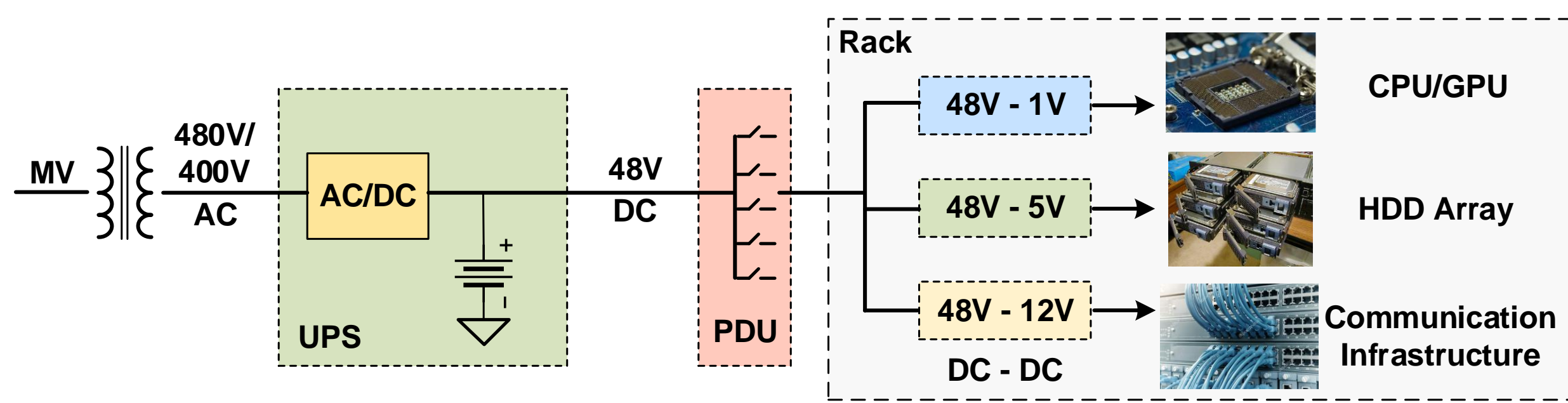


# Stochastic Model and Scaling Factor of Differential Power Processing for Hard Disk Drive Servers

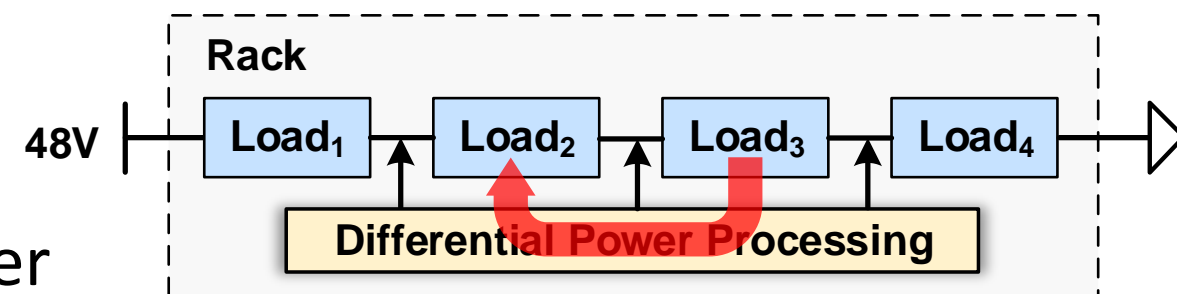
## Motivation

### Power Delivery Architecture in Data Center



### Series-Stacked Power