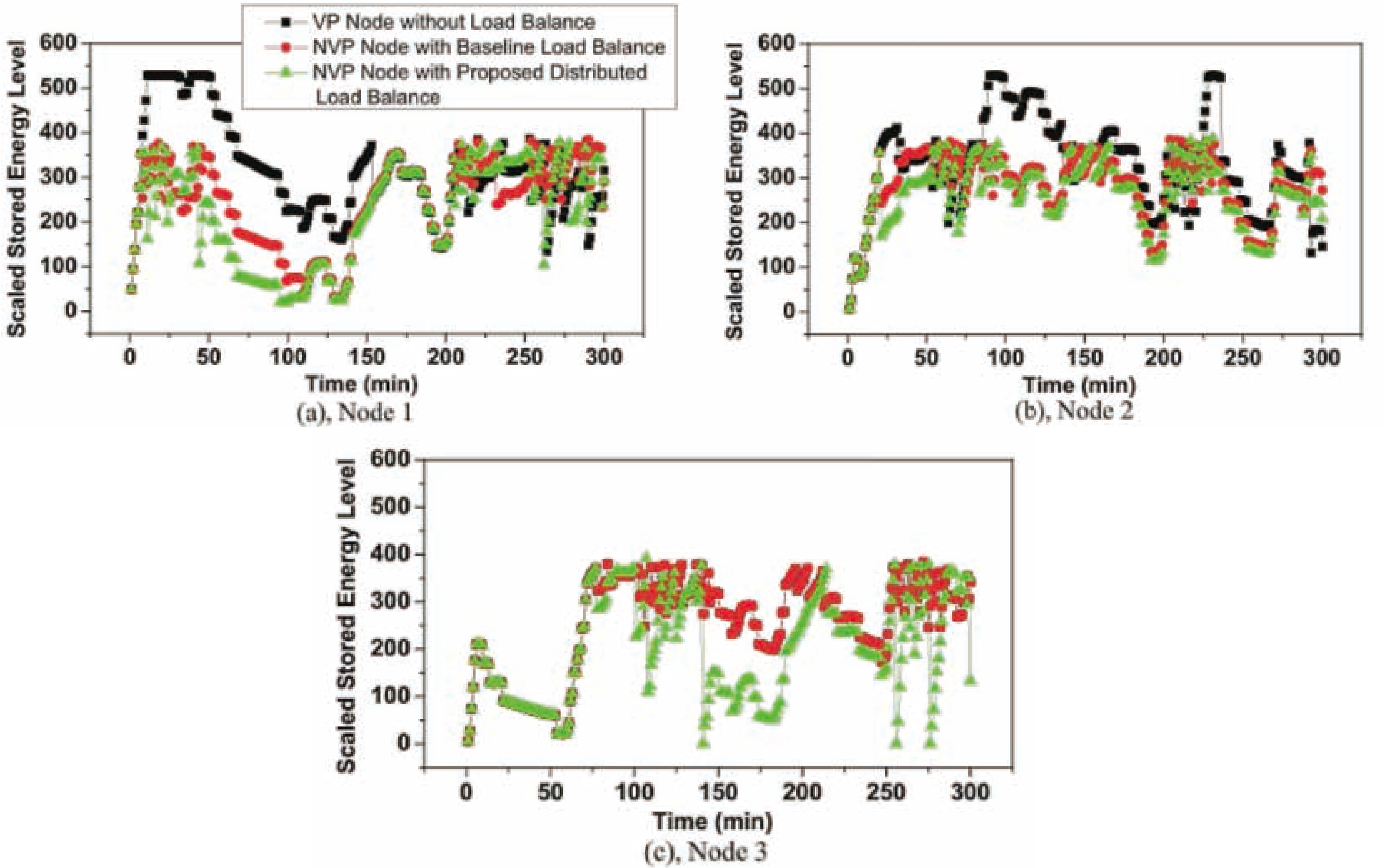
Simulation framework



❖ Boards from cooperator Prof. Yongpan Liu in Tsinghua Univ.

