Ohm's Law in Data Centers:
A Voltage Side Channel for Timing Power Attacks

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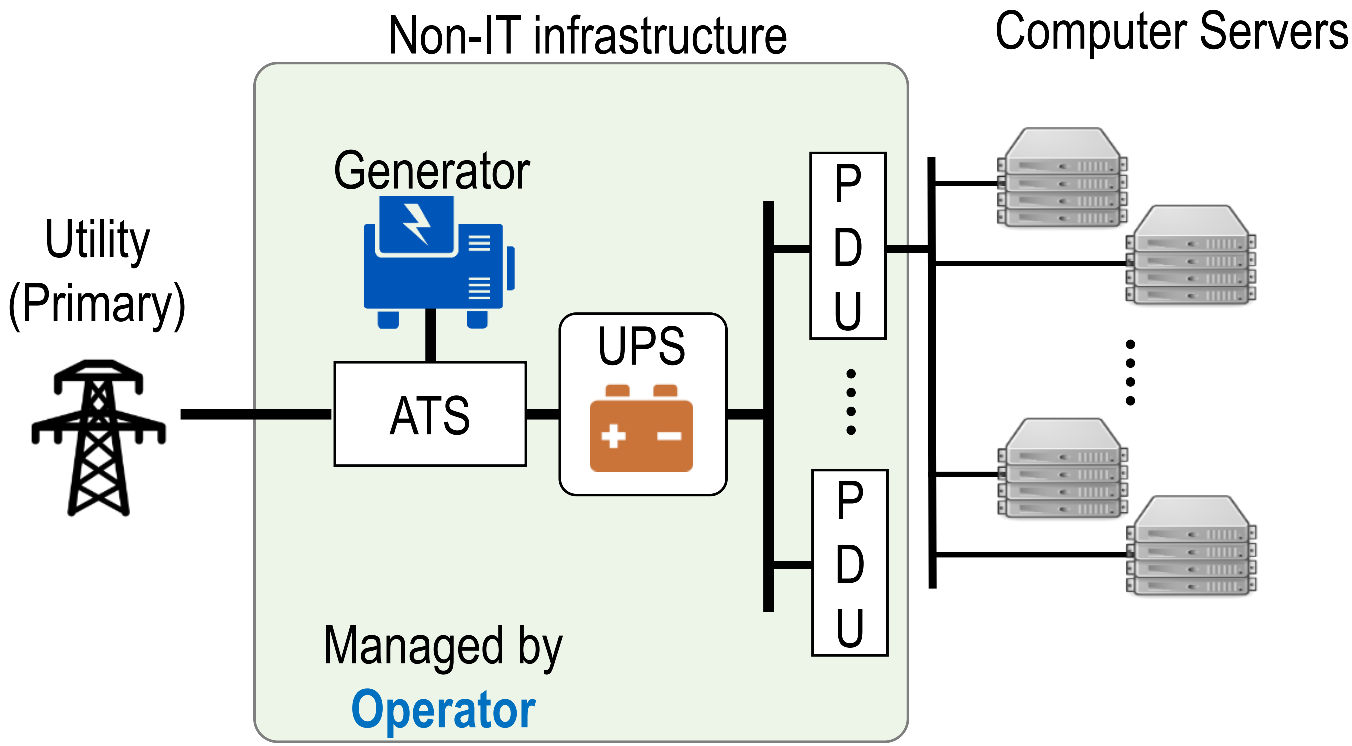
Acknowledgement: This work was supported in part by the U.S. NSF under grants CNS-1551661 and ECCS-1610471.

Cloud data centers

This talk is not about cloud data centers

User/Tenant = Virtual machines

Multi-tenant data centers (a.k.a. “colo”)



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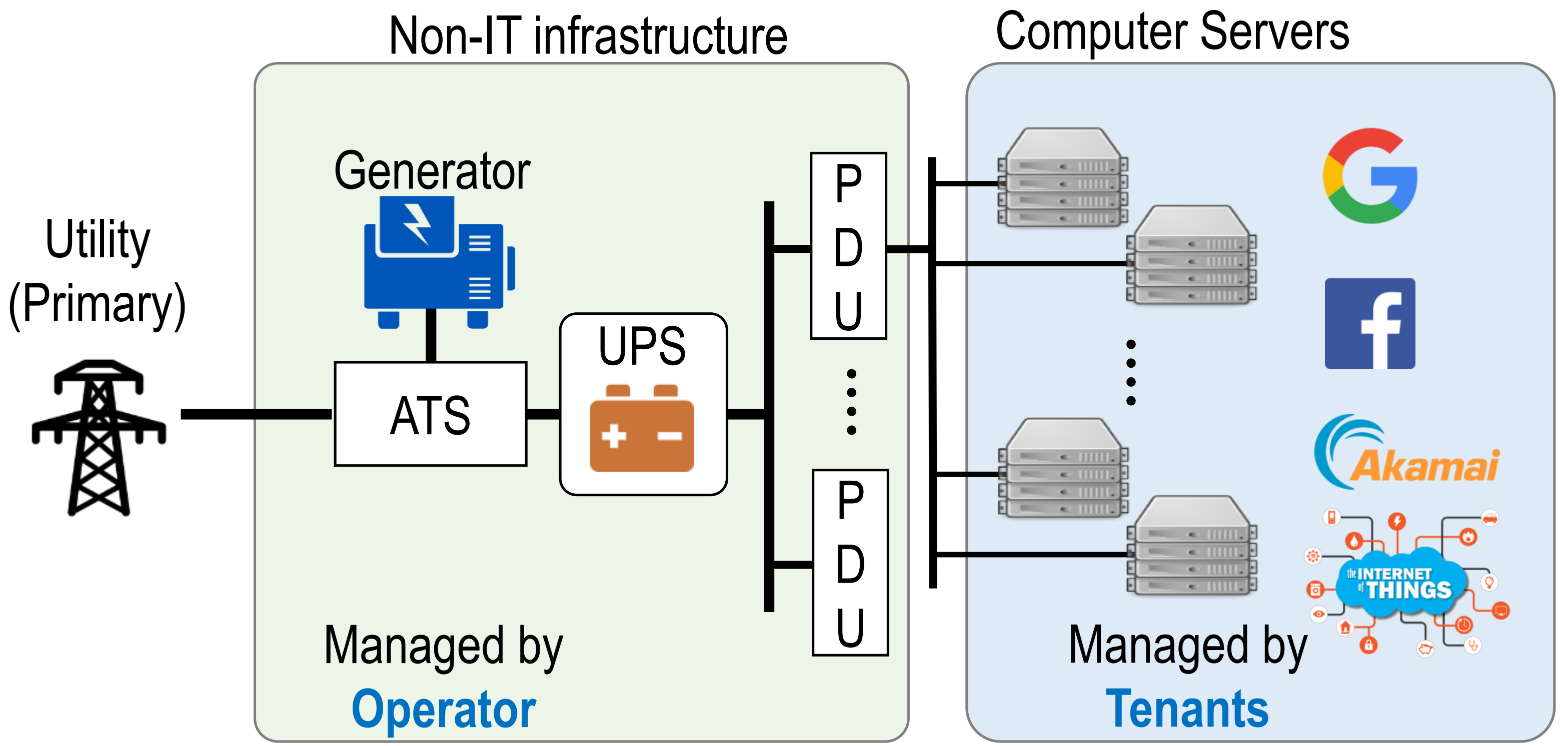
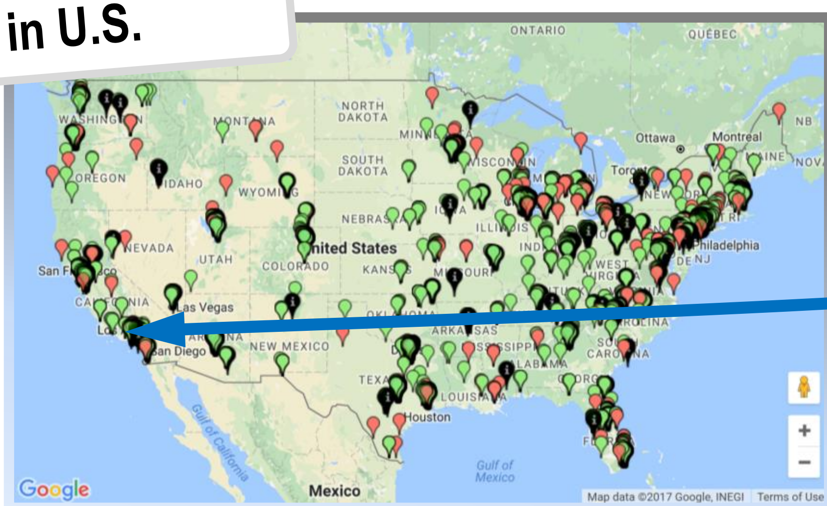
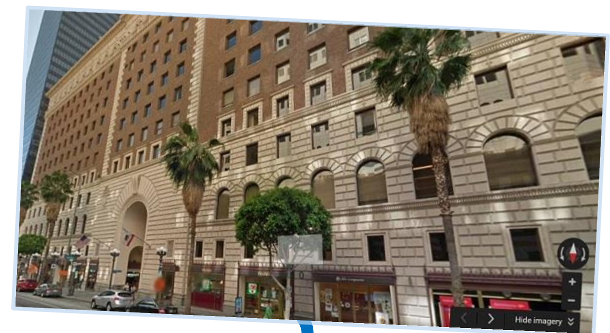


A shared data center facility that houses multiple tenants, each managing its own servers…

Multi-tenant data centers are everywhere…

2,000+ in U.S.





Apple houses 25% of its servers in multi-tenant data centers…

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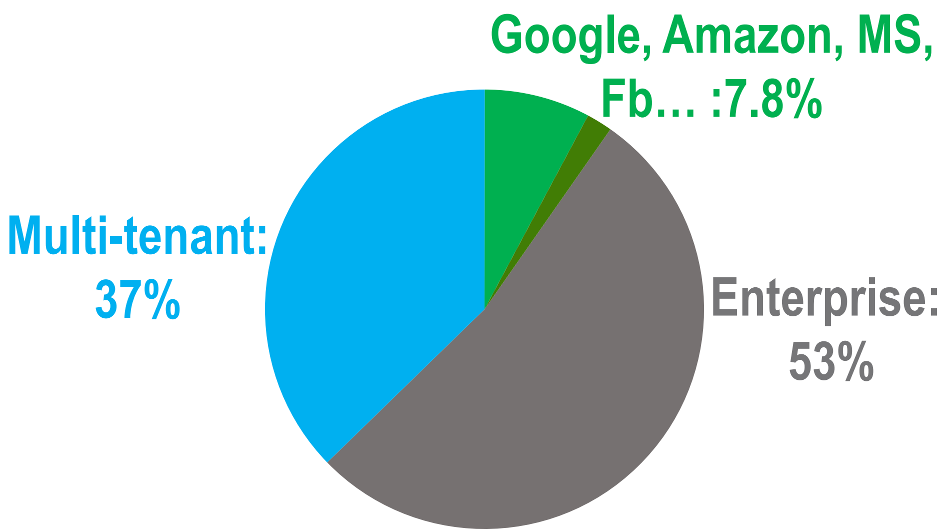
2,000+



Percentage of electricity usage by data center type (source: NRDC 2015)

Apple houses 25% of its servers in multi-tenant data centers…

Data center security

- Mission-critical infrastructure
- Backbone of digital economy
- 50% growth by 2020
- IoT and edge computing
- ……

Securing the cyberspace is well studied

DDoS attack, network intrusion, privacy protection, etc.

[Mirkovic Sigcomm’04][Zhang CCS’12][Moon CCS’15][Dong CCS’17]…

Data center security

- Mission-critical infrastructure
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- 50% growth by 2020

Are the physical infrastructures secure?