Architecture on Rack:

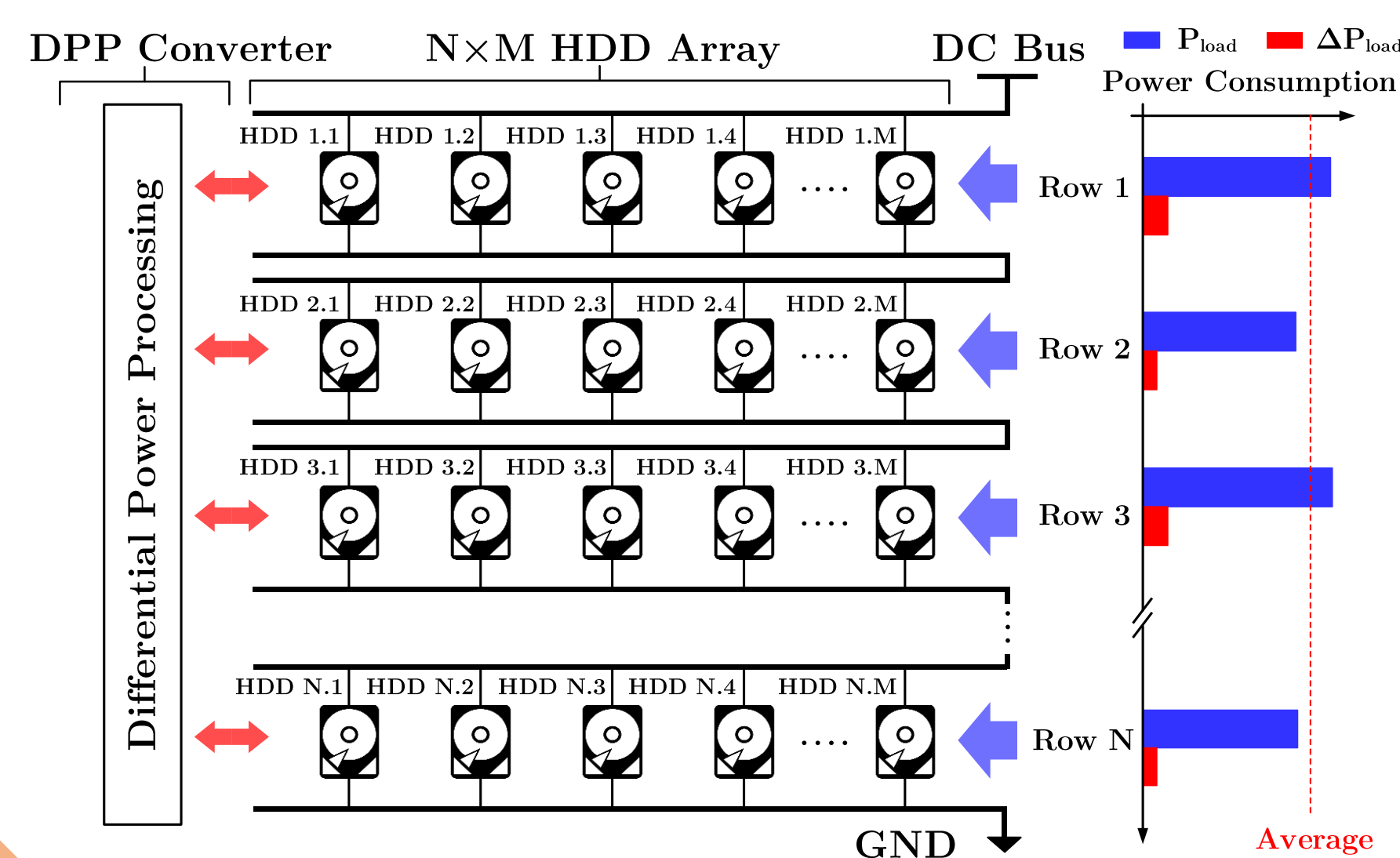
- Inherent voltage step down
- Only little differential power processed by differential power processing (DPP) converter



The authors would like to thank the DOE ARPA-E CIRCUIT program for supporting this work.