Performance of Distributed Load Balancing

Stored energy level of 3 consecutive nodes in a chain



(a), Node 1

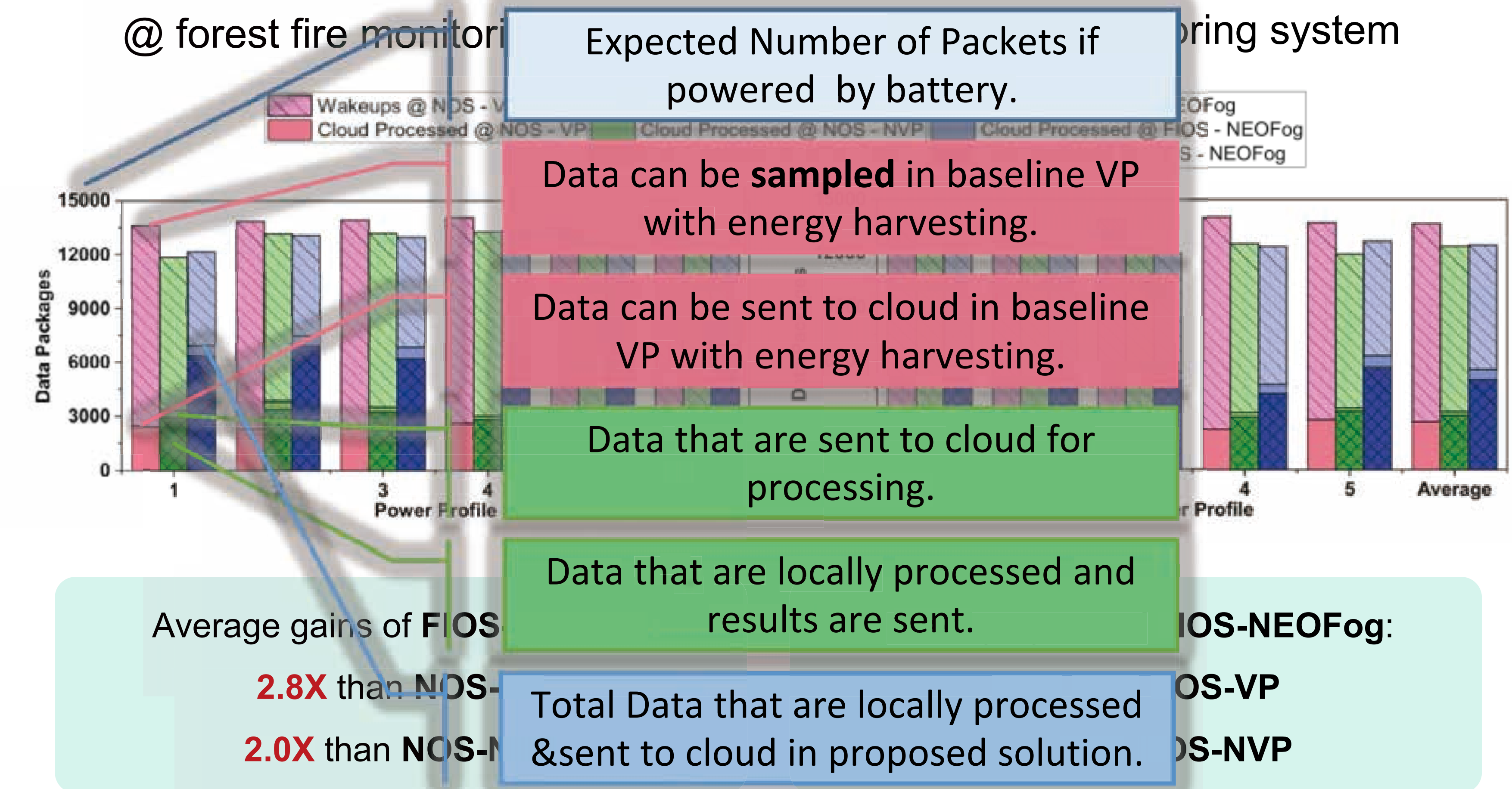
(b), Node 2

(c), Node 3

Performance of Distributed Load Balancing

Independent Power Income @ forest fire monitori[ng system]

Dependent Power Income [@ forest fire monit]oring system



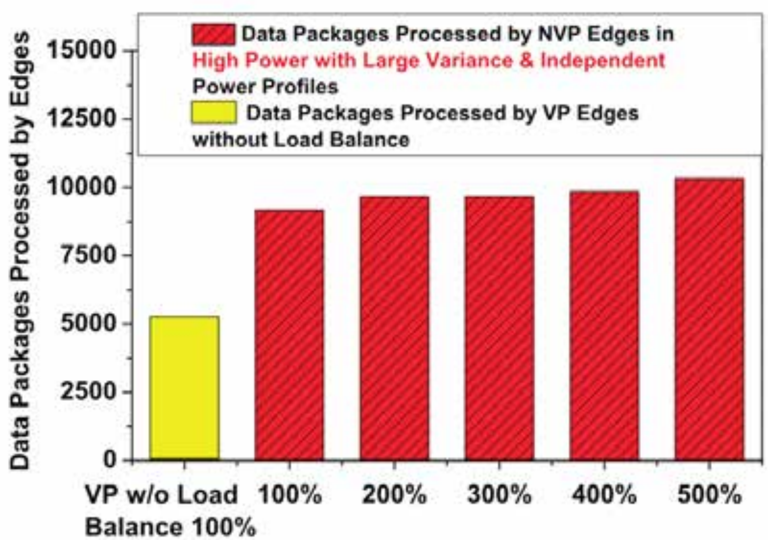
Average gains of FIOS[-NEOFog] ... [F]IOS-NEOFog:

2.8X than NOS-[VP] ... [N]OS-VP

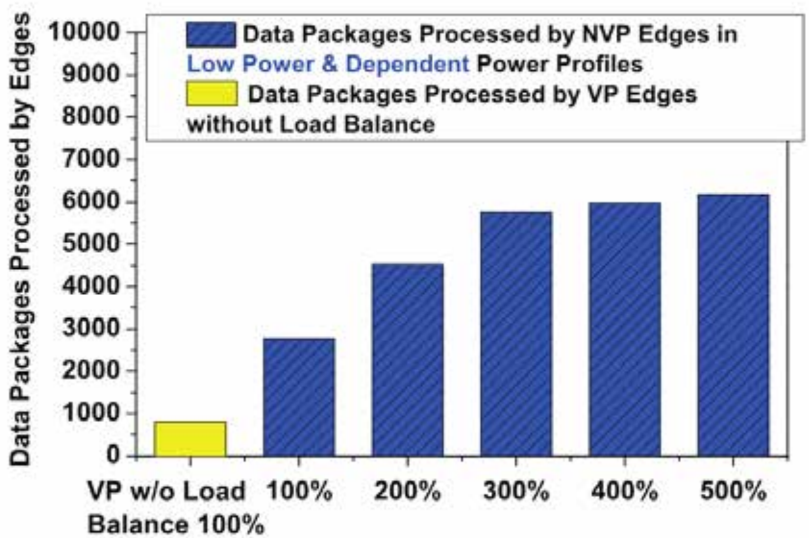
2.0X than NOS-N[VP] ... [N]OS-NVP

Performance of NVD4Q (Virtualization for QoS)