- ……

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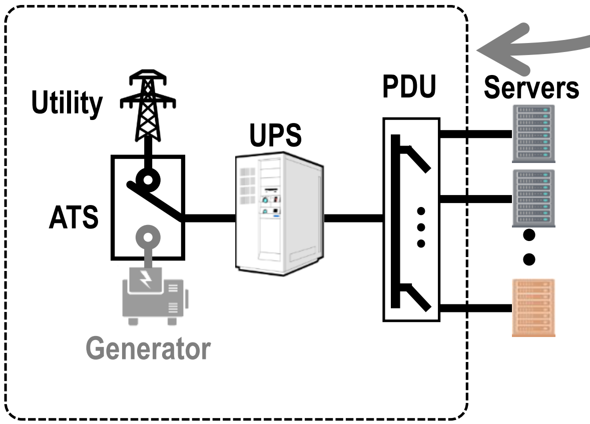
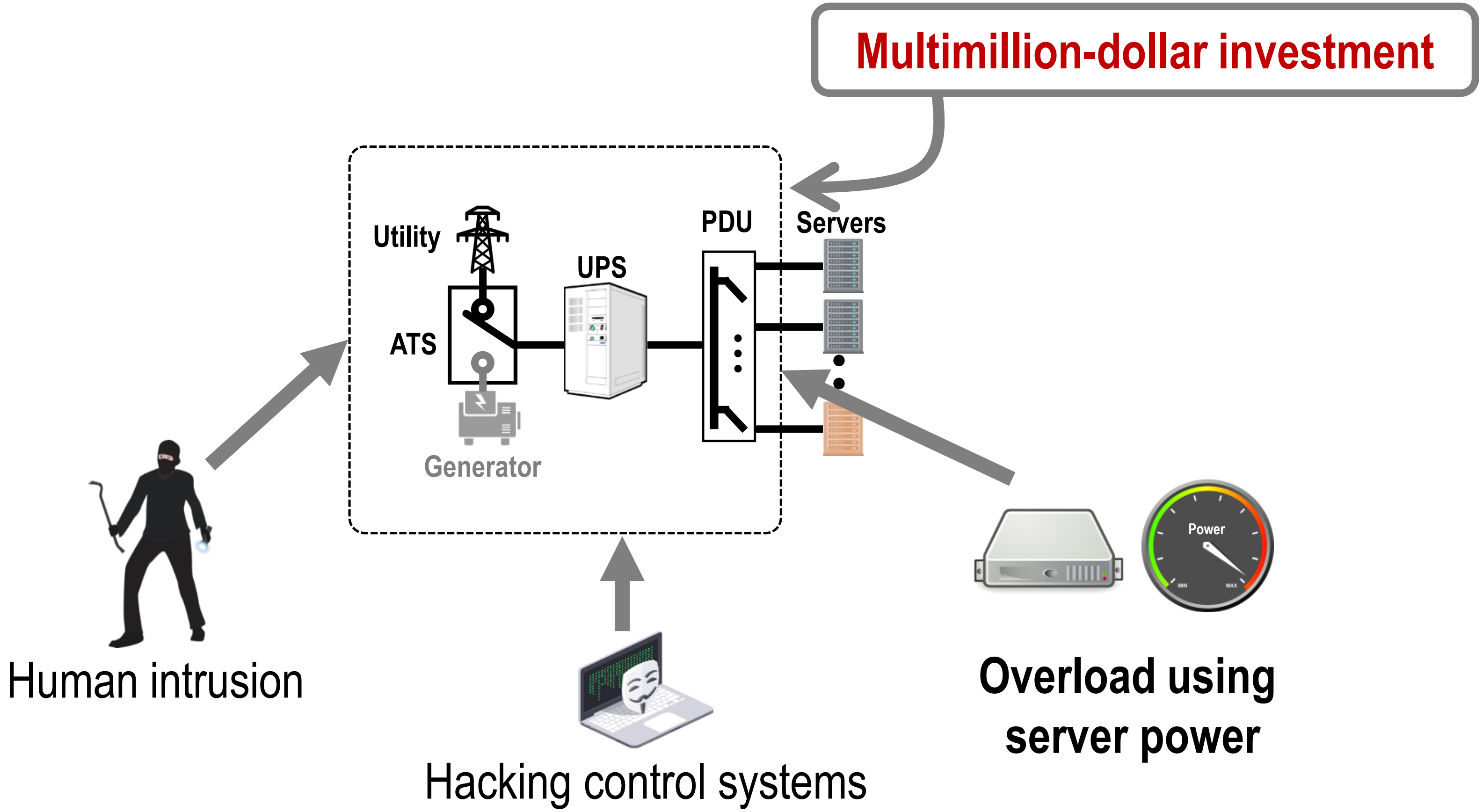
How to attack physical infrastructures?

Multimillion-dollar investment



How to attack physical infrastructures?



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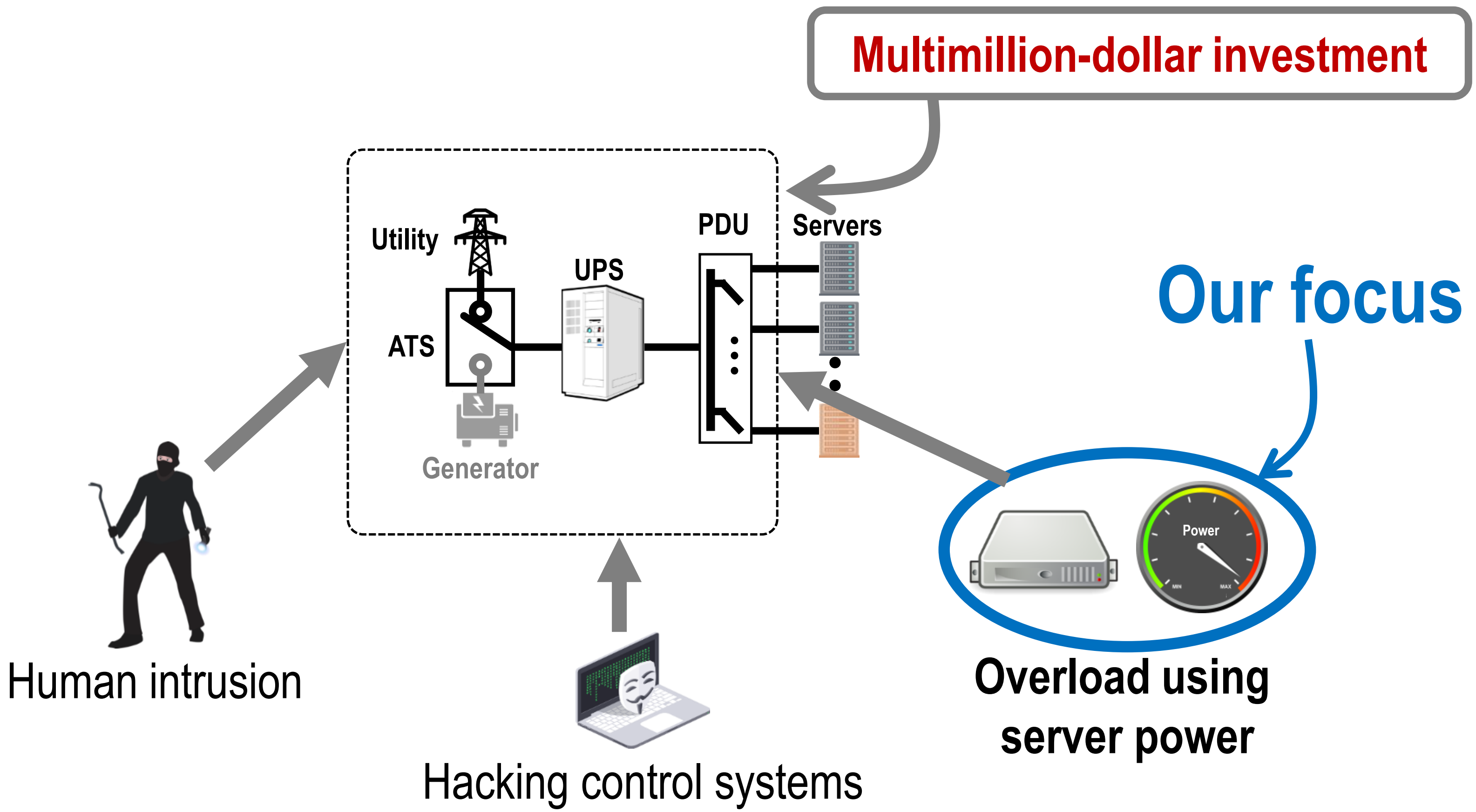
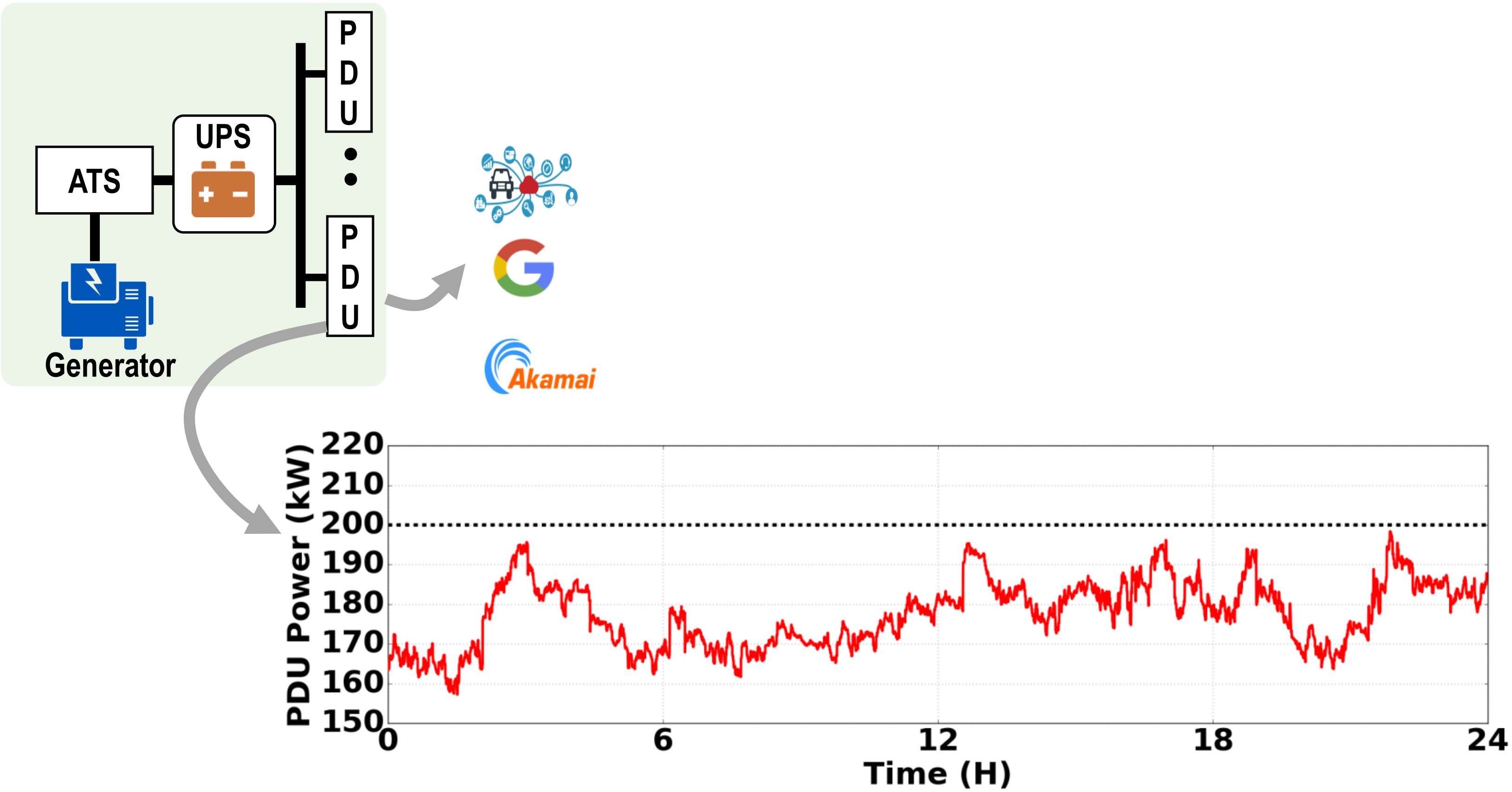