## DPP for HDD Storage Server

### A Very-Large-Scale HDD Array Supported by DPP Converter



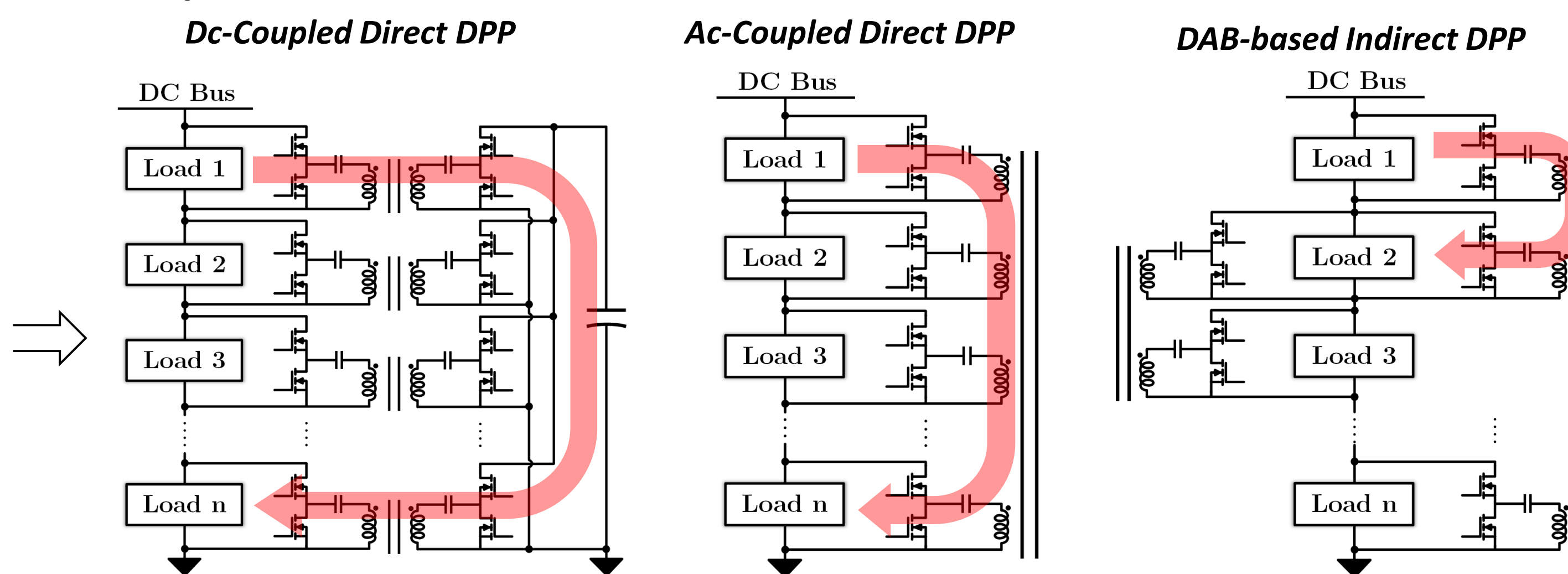
- Uniform voltage rating with similar power consumption
- Major power directly delivered to HDDs
- Very little differential power processed by the DPP converter
- Highly scalable to ultra-large-scale array

