IOWA STATE UNIVERSITY

HARC: A Heterogeneous Array of Redundant Persistent Clocks for Batteryless, Intermittently-Powered Systems

Vishal Deep, Vishak Narayanan, Mathew Wymore, Daji Qiao and Henry Duwe

Introduction

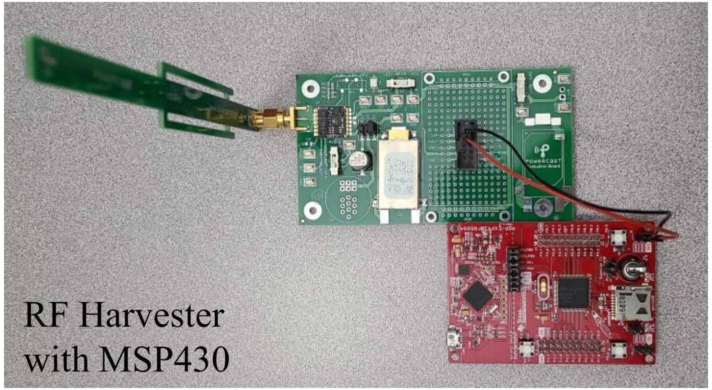
- Growing number of IoT devices
- Why consider Batteryless ?
- Expensive ⇨ Inexpensive capacitor
- Limited lifetime ⇨ Longer lifetime
- Need maintenance ⇨ Maintenance free
- Not environment friendly ⇨ Environment friendly

Batteryless devices have significant benefits for IoT

RF energy harvesting batteryless, intermittent devices

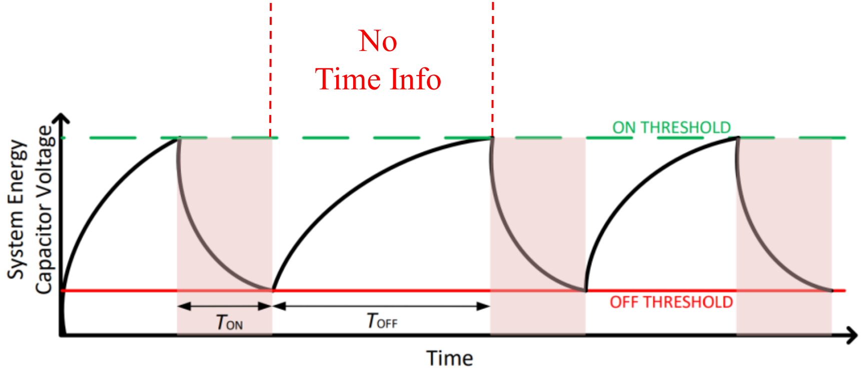
- We consider RF energy harvesting batteryless, intermittent devices

RF Transmitter

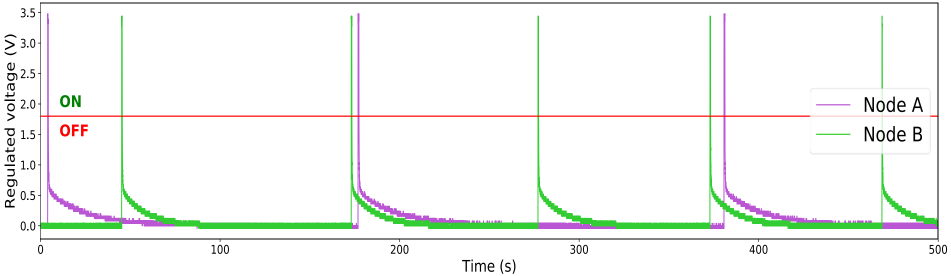


Intermittent Computing

- Why Intermittent?
  - Harvested power < Consumed power
- Little/No control when the device is on
- No power off-time (T_{OFF}) info
- Need time information for
  - Communication, timestamping data, check for staleness etc.
- Demonstration use-case: Communication

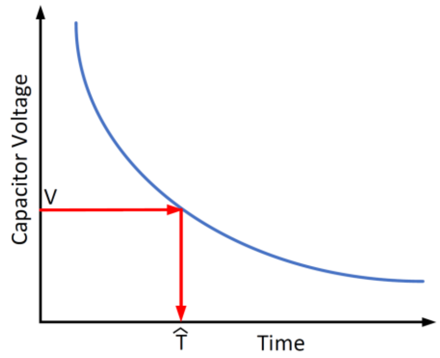


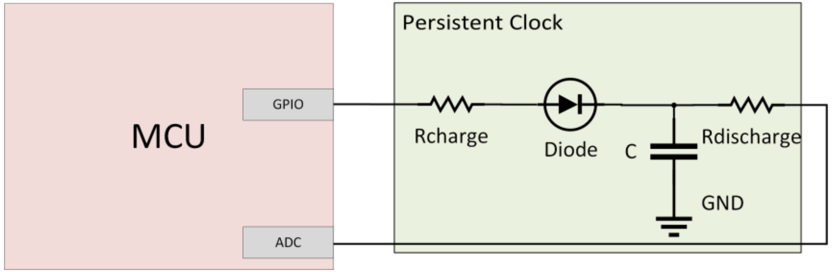
Off-time info is needed



Persistent Clock

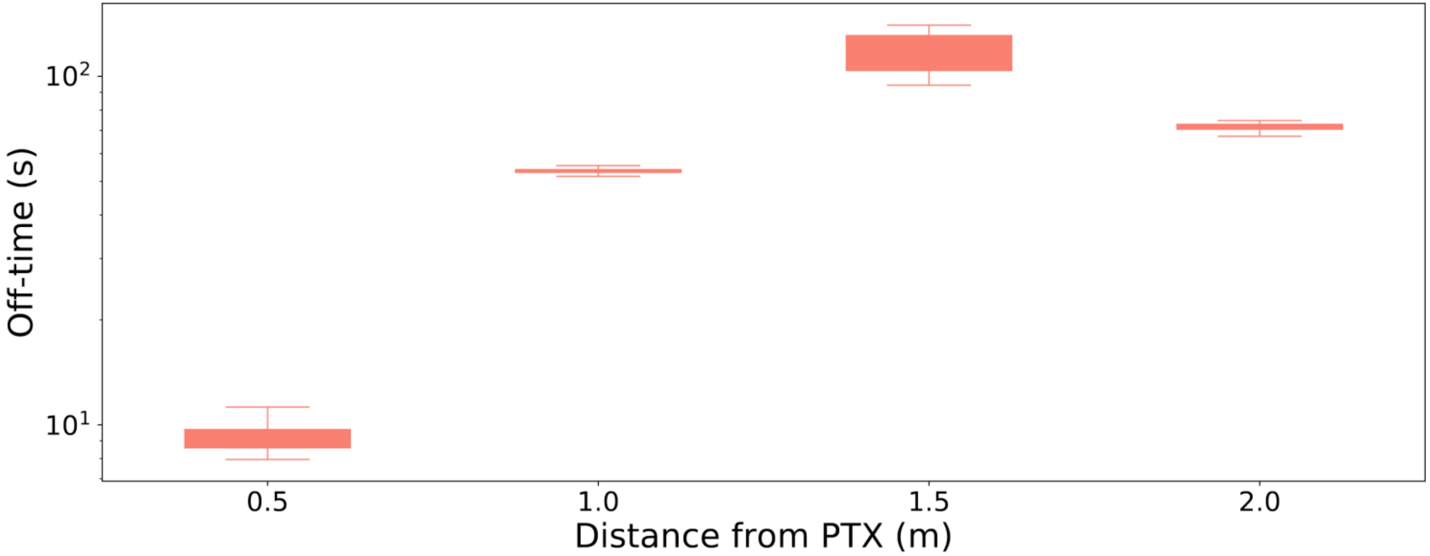
- Known decay of charge on capacitance -> estimate power-off time
- MCU charges the capacitor(C) with a GPIO
- ADC reads capacitor voltage