Increasing node multiplexing in
High power with large independent variance



Increasing node multiplexing in
Low power with large dependent variance

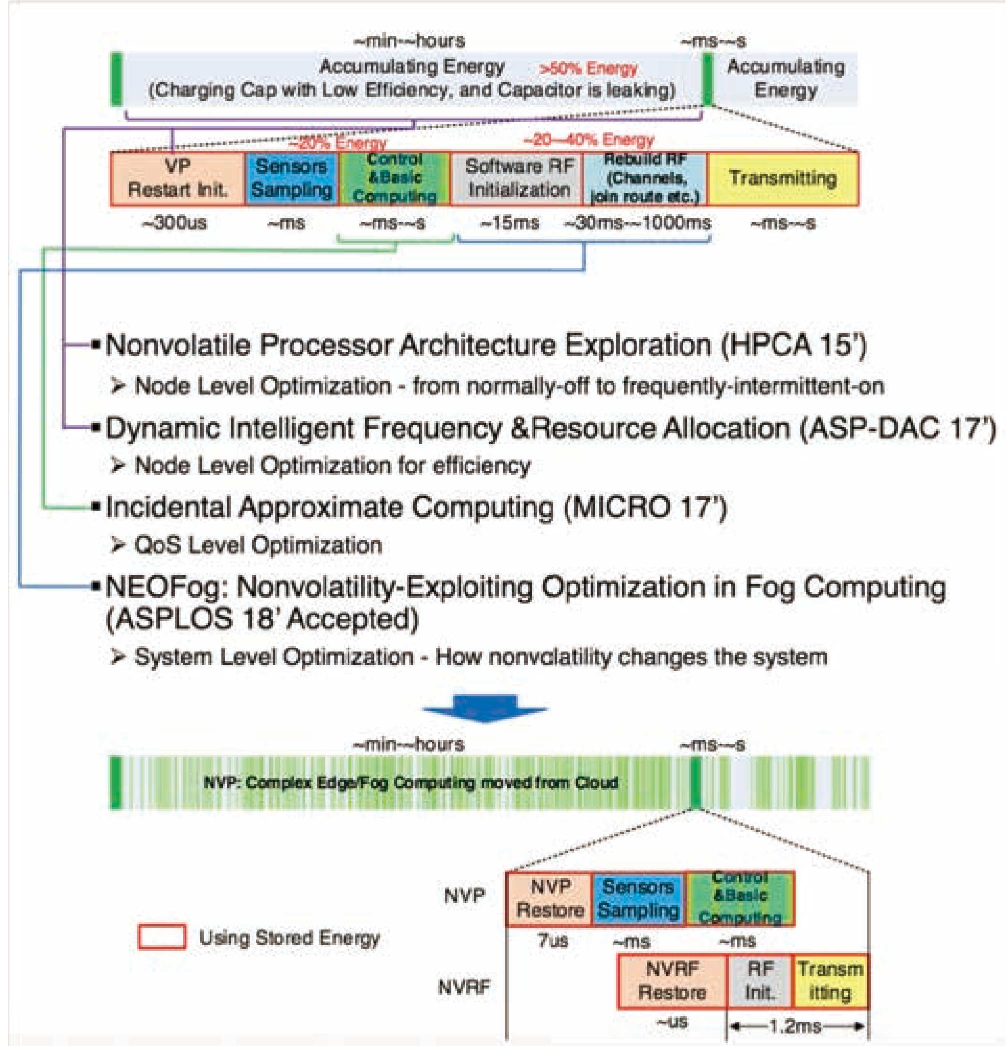


Collectively, these optimizations increase fog-offload capabilities by

4.2X at baseline deployment node count and up to **8X** at 3X multiplexing

Conclusion

- Integrating nonvolatility into nodes changes the system from normally-off to frequently-intermittent-on, improving 2.2-5X performance improvement
- With dynamic intelligent frequency and resource allocation further provides 2.1X performance boost
- Incidental Approximate Computing trades off between progress and quality and is 4.3X faster than precious NVP
- NEOFog provides System Level Optimization - 2.1X local processed data, and another 2X with 3X increase in density.
- From fog node level to system level, a holistic nonvolatile system is explored and optimized. I believe these technologies can be an enabler for energy harvesting applications. The fog computing time for IoT is coming!



Kaisheng's Timeline - This is my Ph.D.

- Graduated from PKU
- Enter MDL@PSU

- Passed Candidacy Exam
- Begin NVP Project

- Best paper award in HPCA.
- IEEE Micro Special Issue.
- Discovery of impacts on system design(TECS).

- IEEE Micro Top Picks.
- Best Graduate Research Award in CSE PSU
- Reported as Cover Feature in NSF ASSIST Research Center Newsletter

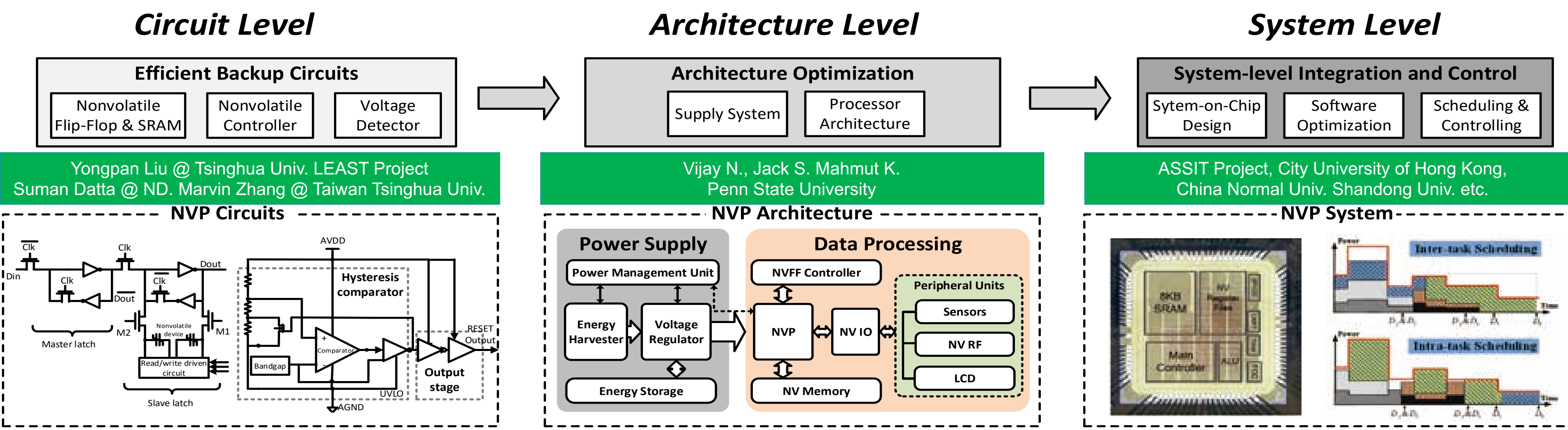
- Best Paper Award ASP-DAC.
- MICRO Published
- ASPLOS Published
- IEEE Micro Special Issue on Approximate Computing

36 Publications(18 first author）, 6 Patents

377 Citations until March, 2018

❖ In all the bulleted item, Kaisheng is the first author, and leads the work.

A Holistic Exploring Approach - Thanks All the Collaborators



❖Source: Liu et al. DAC 2016

Thanks !

Q&A

“People Judge you not from your where you are from,
but from what you do, and how well you are doing it” – Vijay. N., 2015