## Stochastic Loss Model and Performance Limits for Differential Power Processing

### Stochastic Loss Model

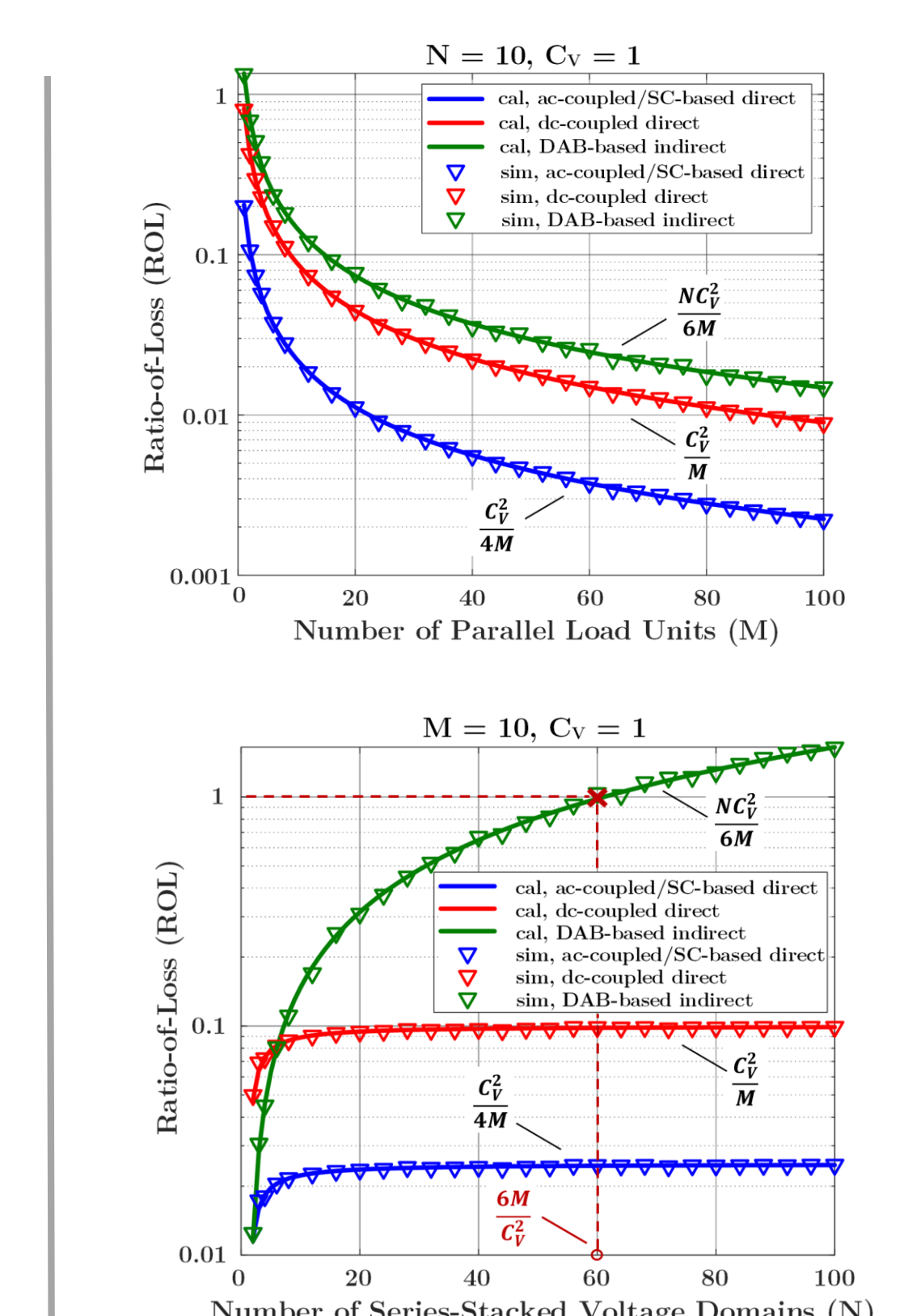
- Each load power is  $P_{ij}(t)$ ;  $P_{ij}(t)$ 's are i.i.d random variables.
- Total power at the  $i^{th}$  domain:  $P_i(t) = \sum_{j=1}^M P_{ij}(t)$
- Diff. power:  $\Delta P_i(t) = \frac{\sum_{k=1}^N P_k(t)}{N} - P_i(t)$