Threat model



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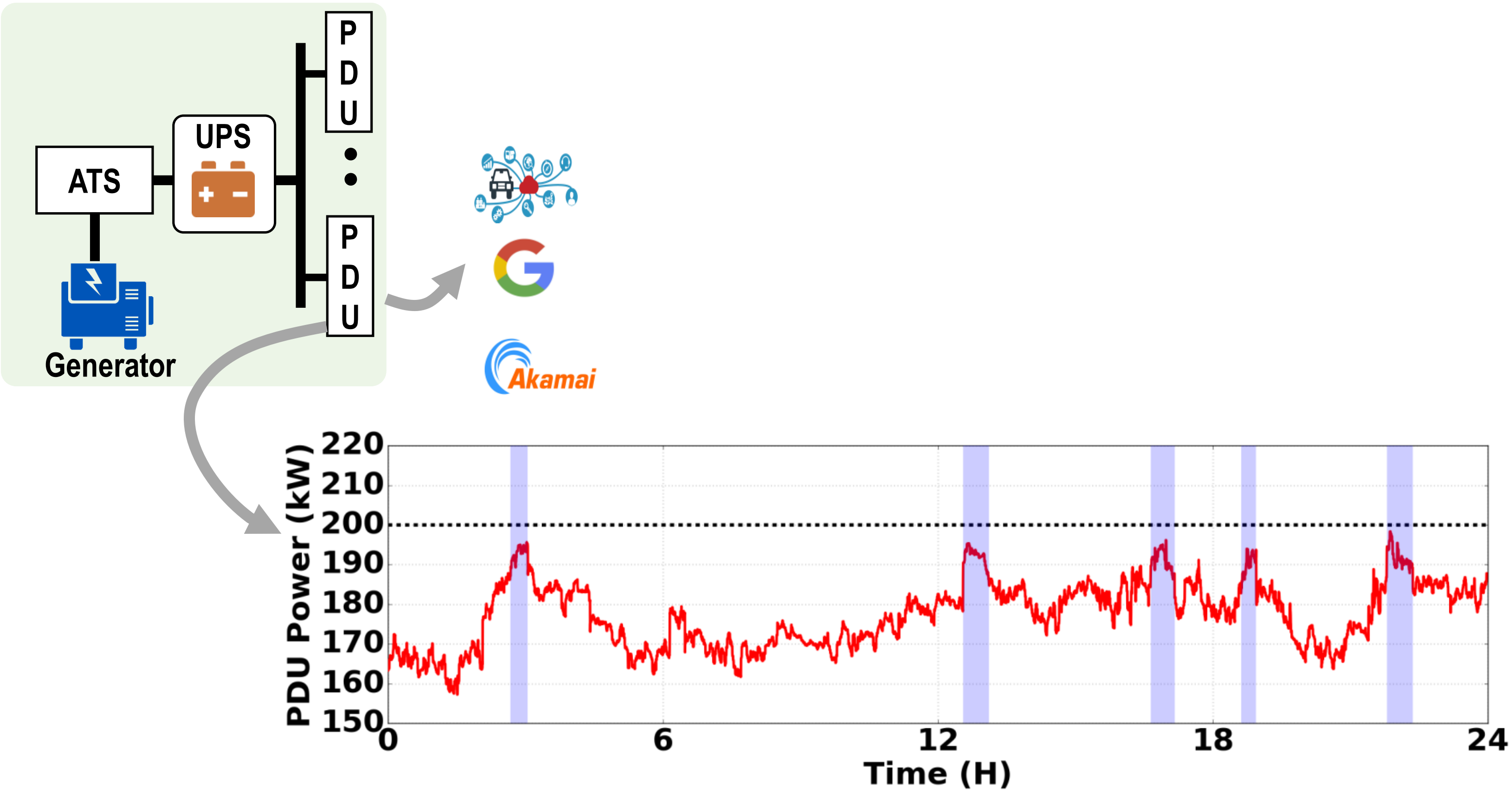

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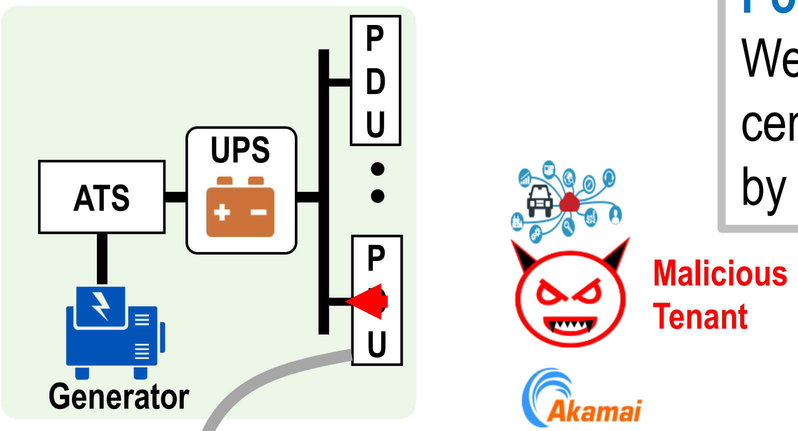
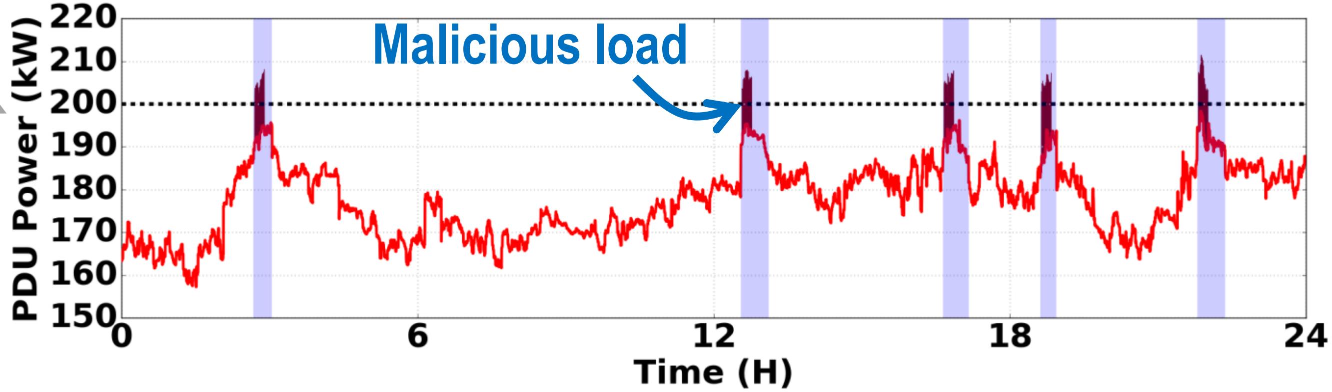


Power attack:
Well-timed power injection to overload the shared data center capacity, subject to all applicable constraints set by the operator

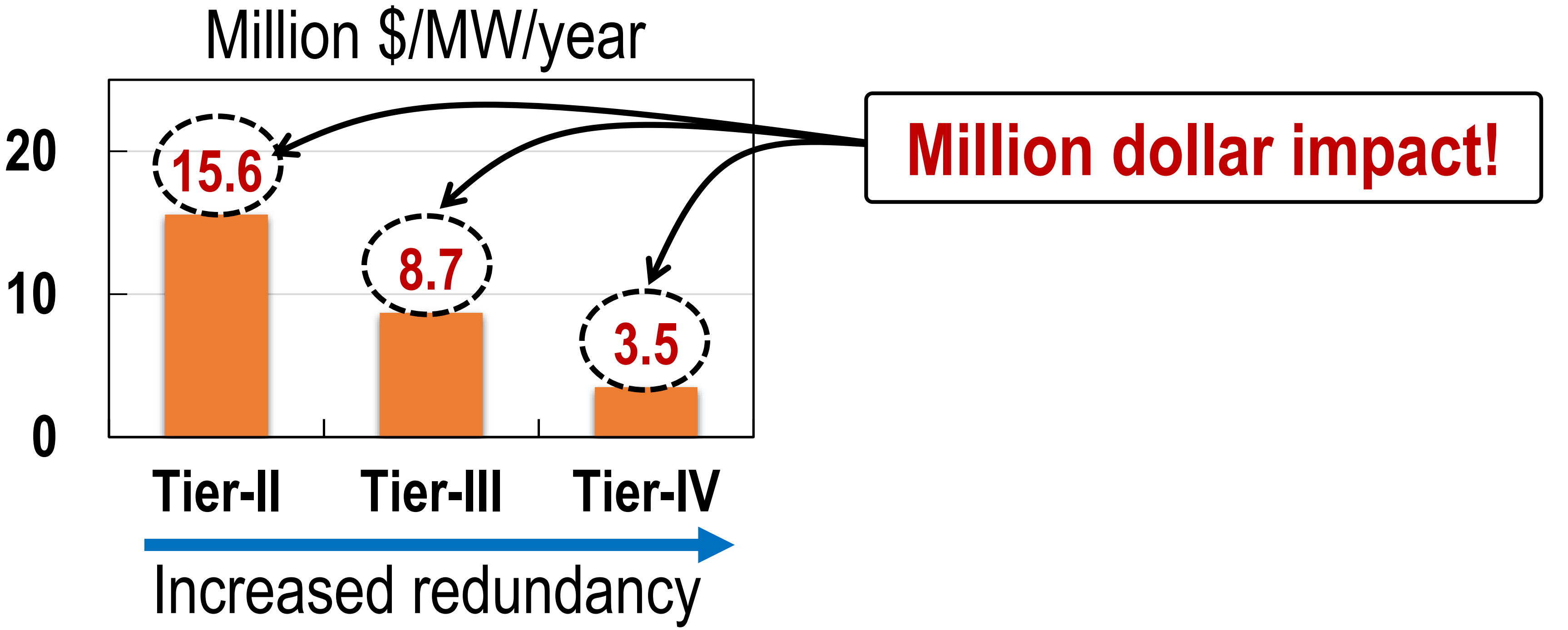


Threat model

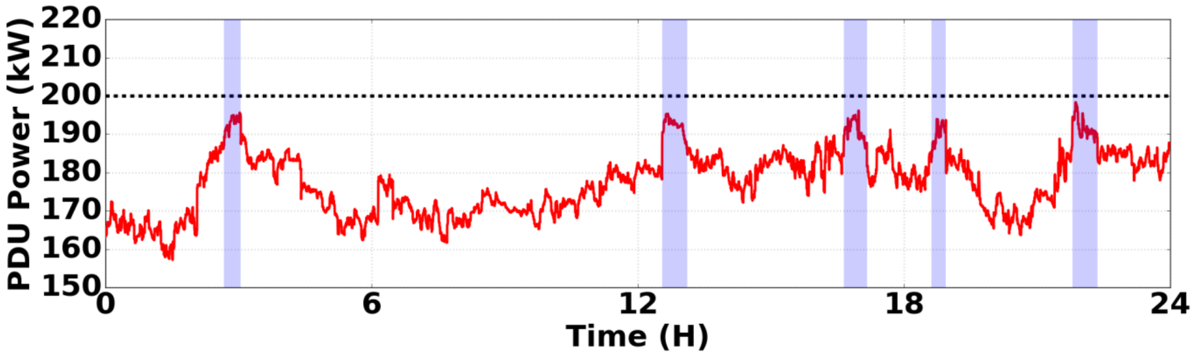
Power attacks make outages more likely
(~280x more likely for a Tier-IV data center)

Cost analysis of power attacks

Estimated impact of overloads (5% of the time, size: 1MW-10,00sqft)



How to precisely time power attacks?