Persistent clocks can be used for time keeping during power-off period

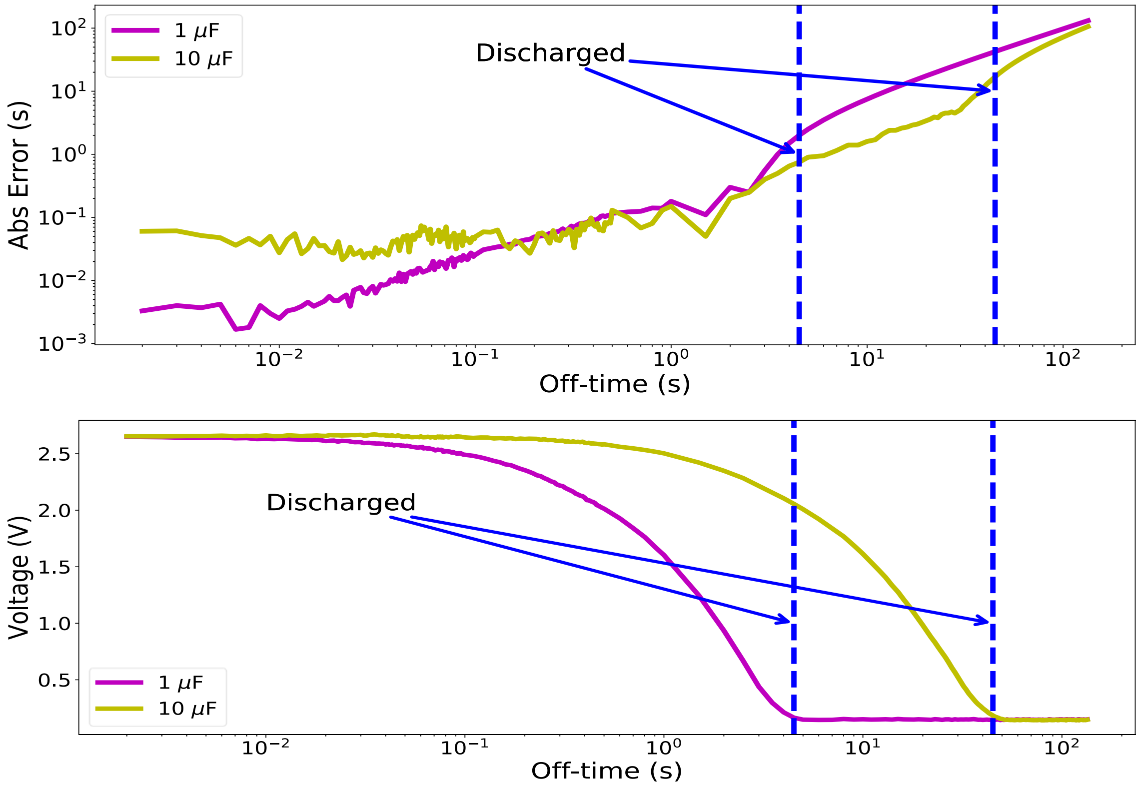
Observation #1



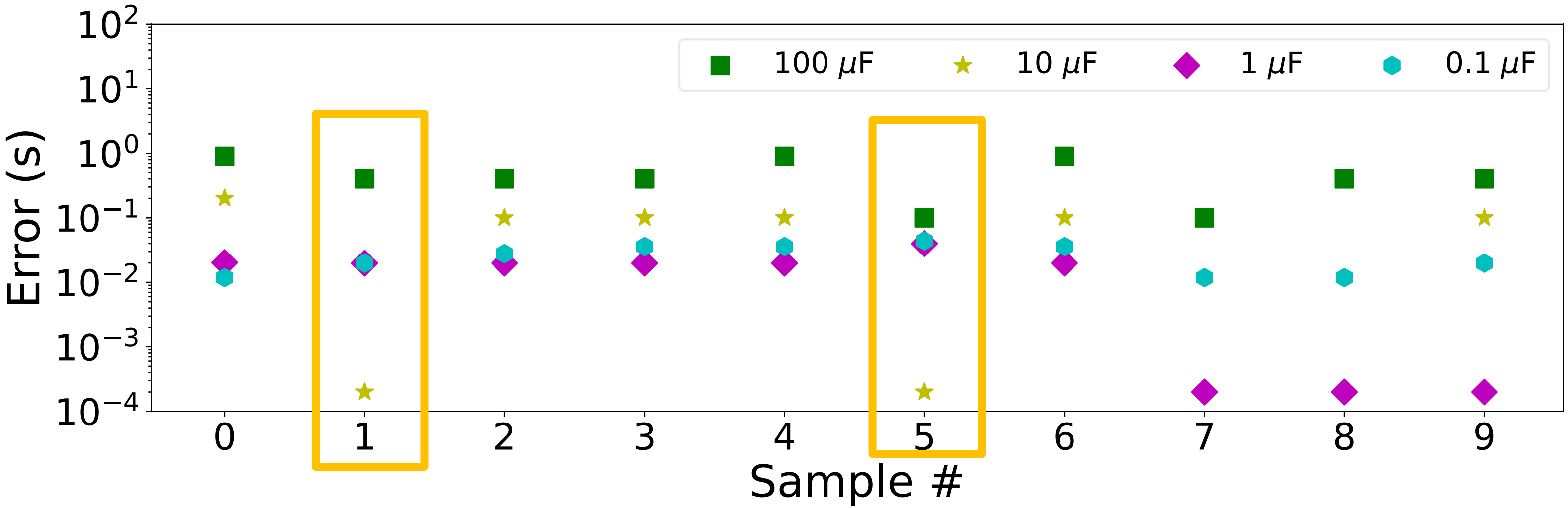
Off-time varies significantly with distance and relative reflection, diffraction, interference, and scattering

Observation #2

Precision is inversely proportional to max measurable off-time

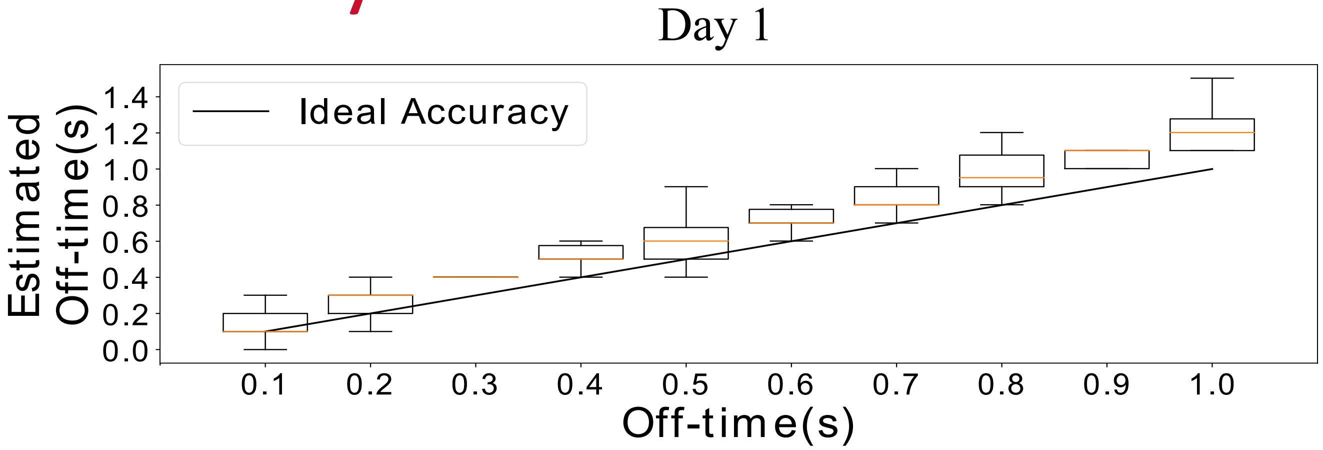


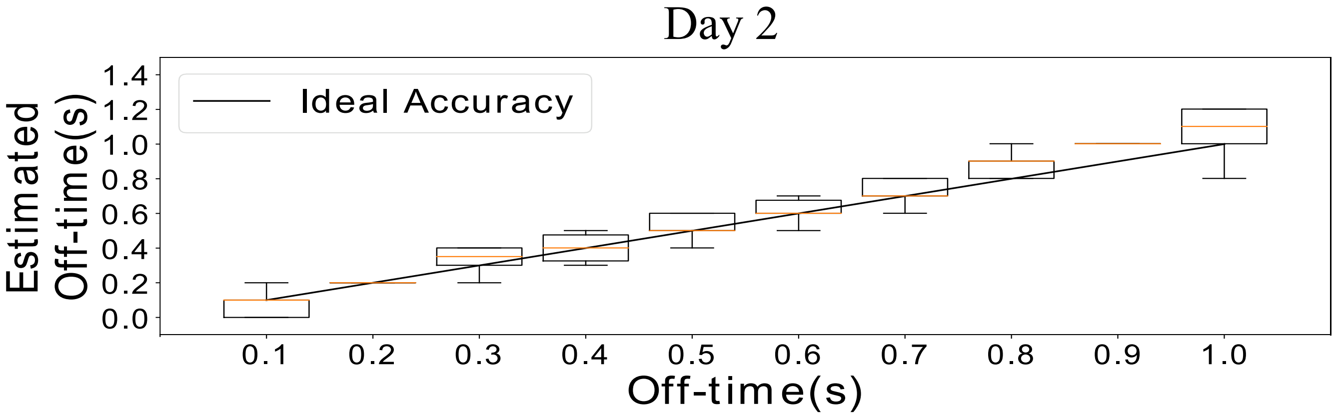
Observation #3a – Local Variations



Large variations across samples within a single persistent clock, although other clocks retain time info

Observation #3b – Systemic Variations





Variations can also happen on systemic level.