### Comparison between Different DPP Architectures



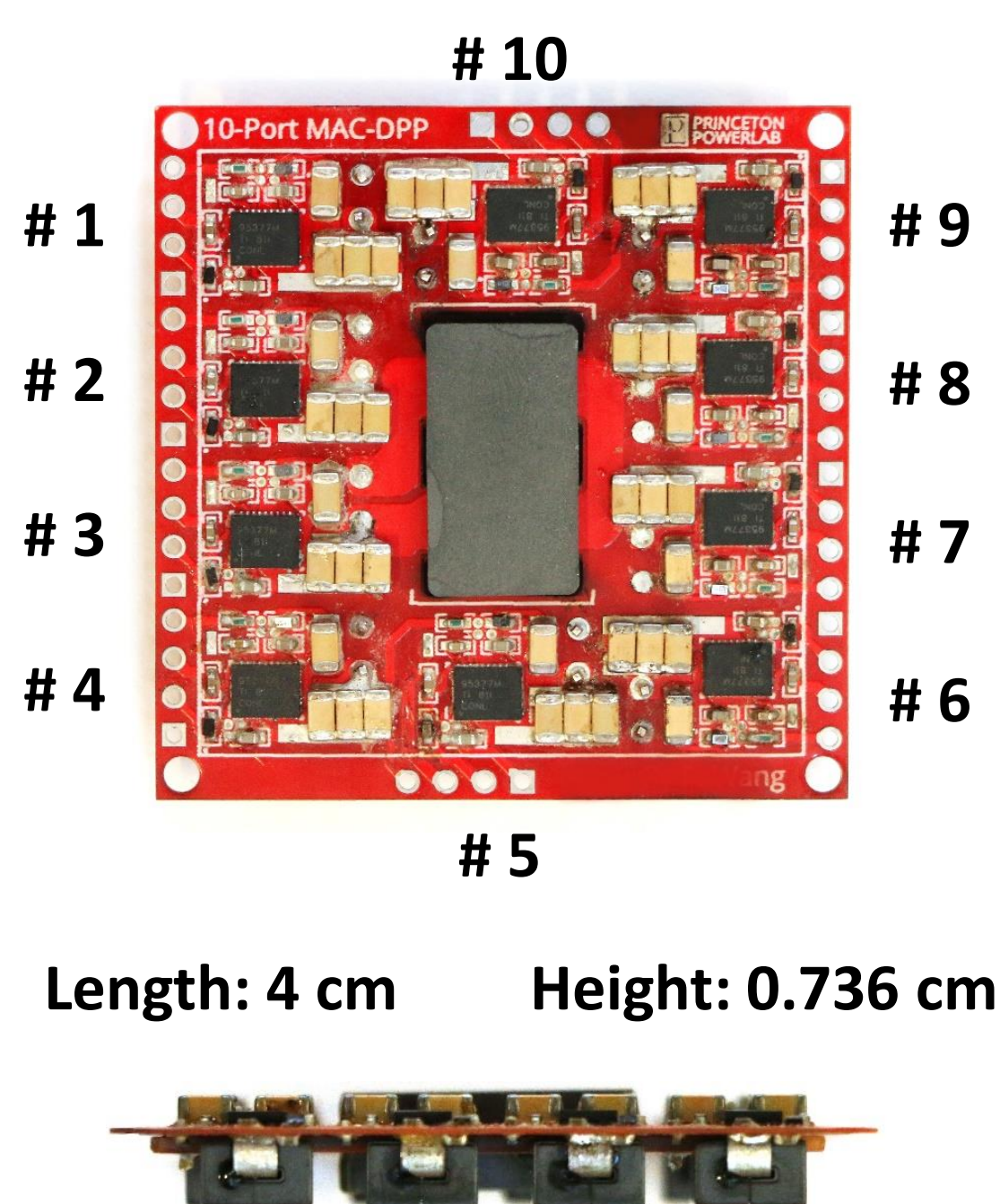
	Topology	Output Resistance	Expected Loss	Scaling Factor
Direct-Coupled	Ac-Coupled	$\frac{8N}{G_{SW}} + \frac{4N}{G_M}$	$M(N-1)\sigma^2(P_{ij}(t)) \times \frac{R_{out}}{V_0^2}$	$S(MN)$
	Dc-Coupled	$\frac{32N}{G_{SW}} + \frac{16N}{G_M}$		
Indirect-Coupled	DAB-based	$\frac{32N-32}{G_{SW}} + \frac{16N-16}{G_M}$	$\frac{M(N-1)(N+1)}{6} \sigma^2(P_{ij}(t)) \times \frac{R_{out}}{V_0^2}$	$S(MN^2)$
N:1 Converter	DAB	$\frac{32}{G_{SW}} + \frac{16}{G_M}$	$(MN\sigma^2(P_{ij}(t)) + M^2N^2\mu^2(P_{ij}(t))) \times \frac{R_{out}}{V_0^2}$	$S(M^2N^2)$