- Random attacks are unlikely to be successful, while constant full power is prohibited

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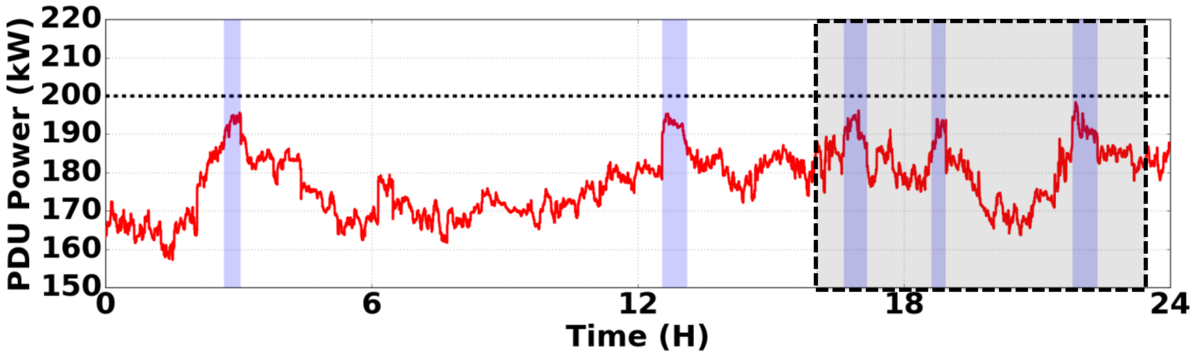

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- Coarse timing (e.g., based on “peak” hours) is ineffective

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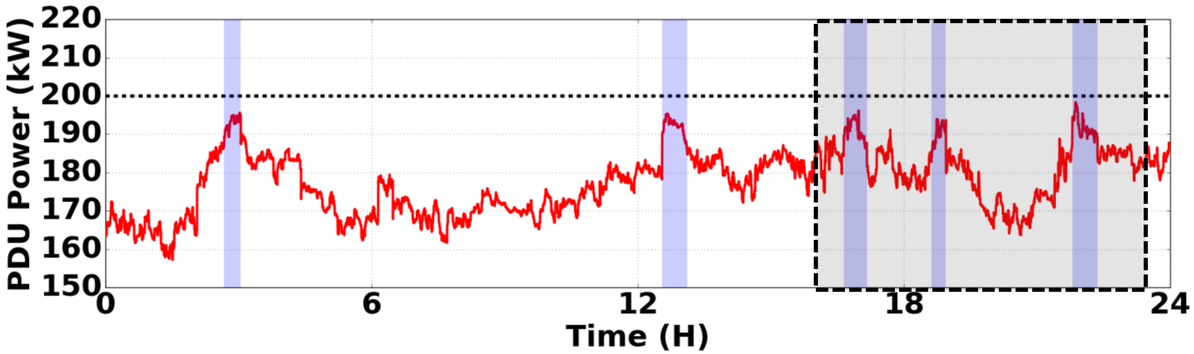

- Random attacks are unlikely to be successful, while constant full power is prohibited
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How to estimate the power load without power meters?

“Wireless” side channels

Thermal: Higher power produces more heat

- Requires heat recirculation model
- Slow responses
- Only applicable to raised-floor designs

References

- M. A. Islam, **S. Ren**, and A. Wierman, “Exploiting a Thermal Side Channel for Power Attacks in Multi-Tenant Data Centers,” ACM Conference on Computer and Communications Security (**CCS**), 2017.
- M. A. Islam, L. Yang, K. Ranganath, and **S. Ren**, “Why Some Like It Loud: Timing Power Attacks in Multi-tenant Data Centers Using an Acoustic Side Channel,” ACM International Conference on Measurement and Modeling of Computer Systems (**SIGMETRICS**), 2018.

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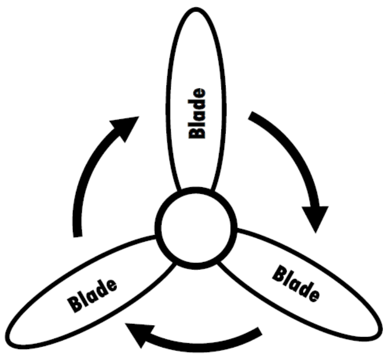

Acoustic: More heat requires more cold air
- Inaccurate timing due to near-far effects
- Limited distance
- Easy to degrade by injecting additional noise

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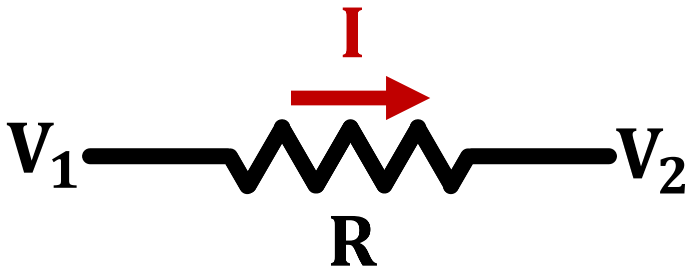
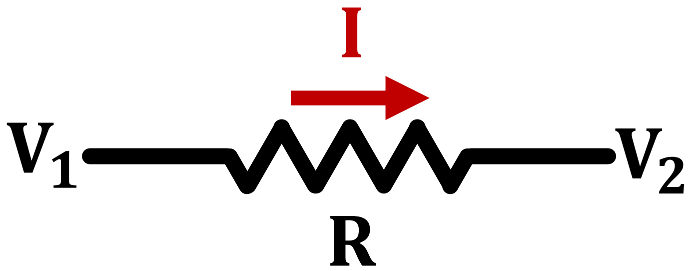
A voltage side channel due to Ohm’s Law

Ohm’s Law



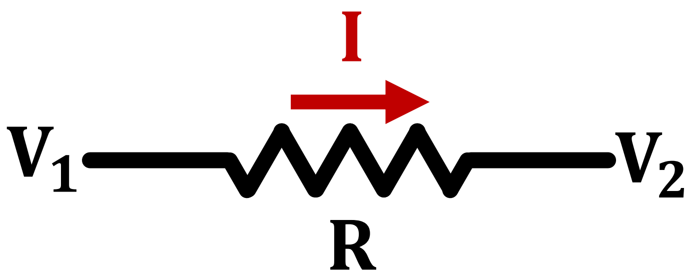
$$\mathbf{V} = \mathbf{I} \cdot \boldsymbol{R}$$

Ohm's Law



$$\mathbf{V_1} - \mathbf{V_2} = \mathbf{I} \cdot \boldsymbol{R}$$

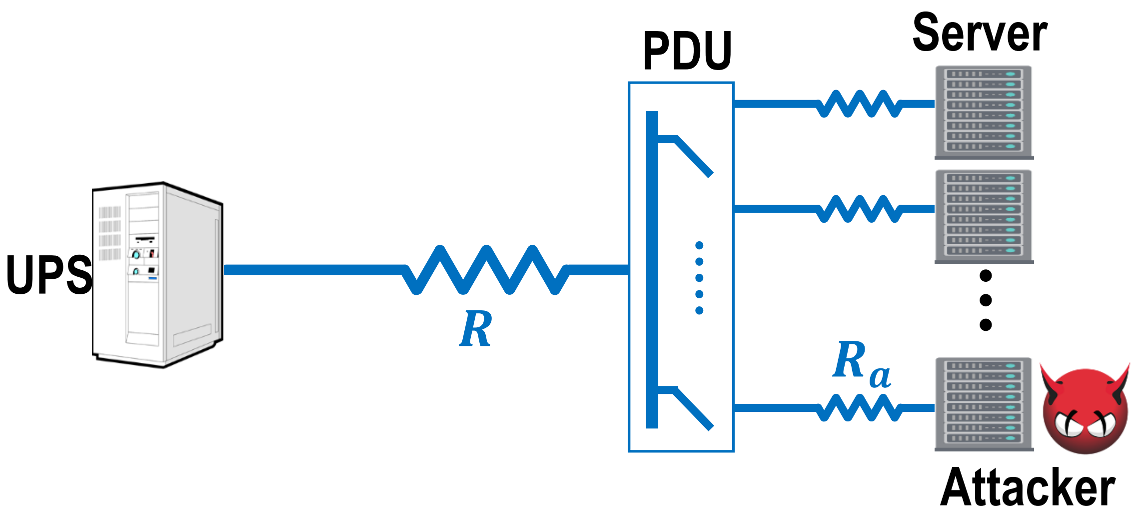
Ohm’s Law



$$\boxed{\mathbf{V_2}} = \mathbf{V_1} - \boxed{\mathbf{I}} \cdot \boldsymbol{R}$$

The voltage at the other end depends on the current

Ohm's Law in data centers



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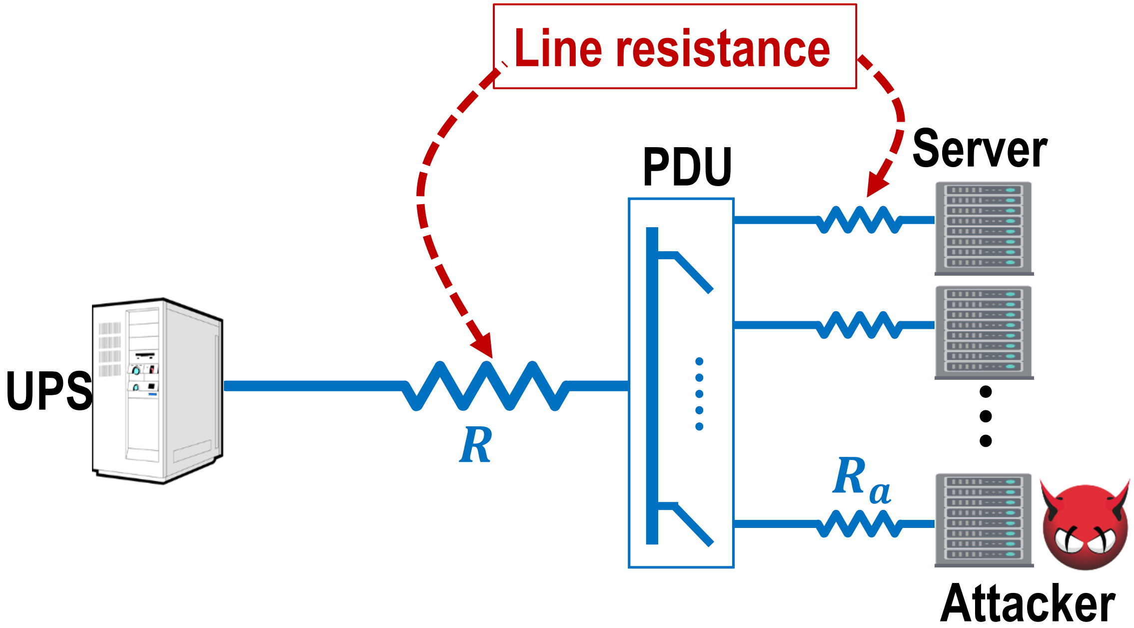

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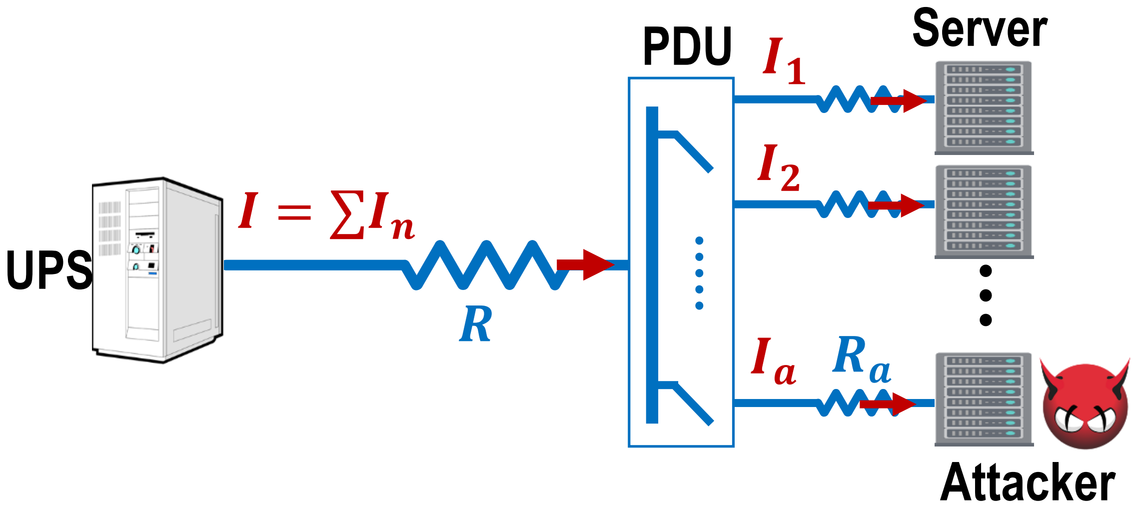