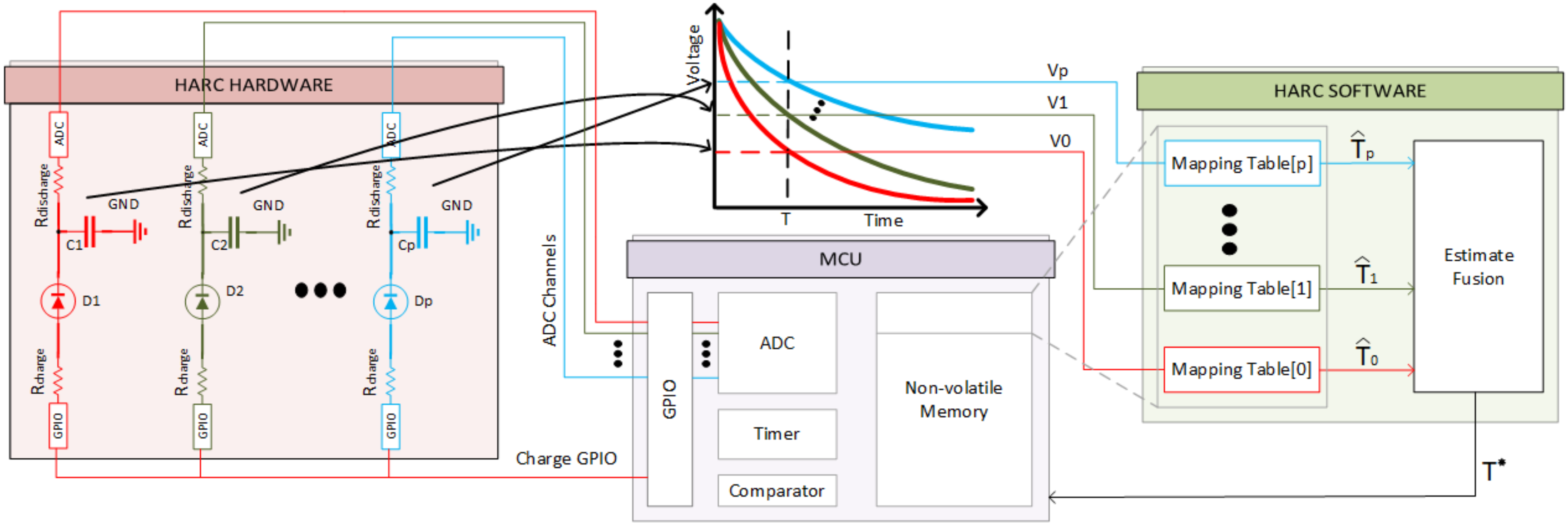
Goal of the work

- Increase the accuracy and reliability of **persistent clocks** over wide range of off-time
- Resilience to local and systemic variation
- Leverage the energy accuracy trade-off

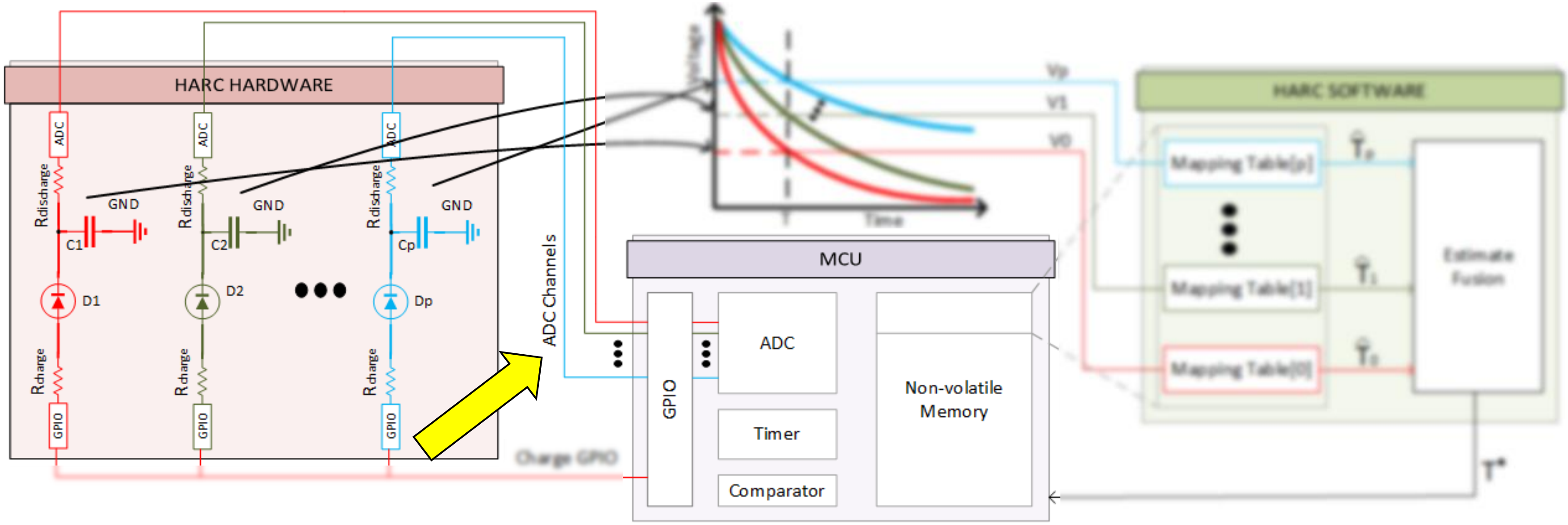
Insights

- Insight #1: A persistent clock must be able to provide accurate timing information across a wide range of off-times.
- Insight #2: Multiple persistent clocks with heterogeneous decay rates must be used in parallel.
- Insight #3: Multiple redundant and heterogenous clocks need to be used.

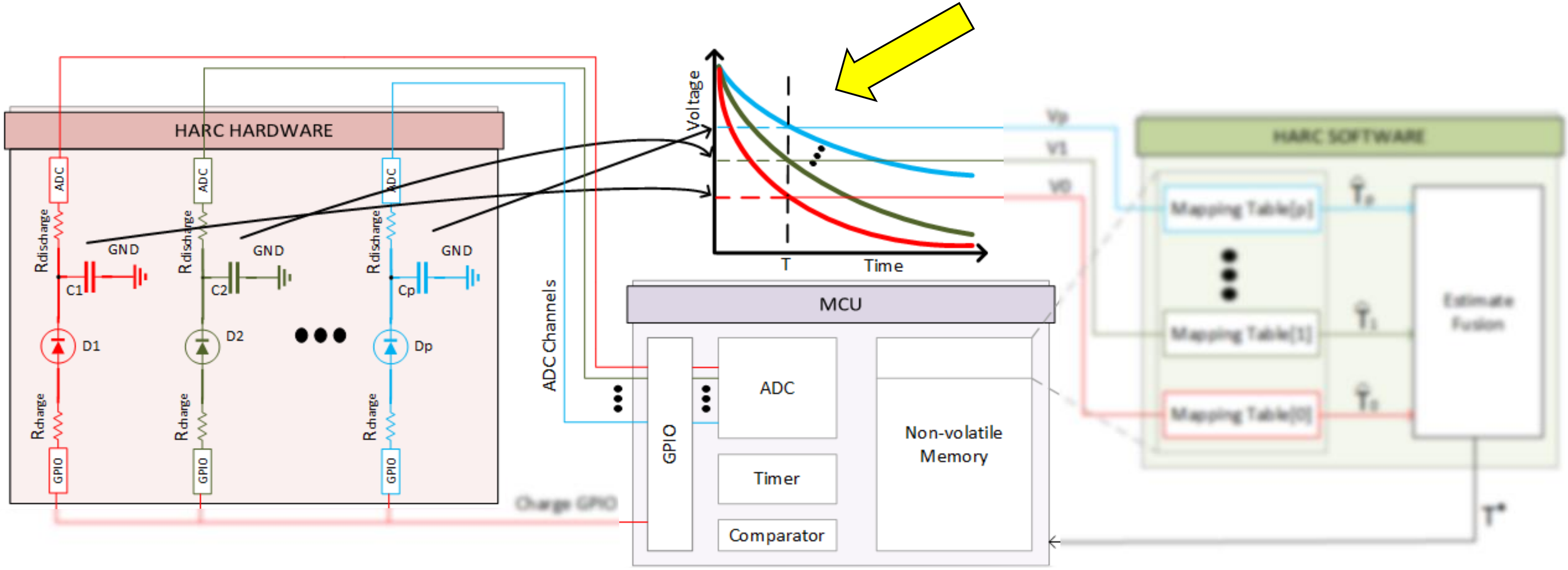
HARC: Heterogeneous Array of Redundant Persistent Clocks



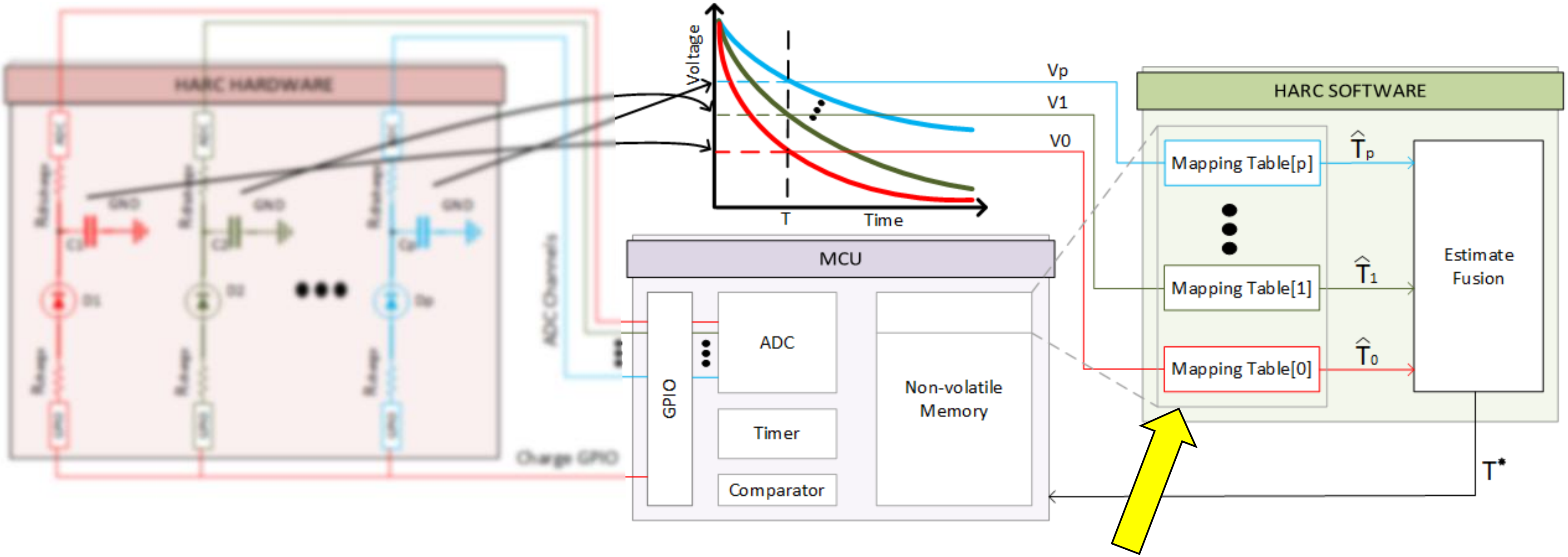
HARC: Heterogeneous Array of Redundant Persistent Clocks