### Simulation Verification



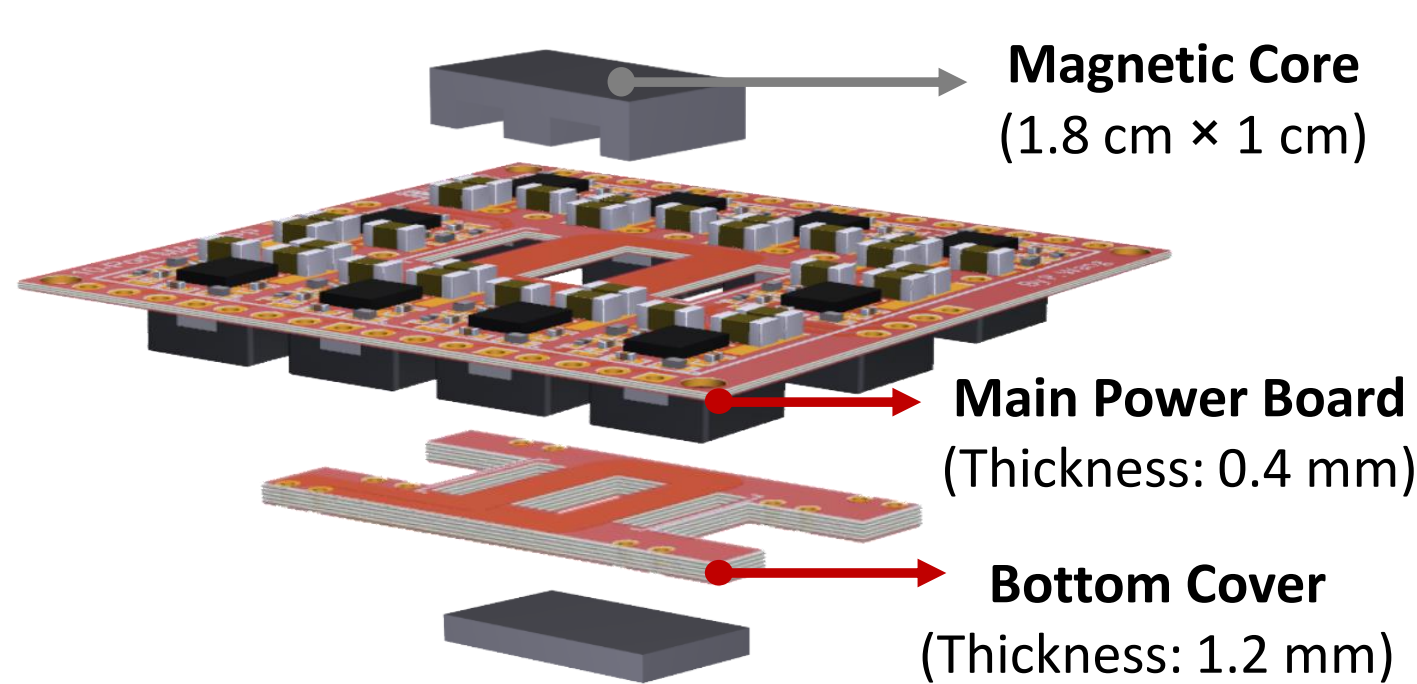
## MAC-DPP Prototype

### 450 W 10-Port MAC-DPP



### Stacked PCB Planar Magnetics

- 10x magnetics size reduction

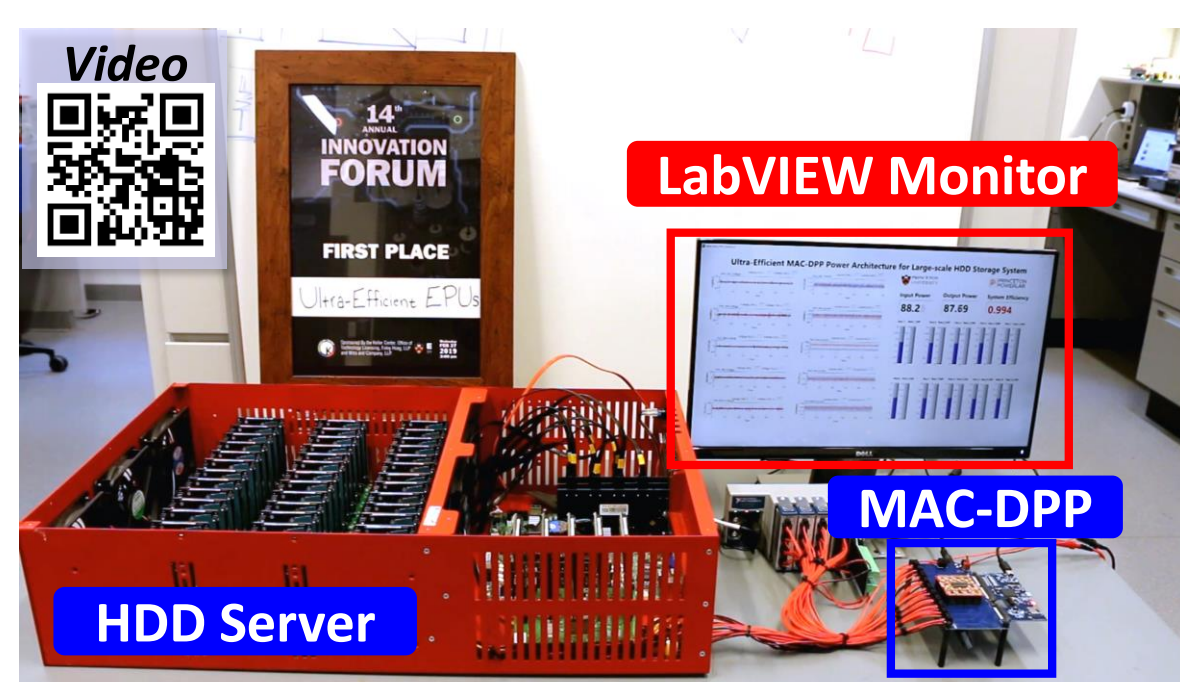