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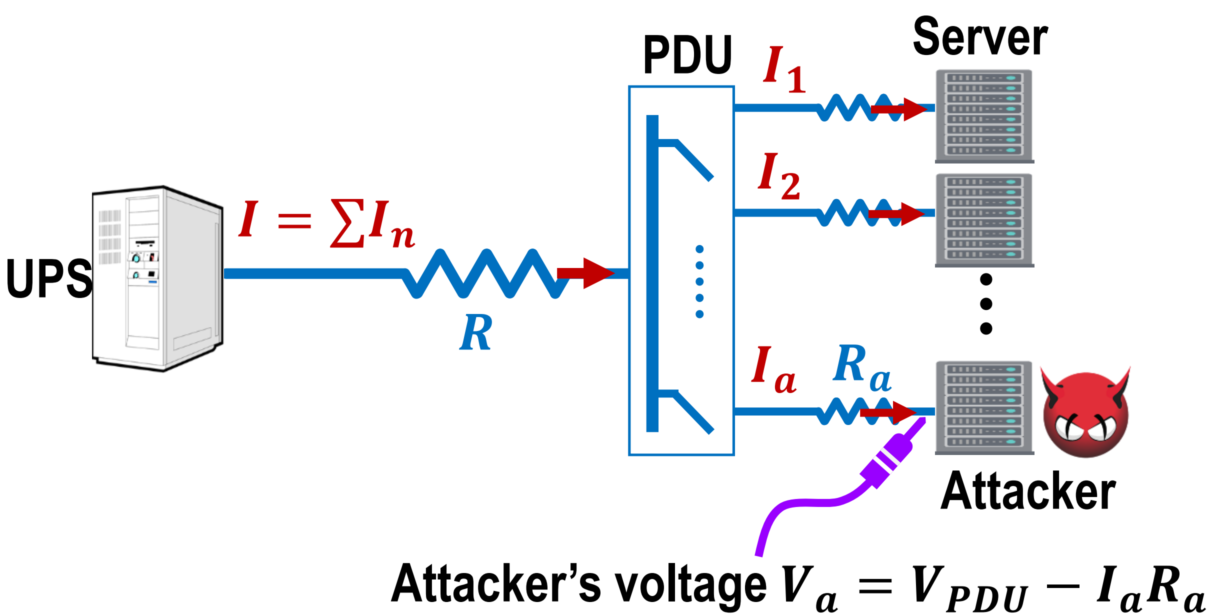

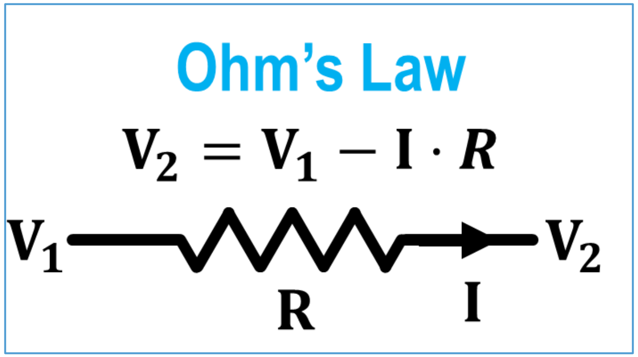

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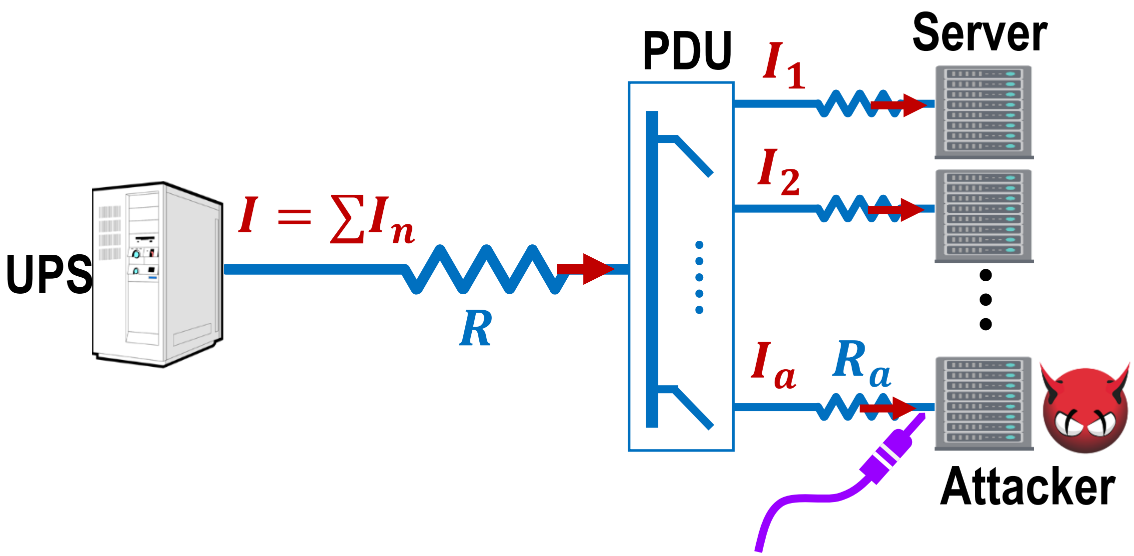

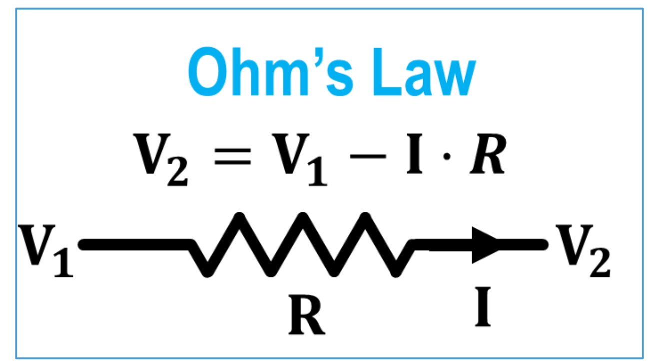

Attacker’s voltage $V_a = V_{PDU} - I_a R_a$

$$= \overbrace{V_{UPS} - \boxed{\sum I_n R}} - \boxed{I_a R_a}$$

Power load is included in V_a

Own impact

A voltage side channel

Attacker's voltage $V_a = V_{UPS} - \boxed{\sum I_n R} - I_a R_a$

A voltage side channel

ΔV based attack:

Low voltage → High current/load→ Attack opportunity?

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Large random variation from power grid

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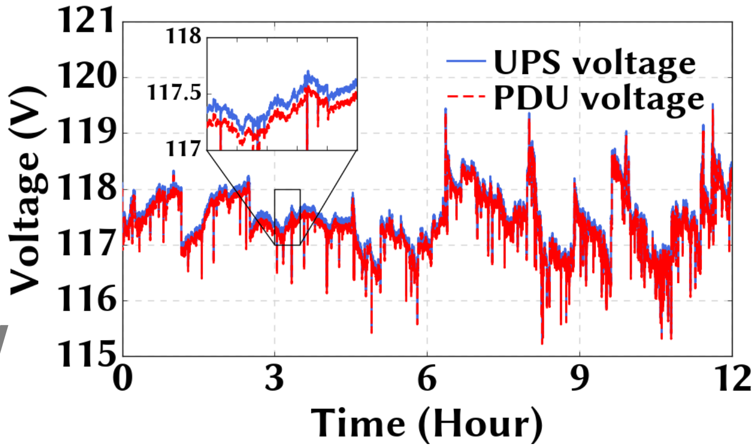
Large random variation
from power grid



- Grid variation = ~3V
- Voltage drop variation = ~10mV

A voltage side channel

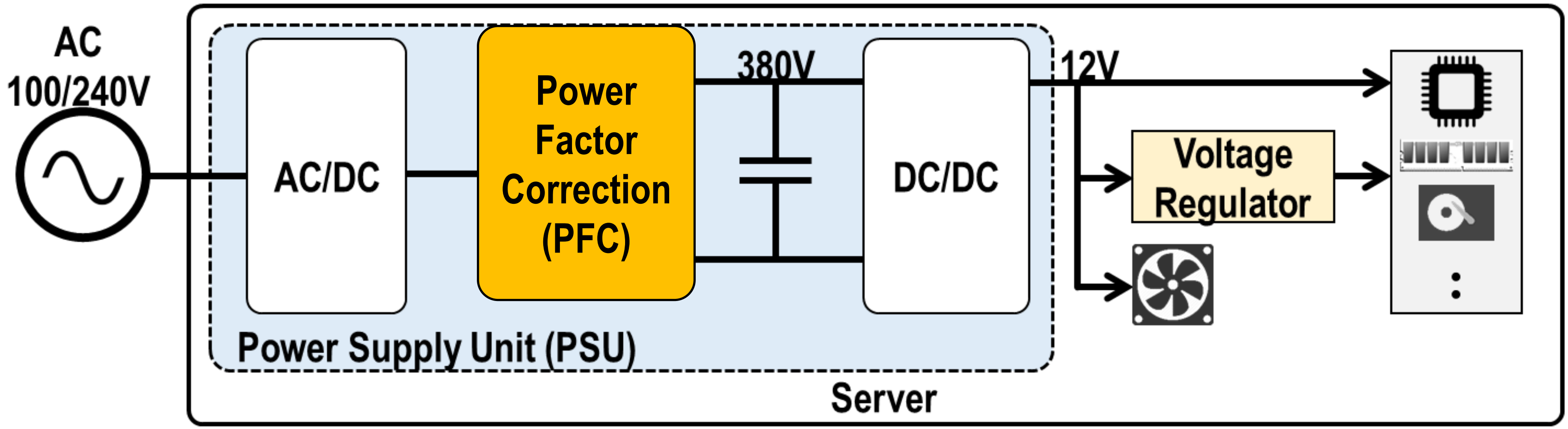
ΔV based attack:
Low voltage → High current/load → Attack opportunity?

How to extract power load information from voltage signals?