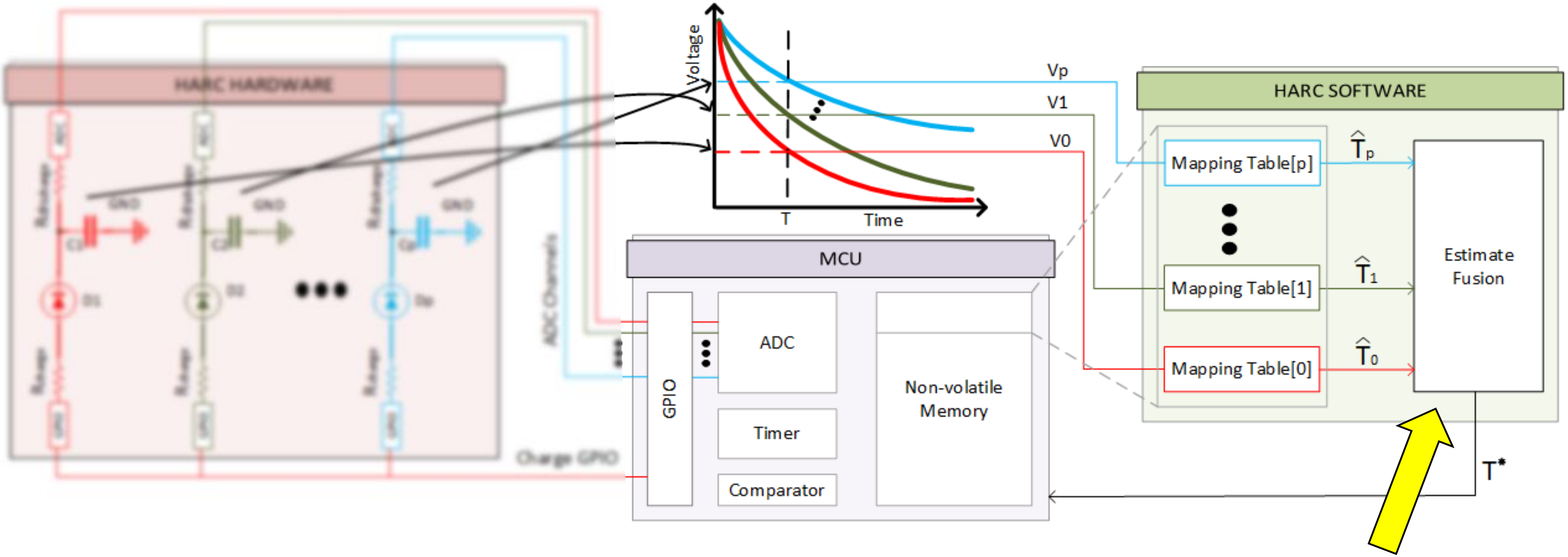
HARC: Heterogeneous Array of Redundant Persistent Clocks



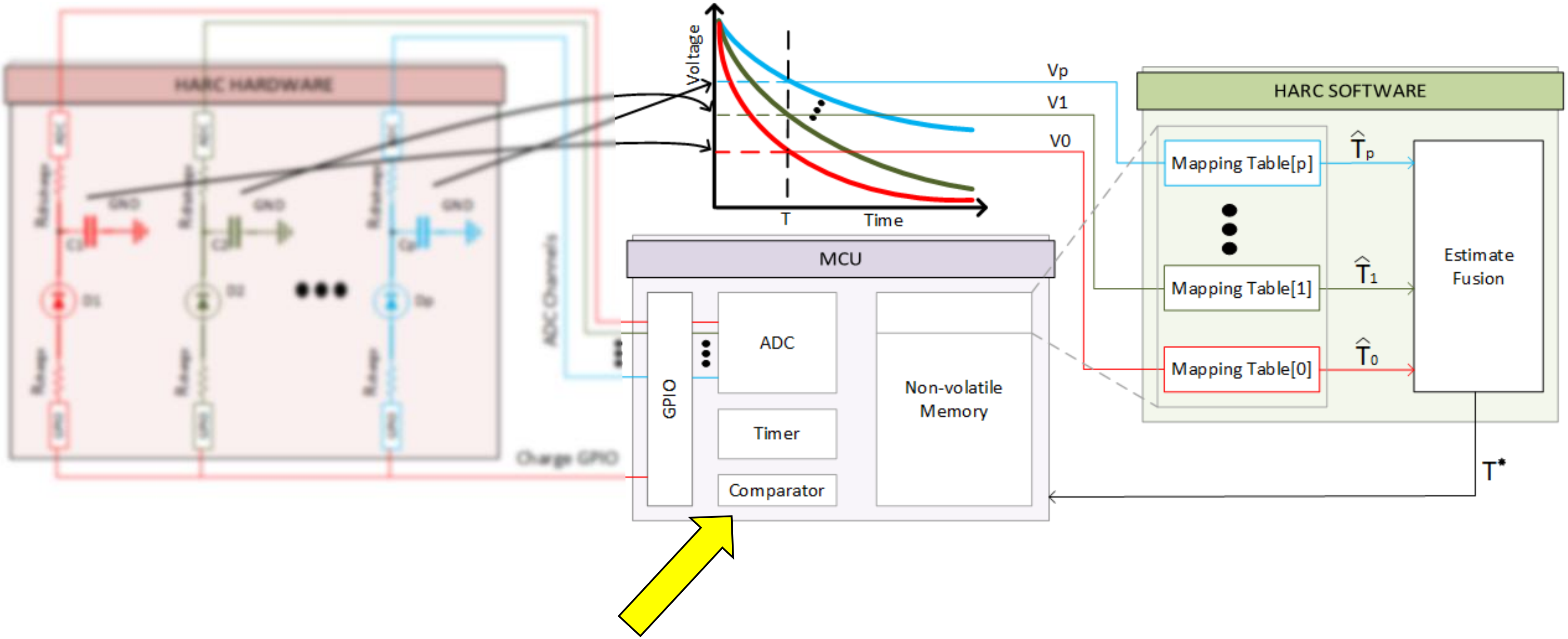
HARC: Heterogeneous Array of Redundant Persistent Clocks



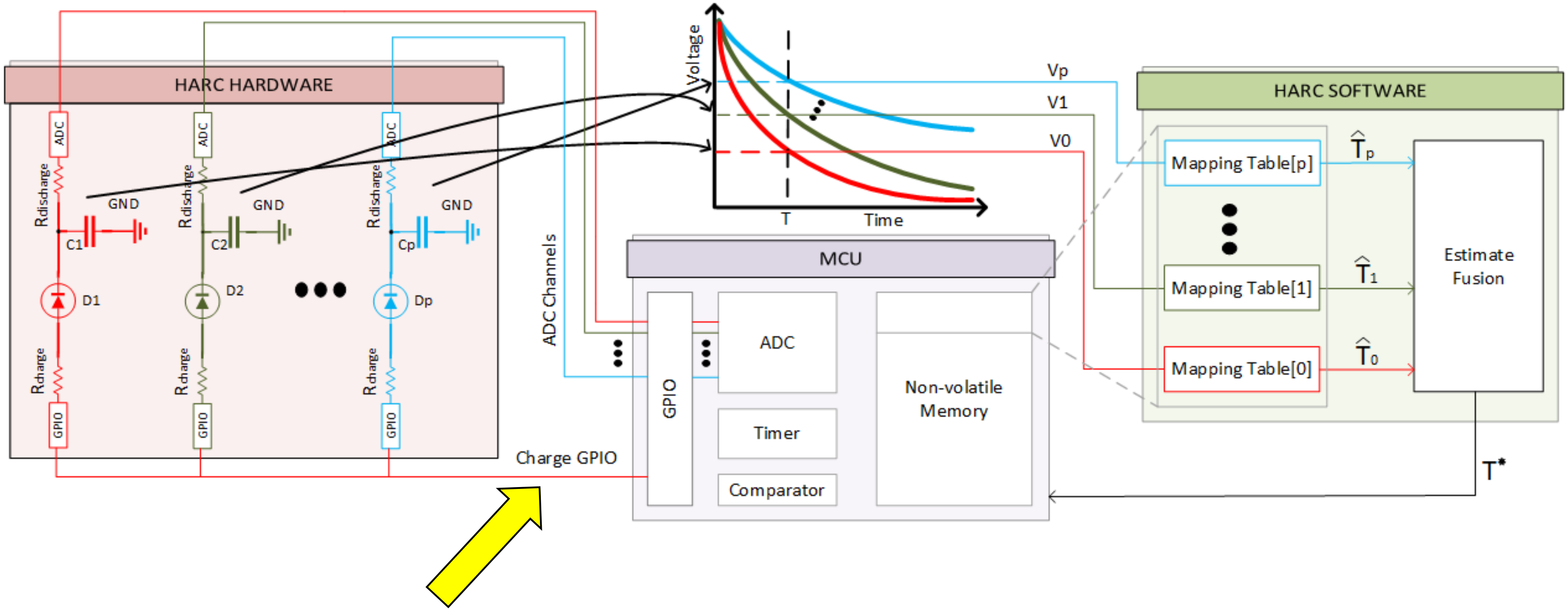
HARC: Heterogeneous Array of Redundant Persistent Clocks