### Performance Specifications

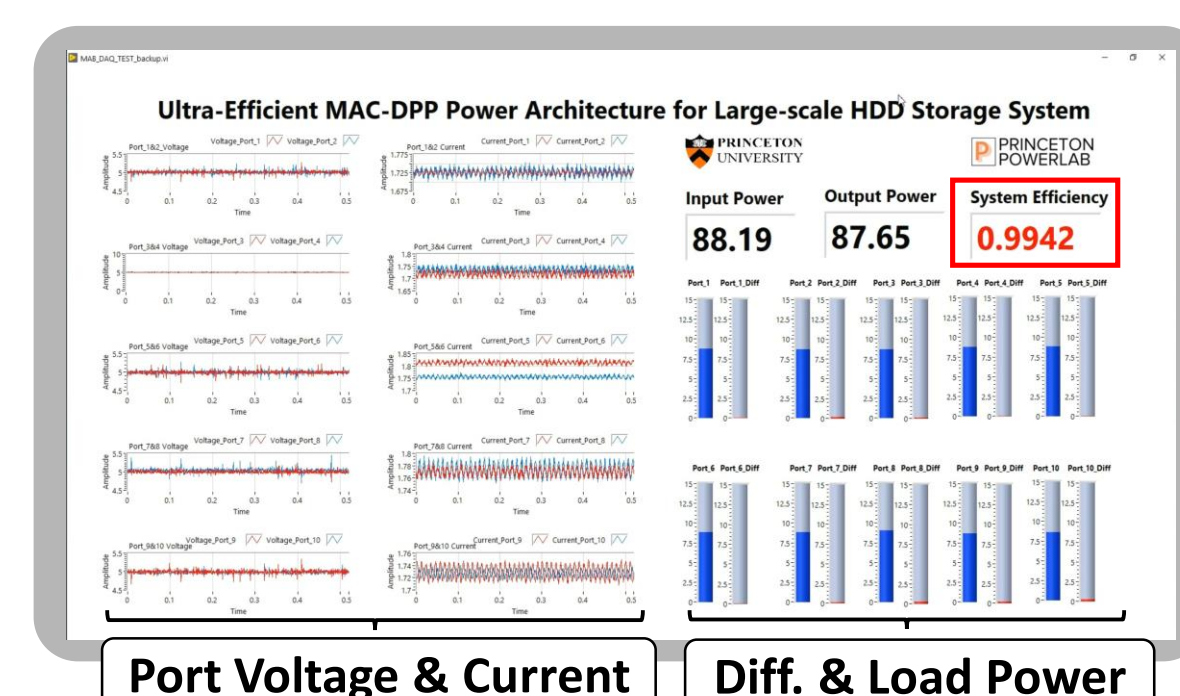
System Efficiency	> 99% at most of operation points
Volume	0.71 in <sup>3</sup>
Power Density	38.6 kW/L (System Power) 19.3 kW/L (Processed Power)