Large random variation from power grid

- Grid variation = ~3V
- Voltage drop variation = ~10mV

A closer look at server's power supply



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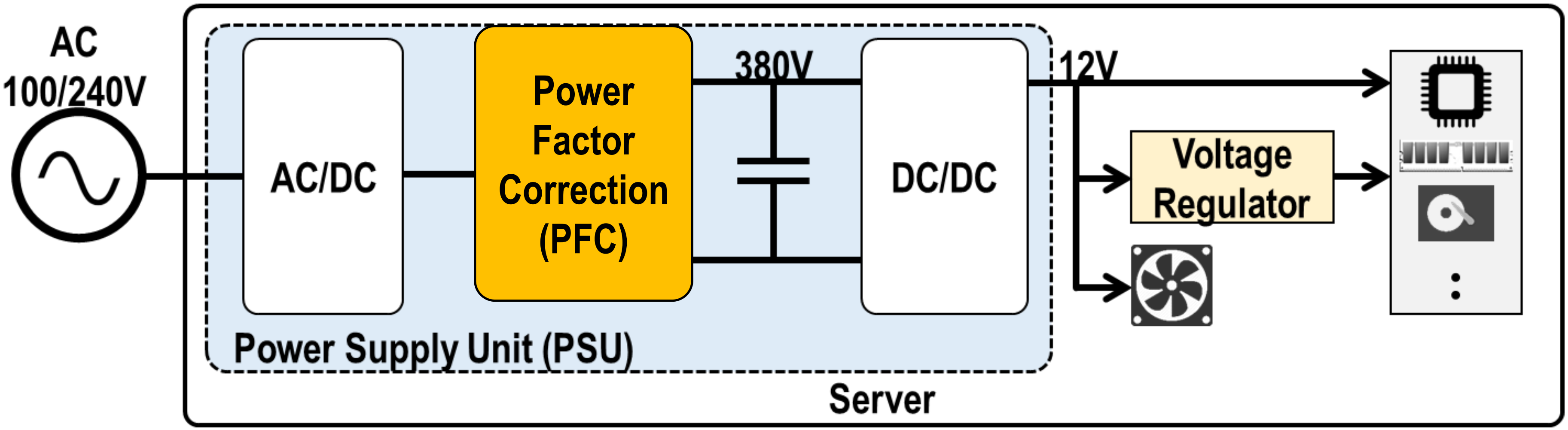
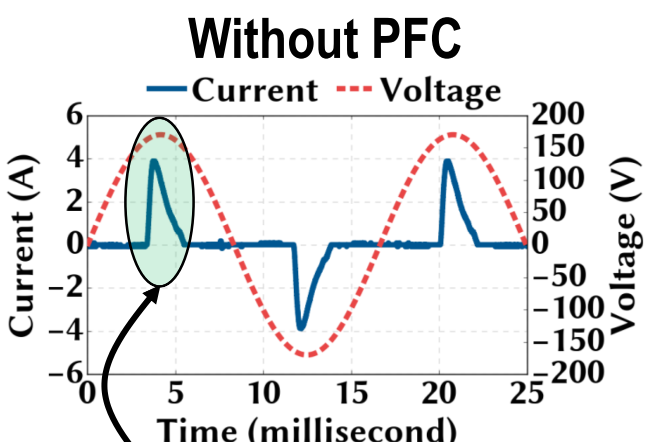
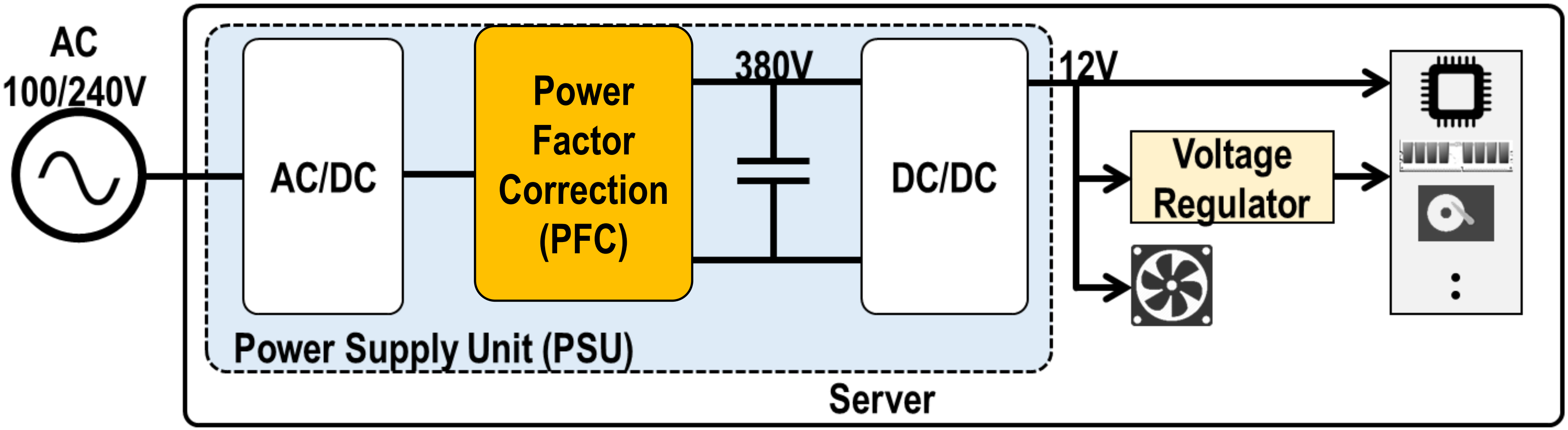
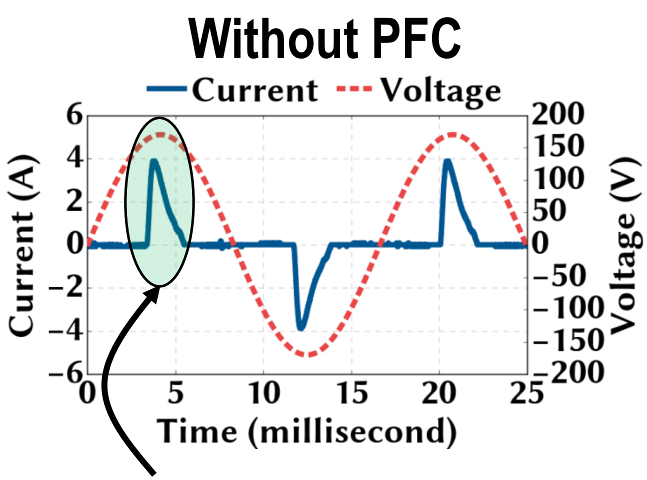




Current draw is bursty

A closer look at server’s power supply





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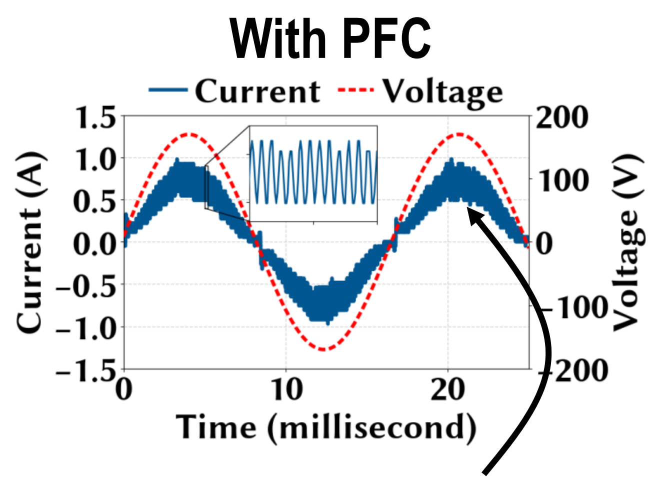
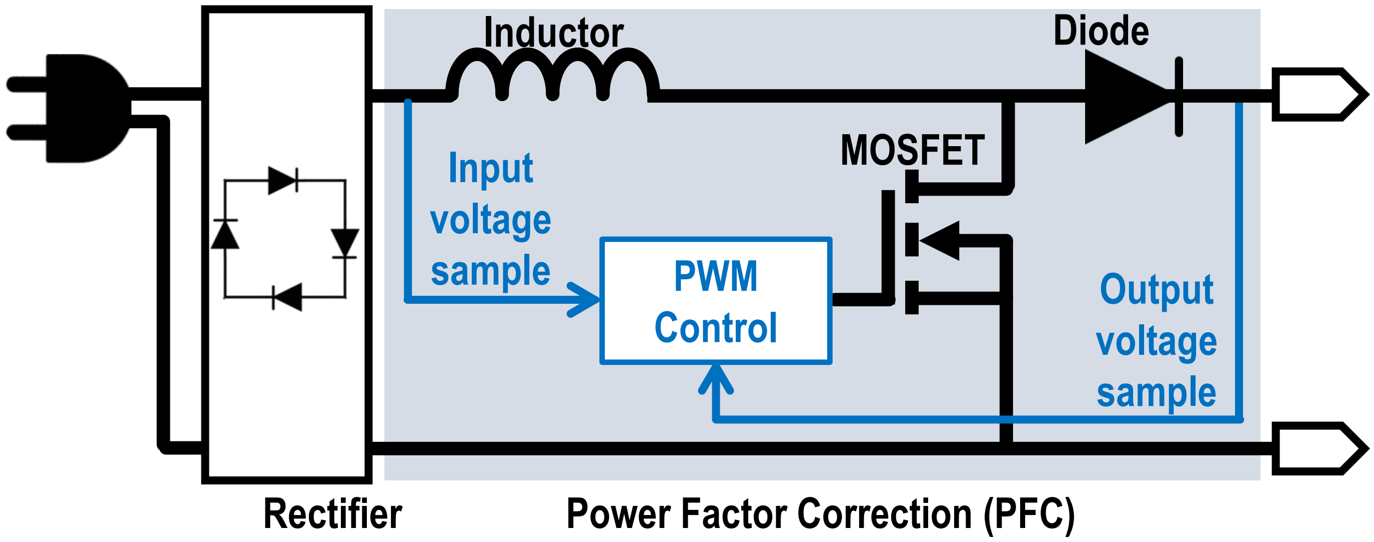


Current follows a sinewave with **high-frequency ripples**

The ripples come from the PFC control



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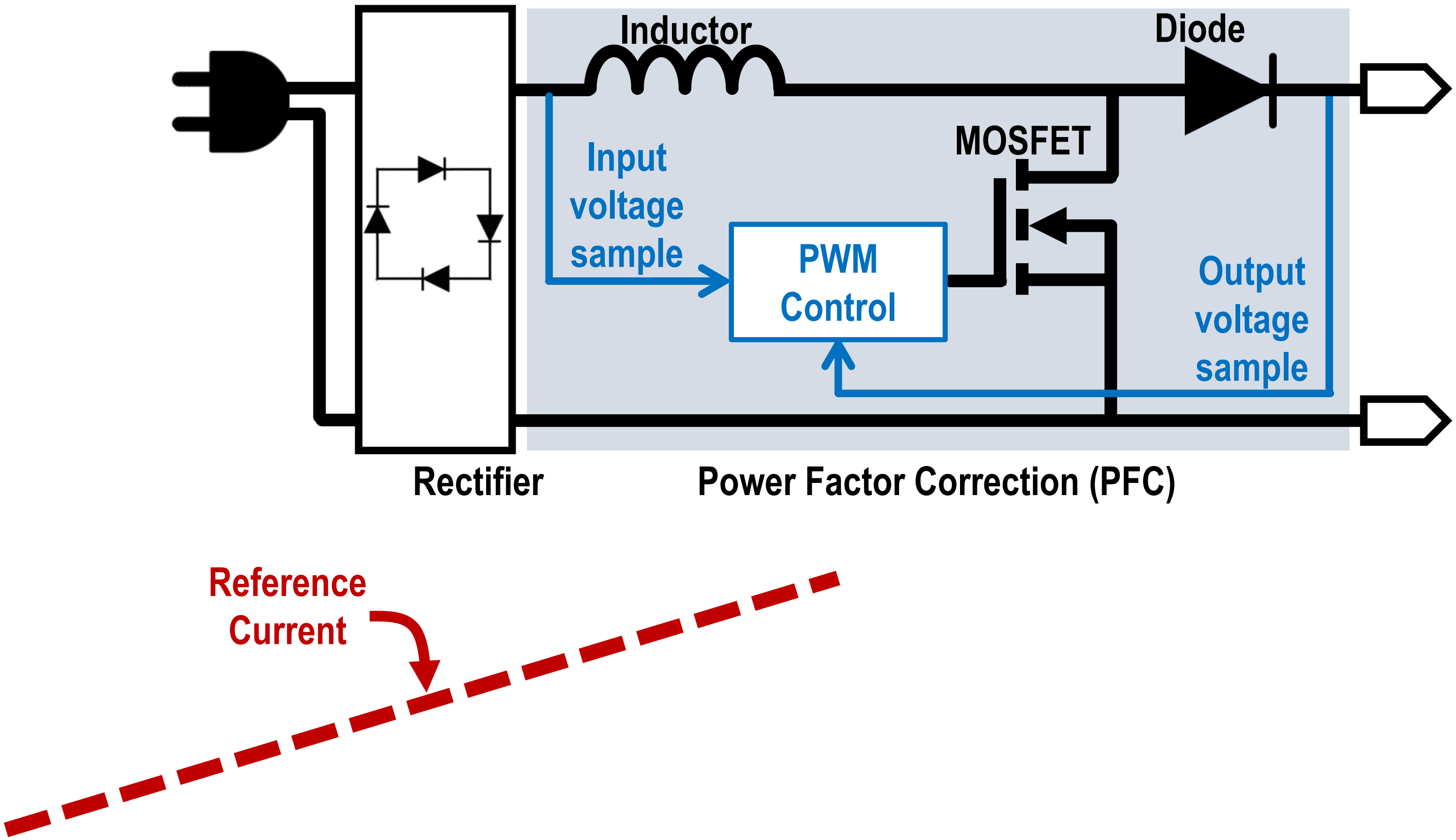