HARC: Heterogeneous Array of Redundant Persistent Clocks

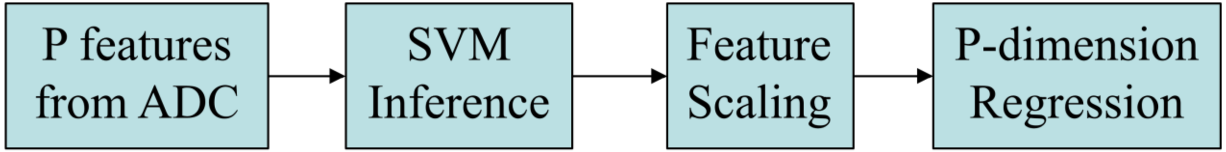


HARC: Heterogeneous Array of Redundant Persistent Clocks



HARC SOFTWARE – Estimate Fusion

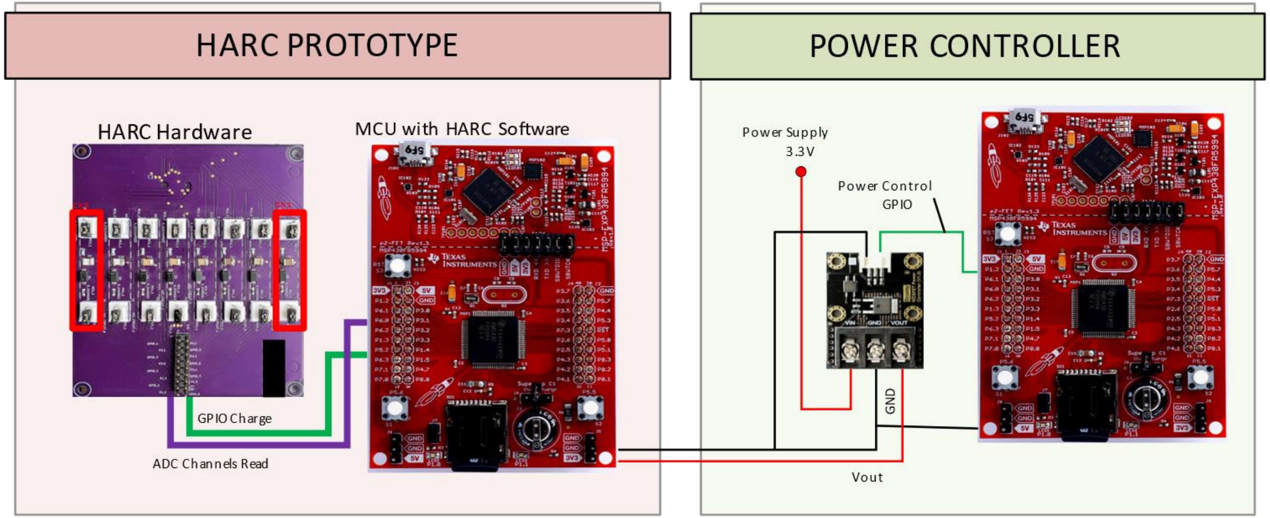
- HARC-naïve
  - Takes average of time estimates
- HARC-reg



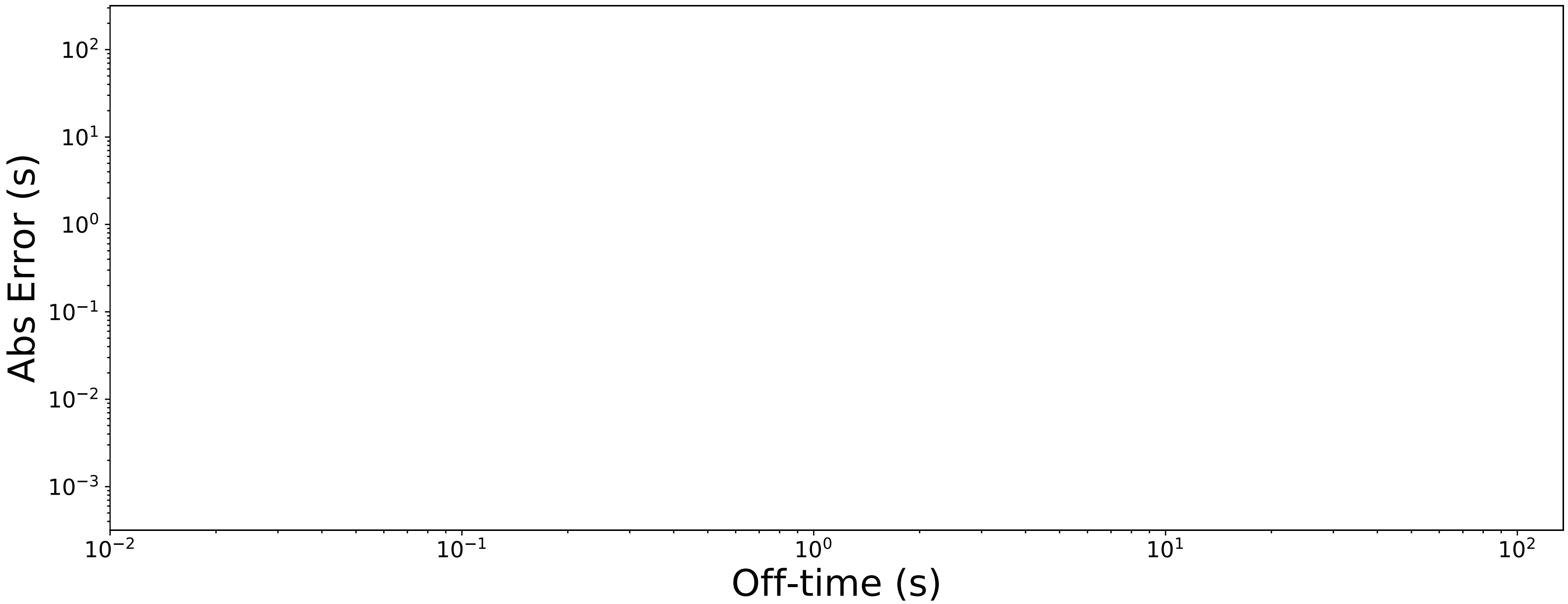
  - Lasso regression technique
- HARC-lite
  - Selects a clock based on the slope

Evaluation

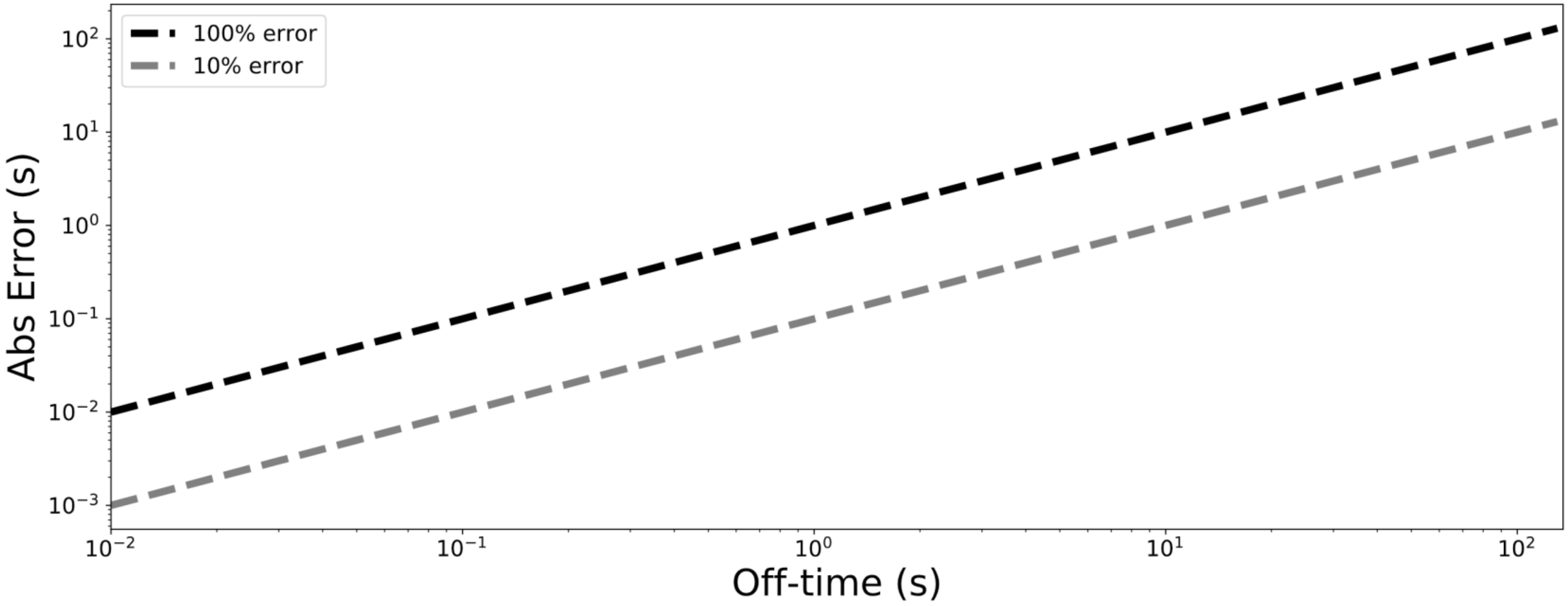
- Experimental Setup
- MSP430FR5994 MCU - 16 MHz, 8KB SRAM, 256 KB FRAM, 12-bit ADC, 16-bit Timers