## HDD Server Testbench & Experimental Results

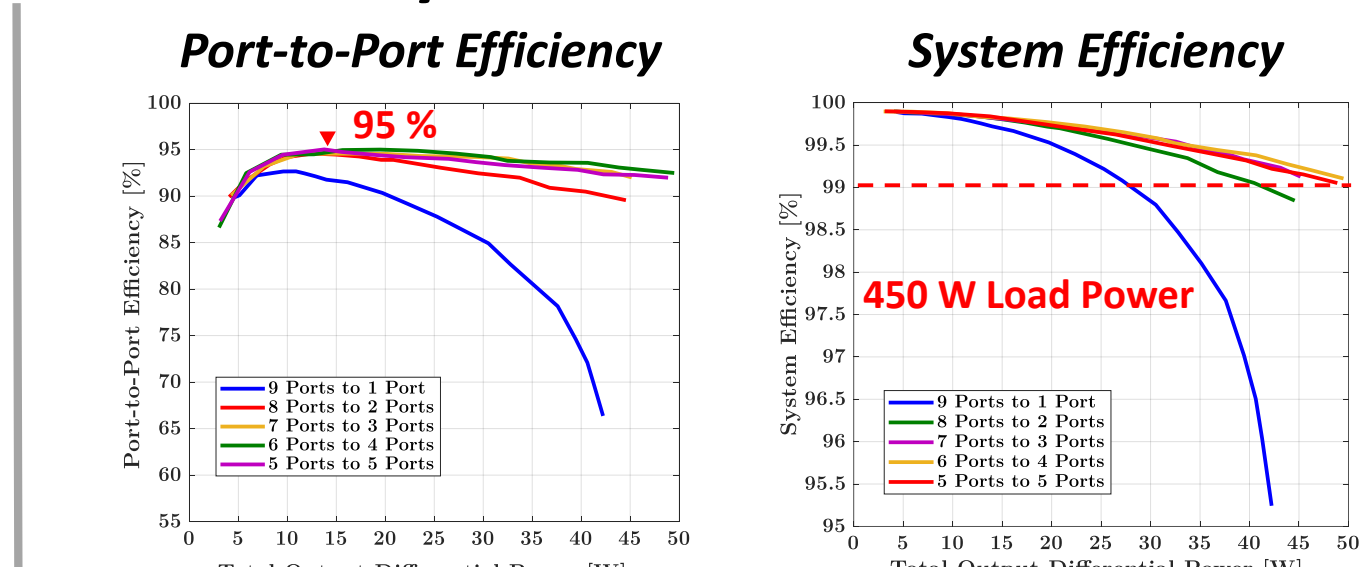
### 50-HDD Storage Server



### LabVIEW Monitoring System



### Efficiency Measurement



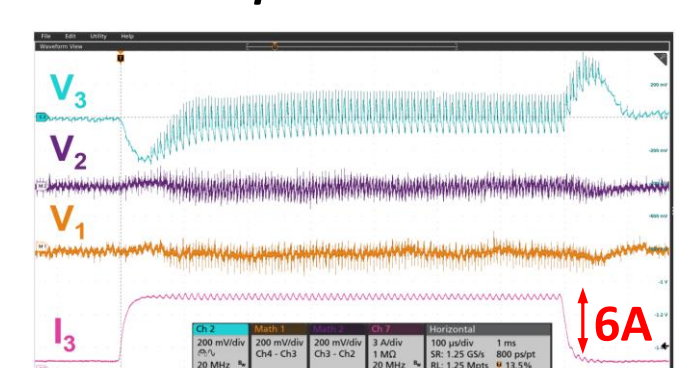
- Peak efficiency: 95% @ (14 W, 5 Ports to 5 Ports)

### Transient Response Hot-Swapping



- Maintain normal operation at worst hot-swapping scenario

### 6 A Step Load Transient



- Voltage overshoot < 250mV
- Settling time < 100 us