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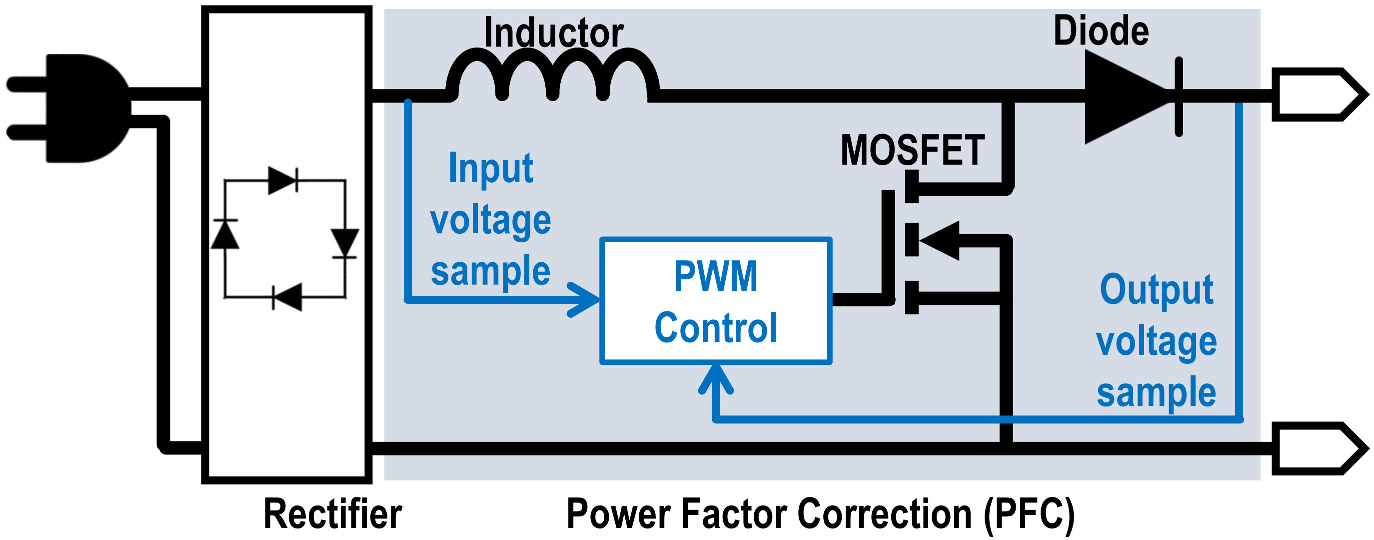

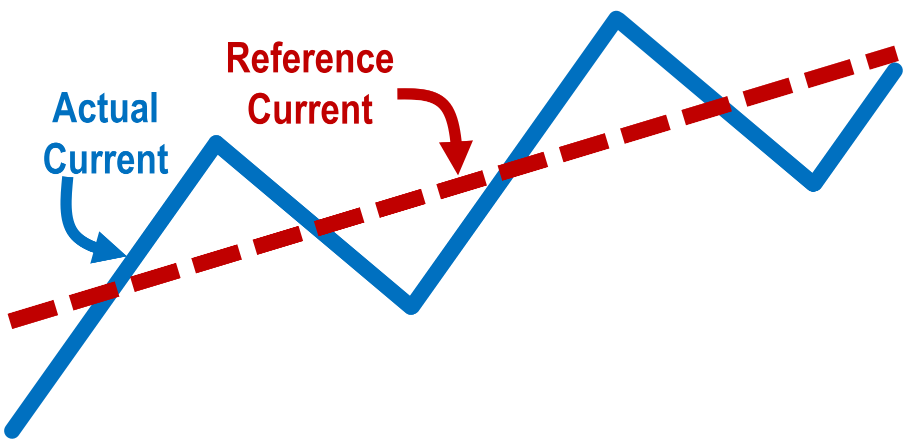

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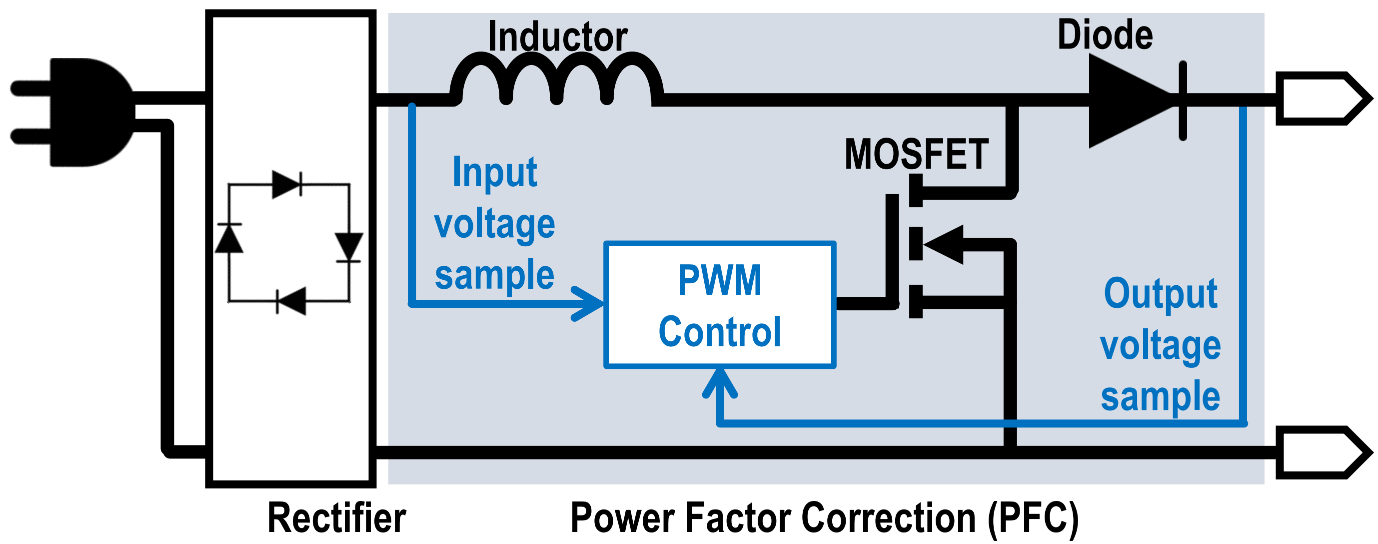

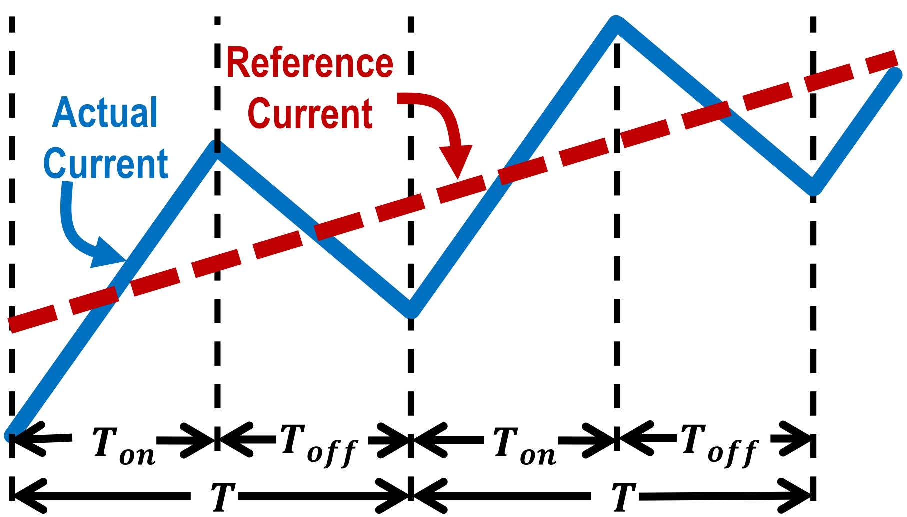

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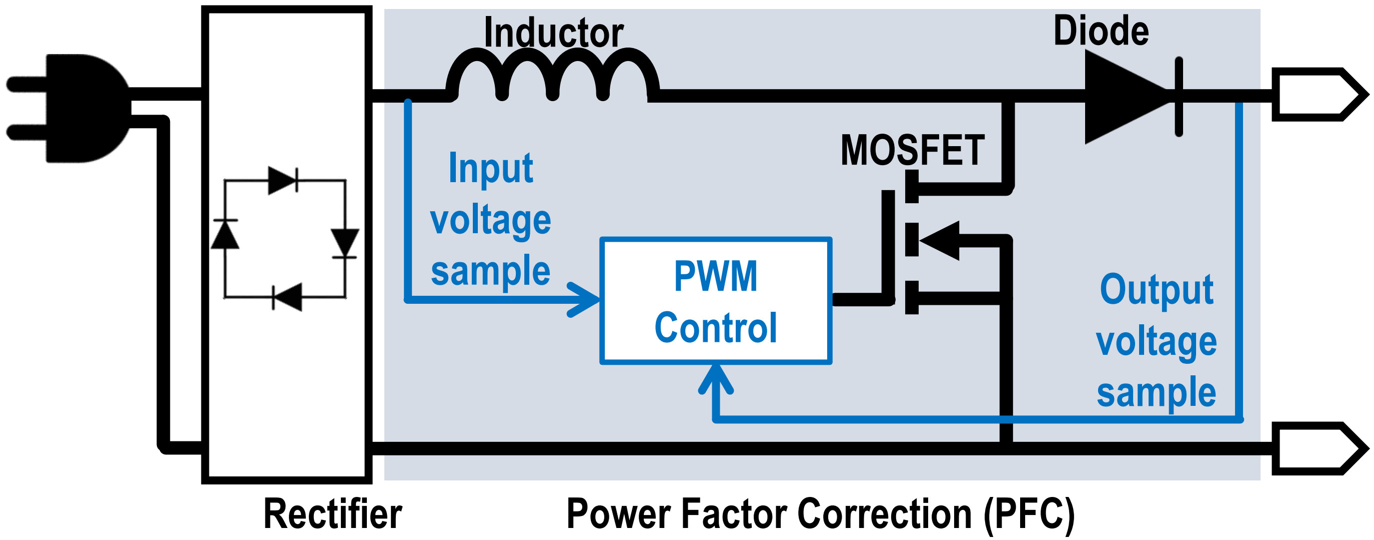
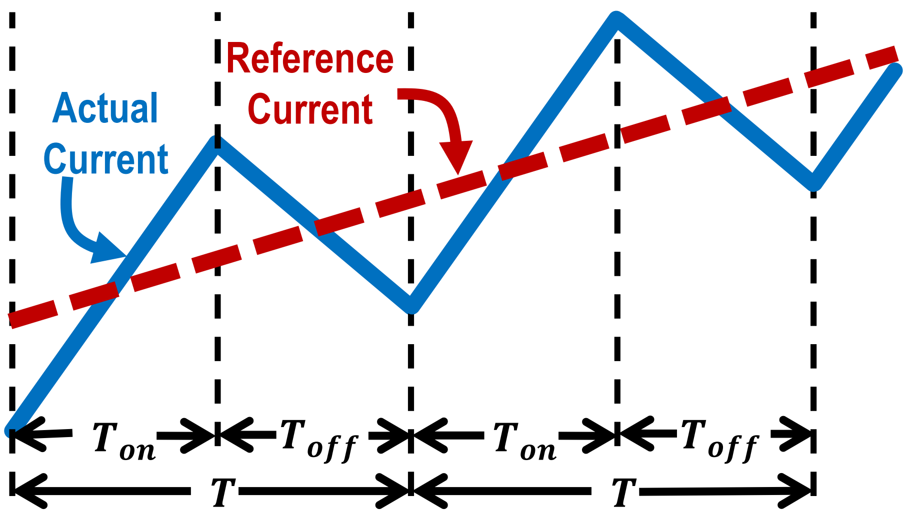
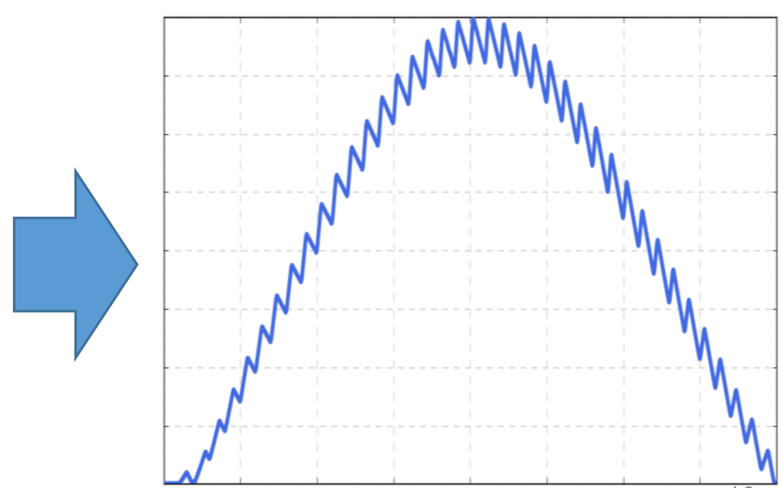
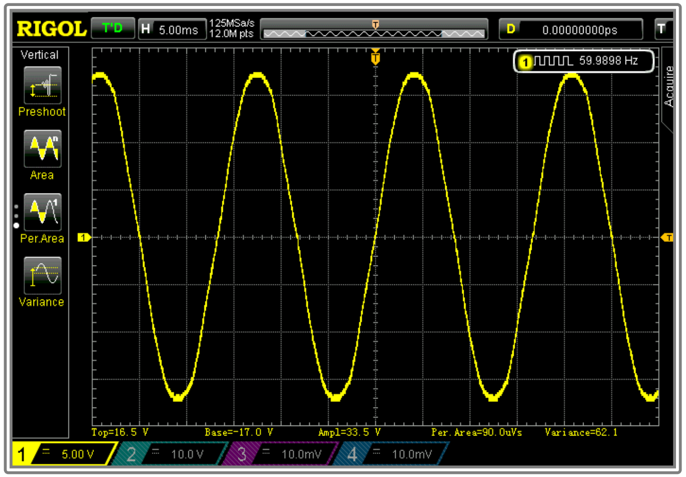