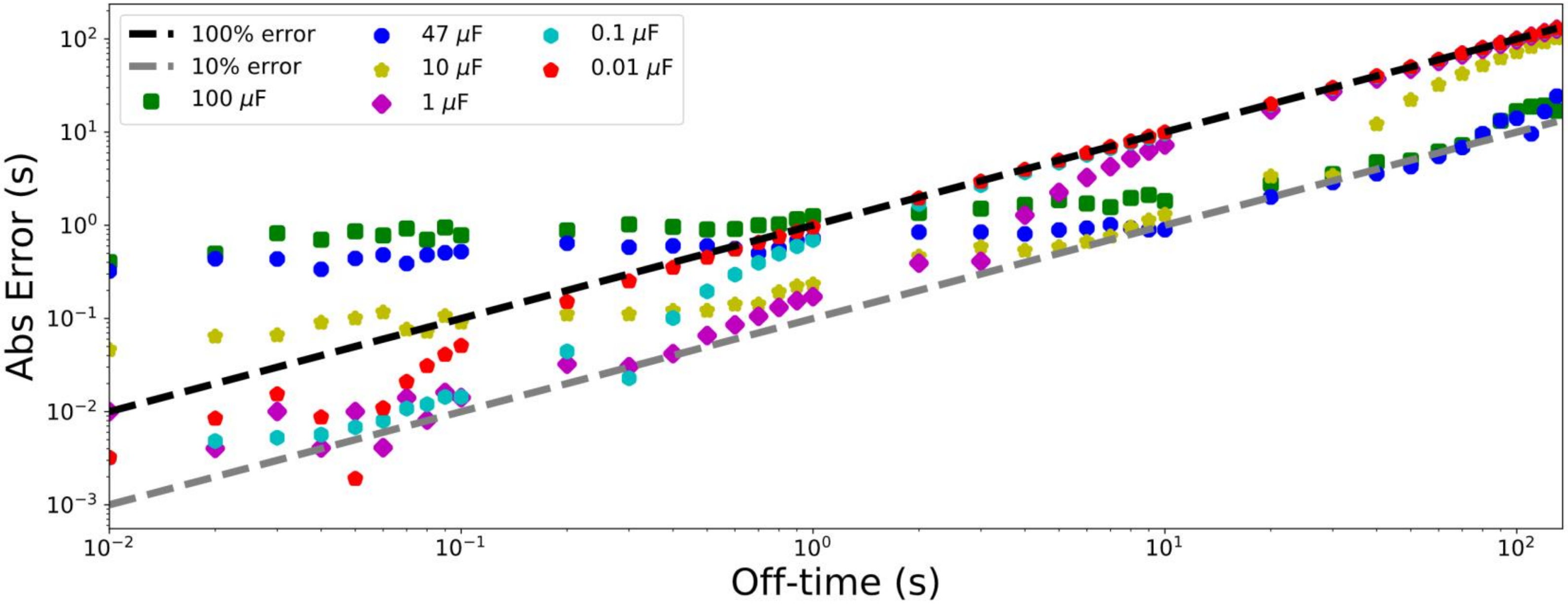
HARC Accuracy



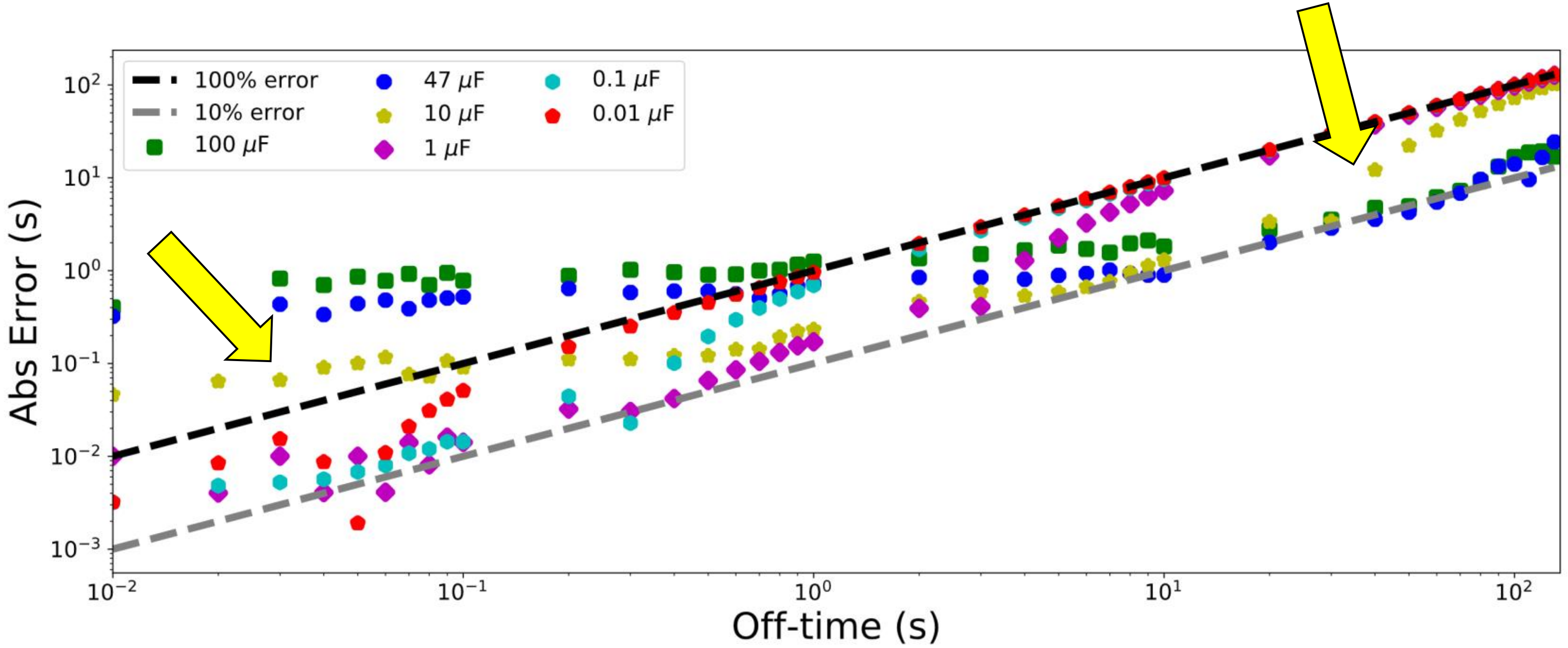
HARC Accuracy



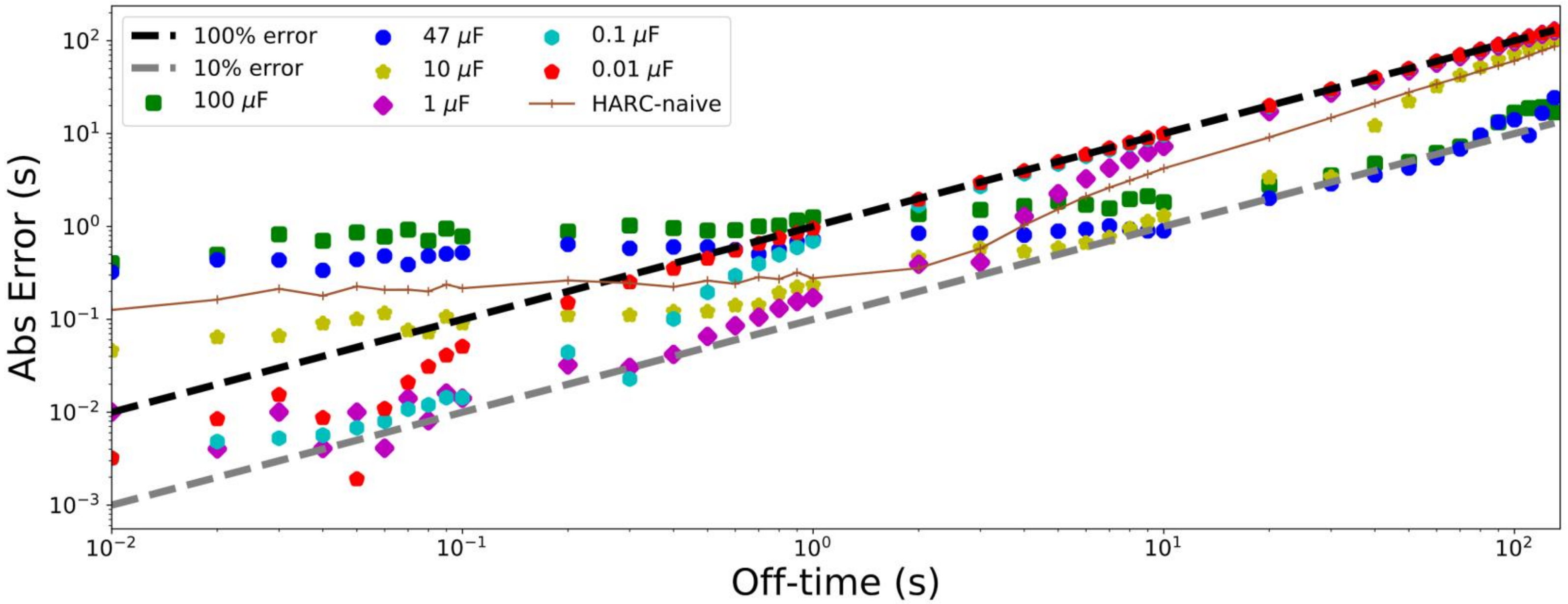
HARC Accuracy



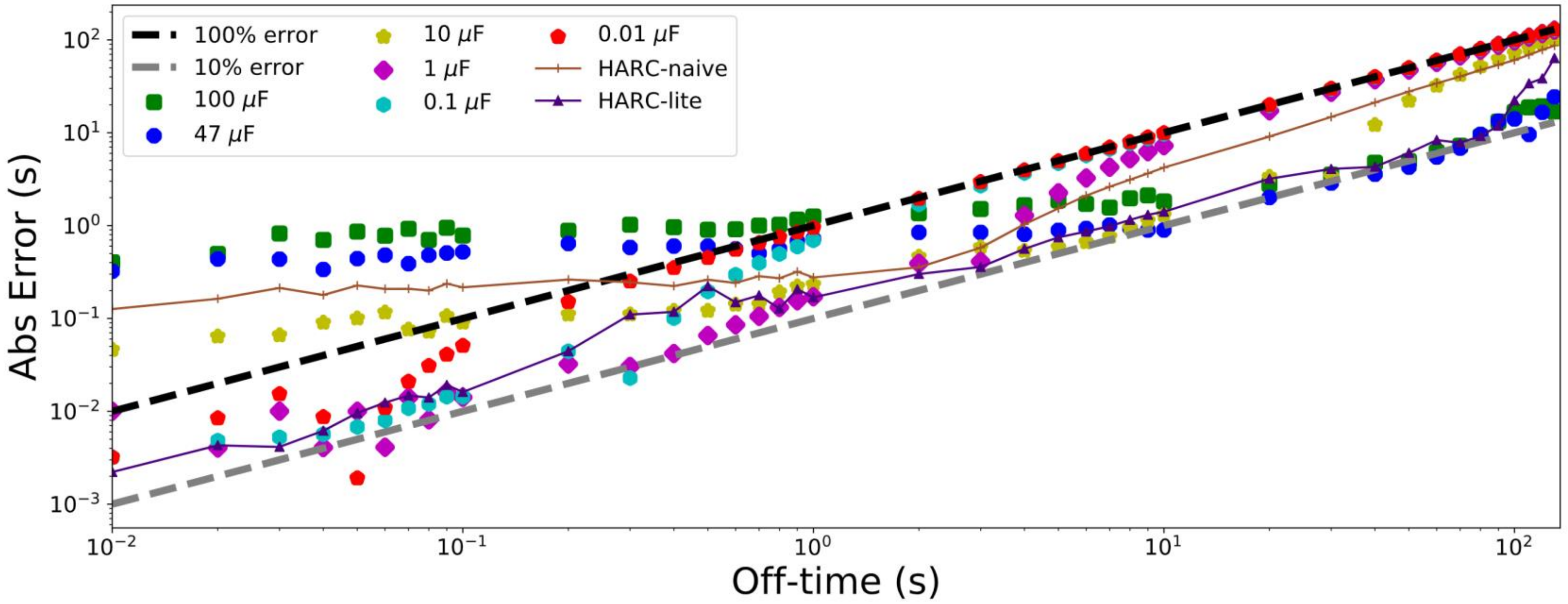
HARC Accuracy



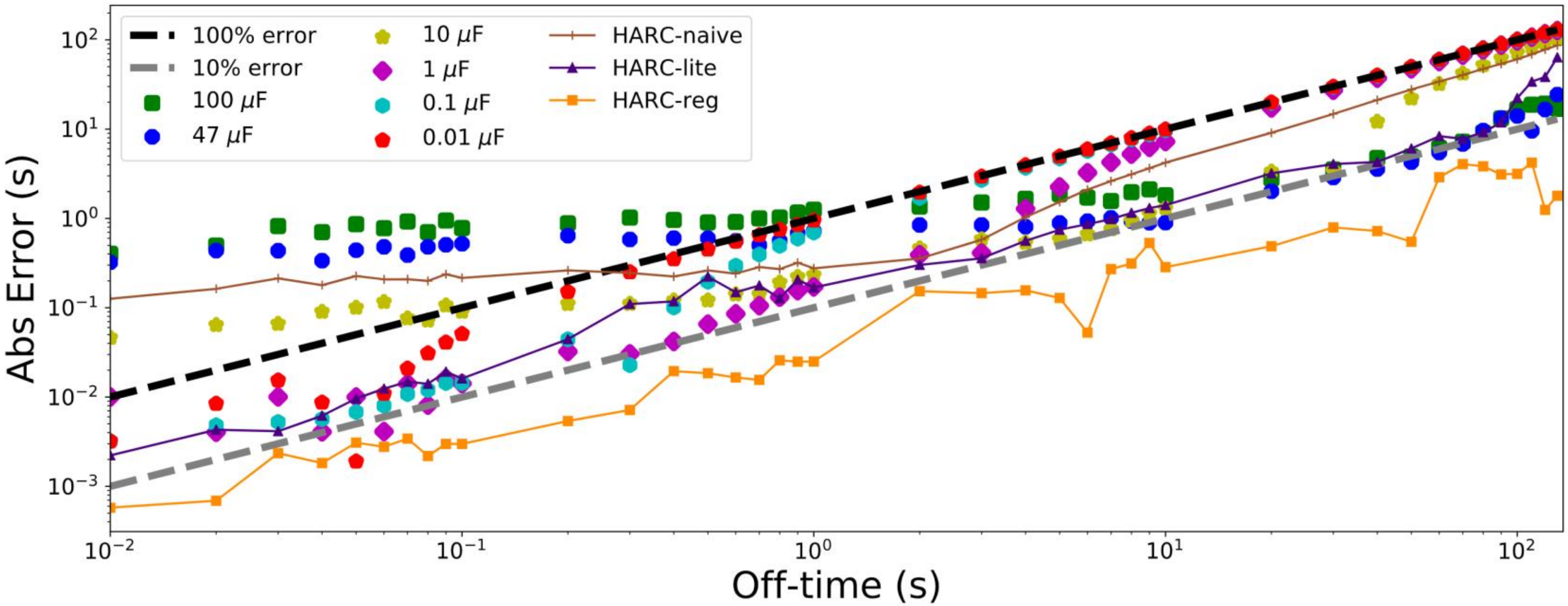
HARC Accuracy



HARC Accuracy

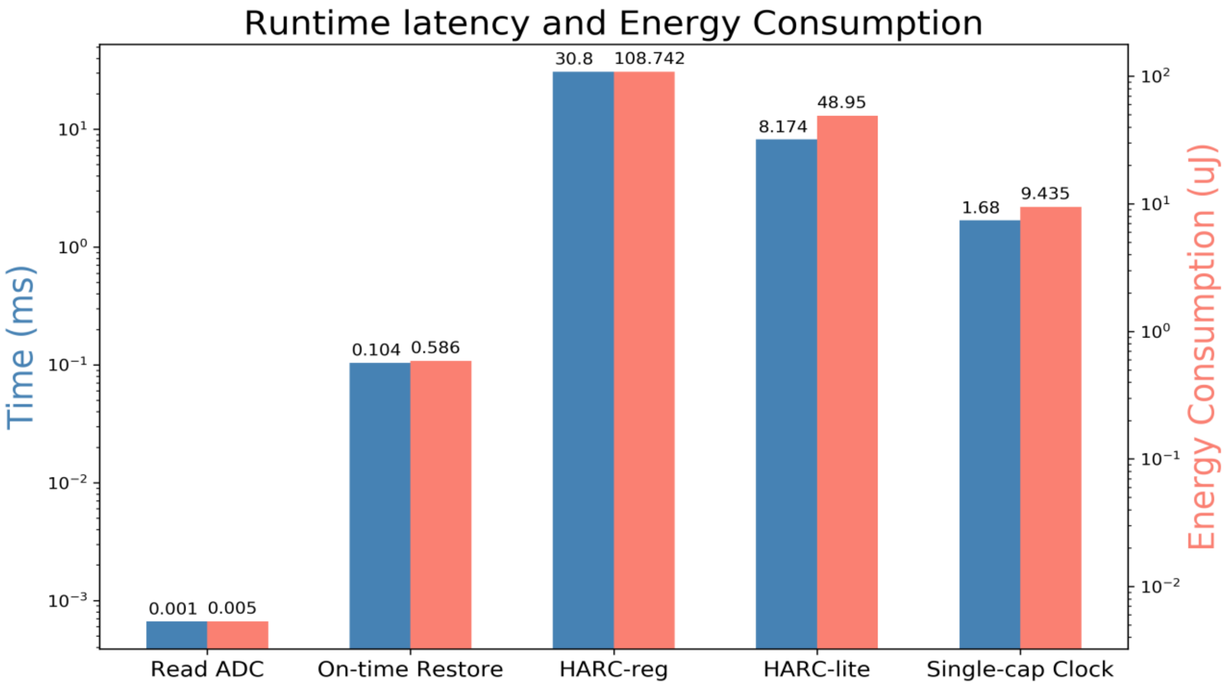


HARC Accuracy



HARC-reg performs best followed by HARC-lite and HARC-naive

HARC Overheads



HARC-reg 6% runtime overhead; ripe for optimization

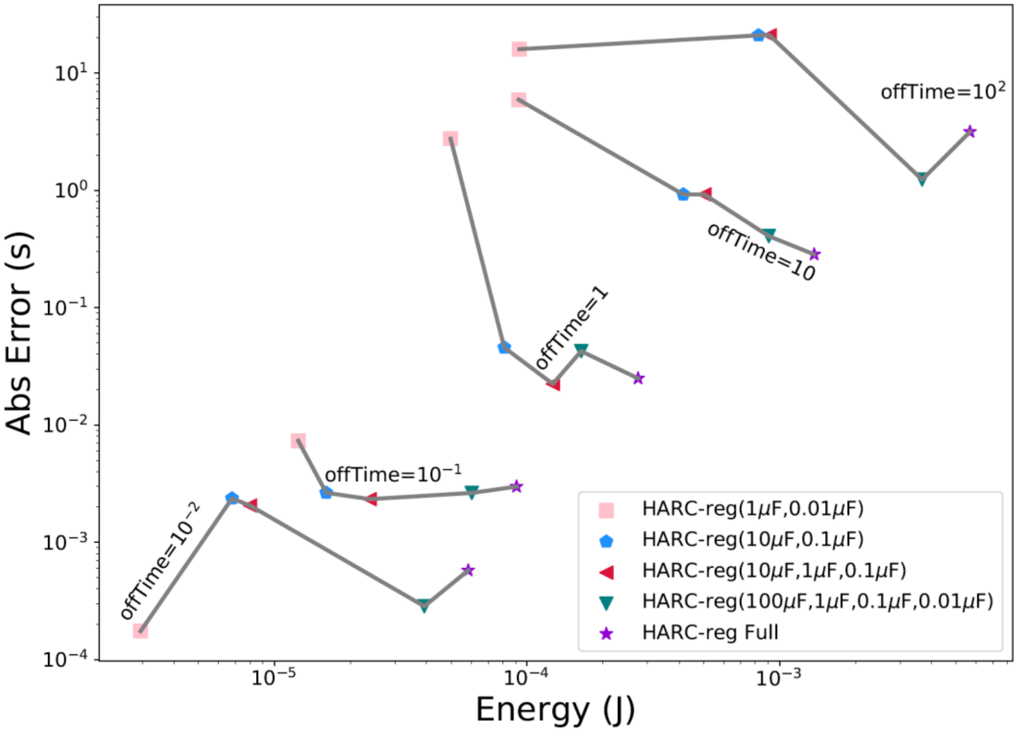
HARC Overheads

- Charging Time and energy consumption

Capacitor	Charging Time	Charging Energy
100 μF	4.5 ms	1.60 mJ
47 μF	2.7 ms	0.686 mJ
10 μF	1.1 ms	86.078 μJ
1 μF	125 μs	6.90 μJ
0.1 μF	10.8 μs	0.884 μJ
0.01 μF	10.4 μs	0.0972 μJ
HARC Total	4.5 ms	2.38 mJ

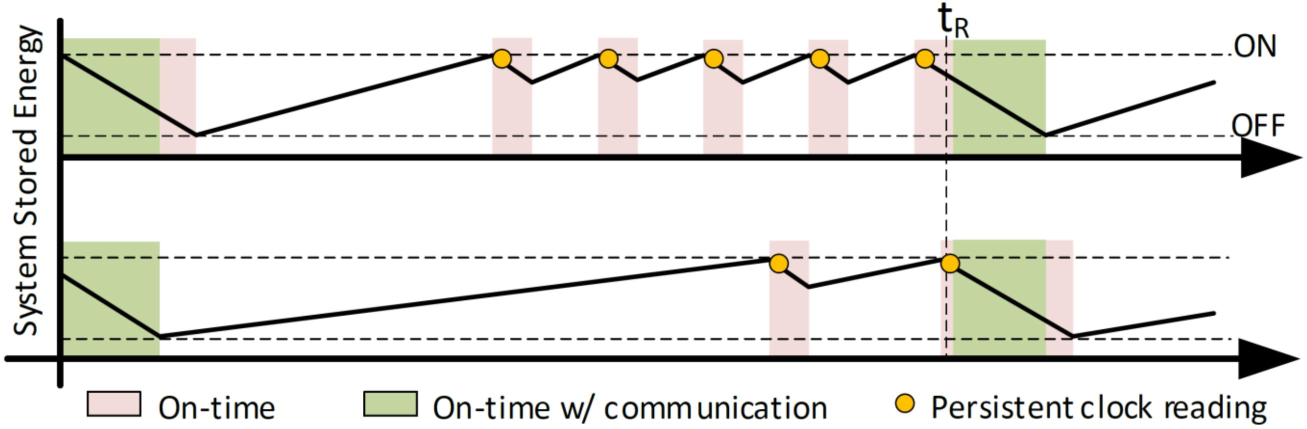
Energy vs. Accuracy Trade-offs

HARC can provide a timing mechanism with an energy vs accuracy setting that is dynamically adjustable after deployment.

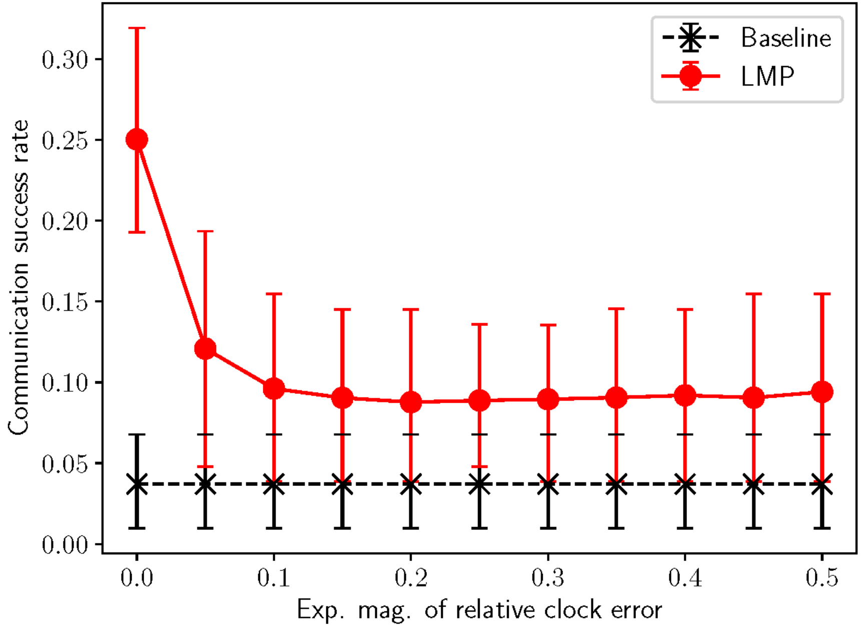


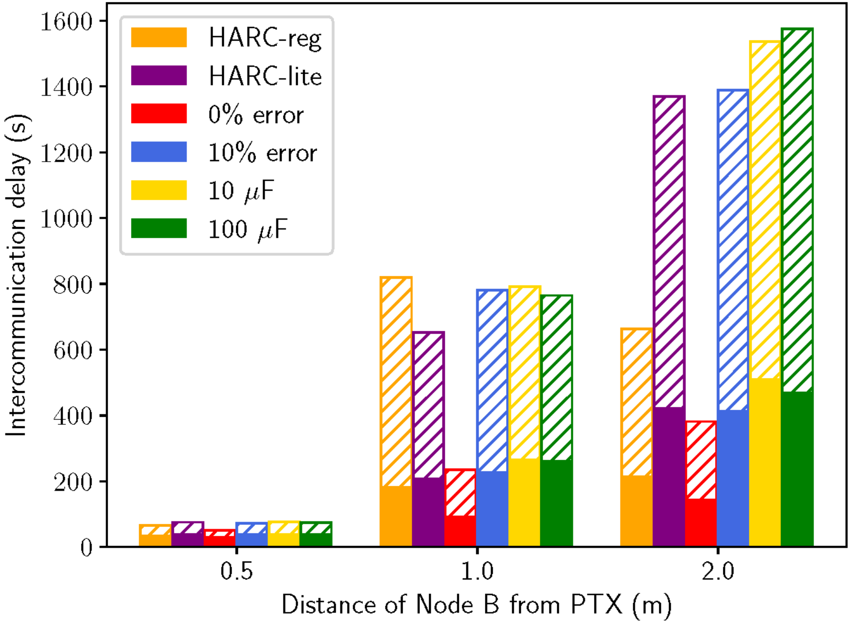
LMP: Lifecycle Management Protocol

- Two nodes decides on a rendezvous and schedule their on-times



Lifecycle Management Protocol (LMP) Evaluation





HARC increases the probability of communication between intermittently-powered nodes

Conclusion

- HARC – heterogeneous, redundant array of capacitor-based persistent clocks
  - Variation-resilient high accuracy over a wide range of power off-times
  - Demonstrated the feasibility and effectiveness of HARC using experimental evaluations on a HARC prototype
  - HARC use case – communication between two intermittently-powered nodes