Voltage measurement of a Dell server



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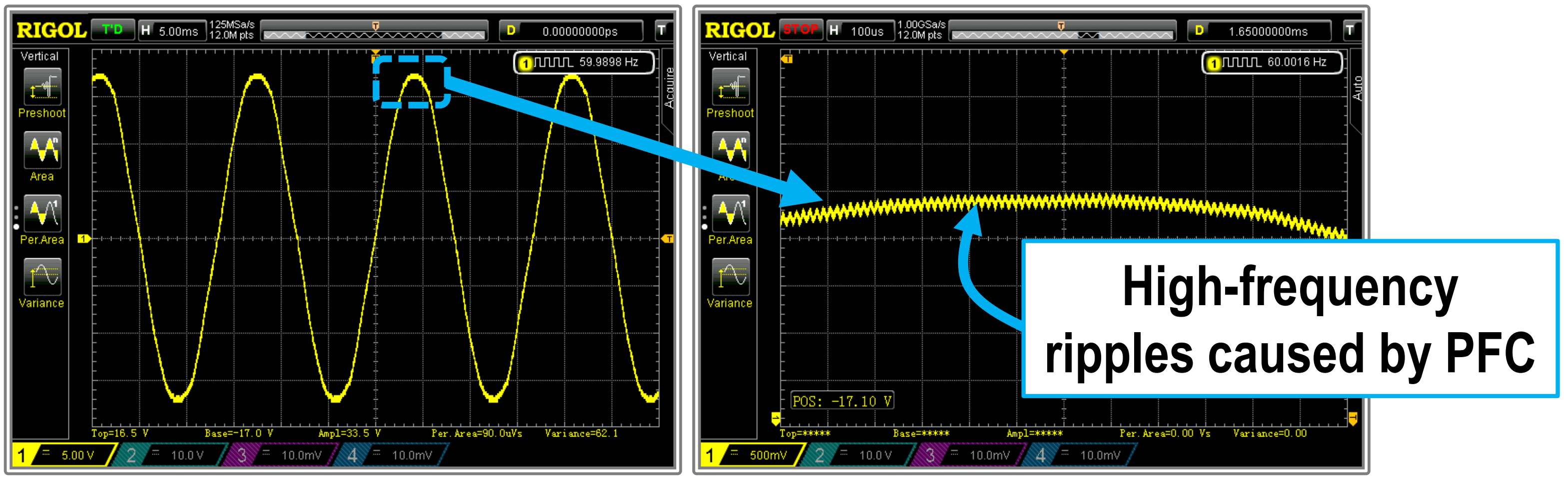

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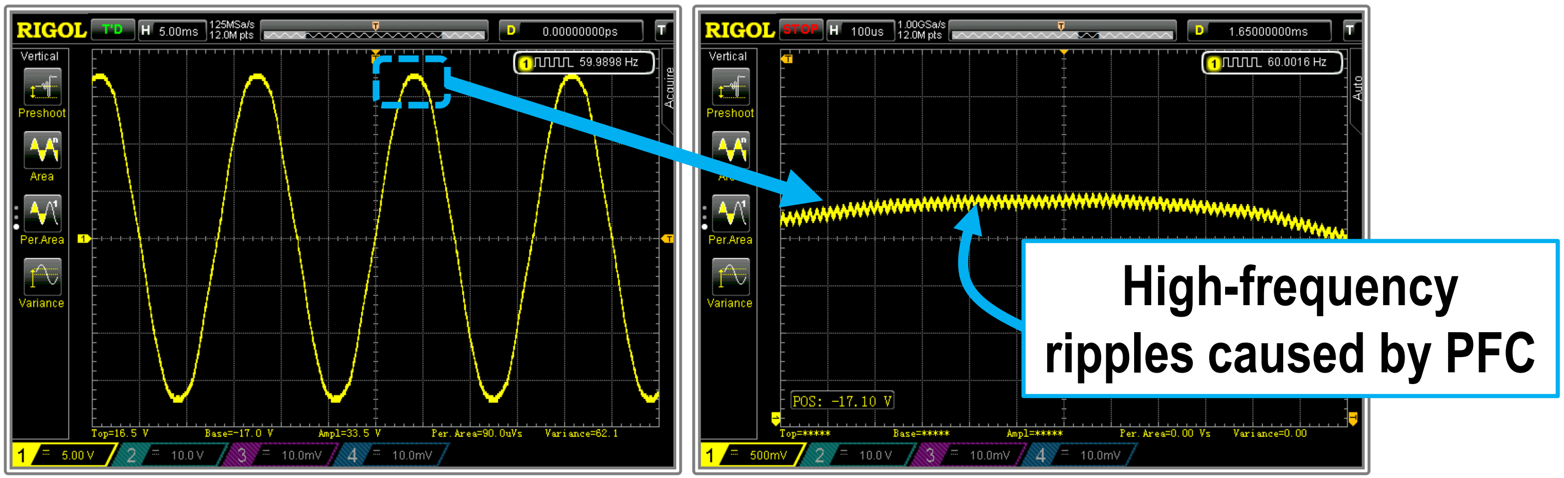
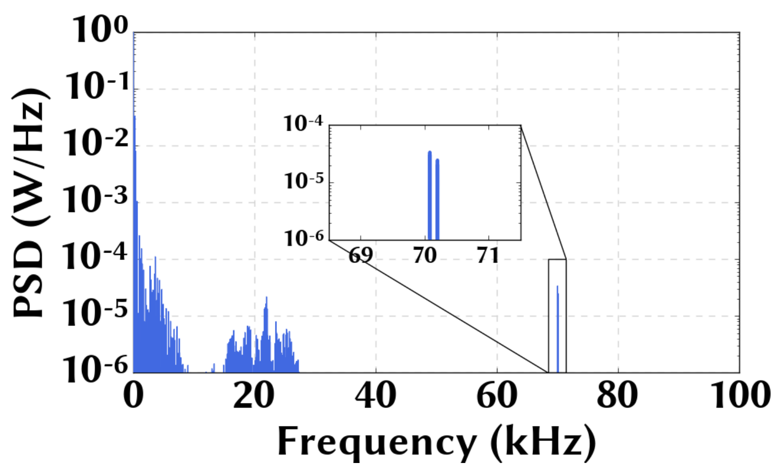


Frequency analysis of the voltage signal



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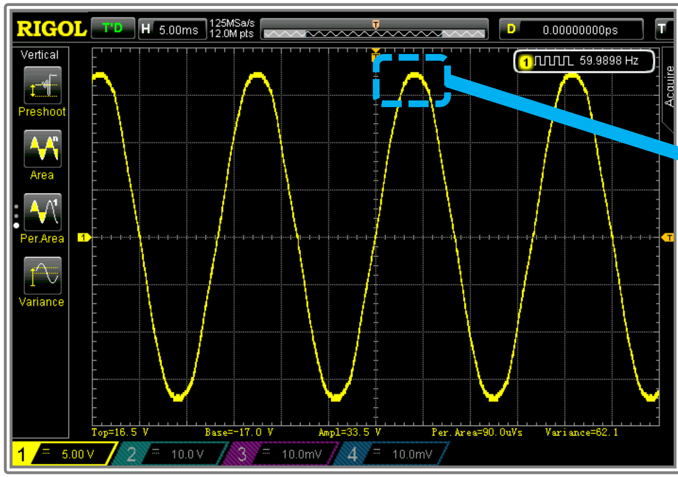
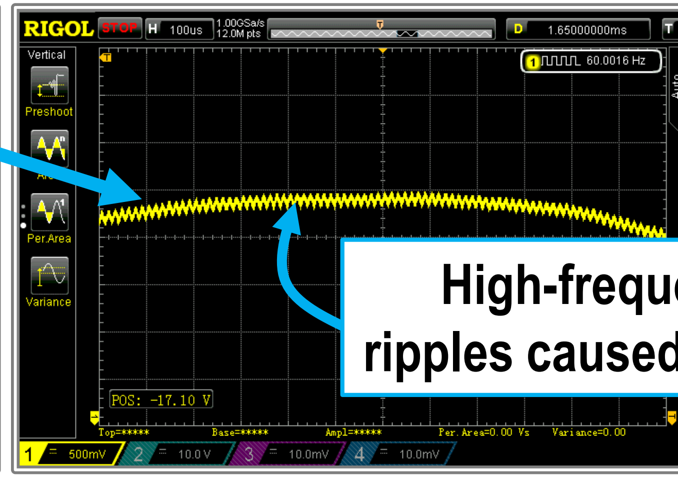
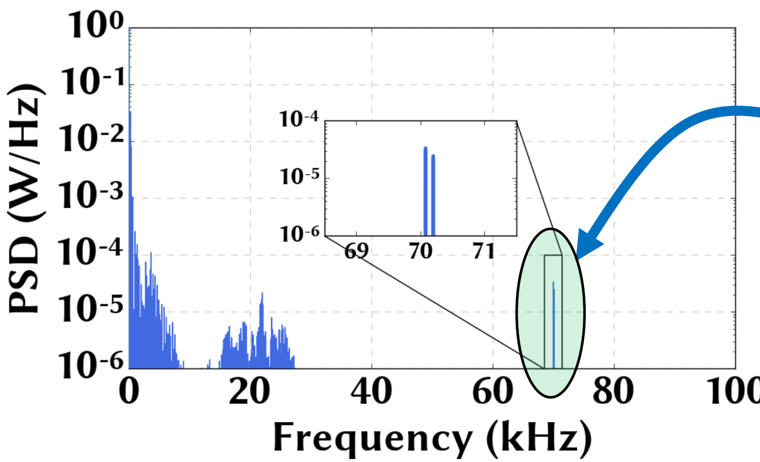




High-frequency ripples caused by PFC

Frequency analysis of the voltage signal



Frequency spike
(at PFC switching frequency)

Can we estimate the power load based on frequency spikes?

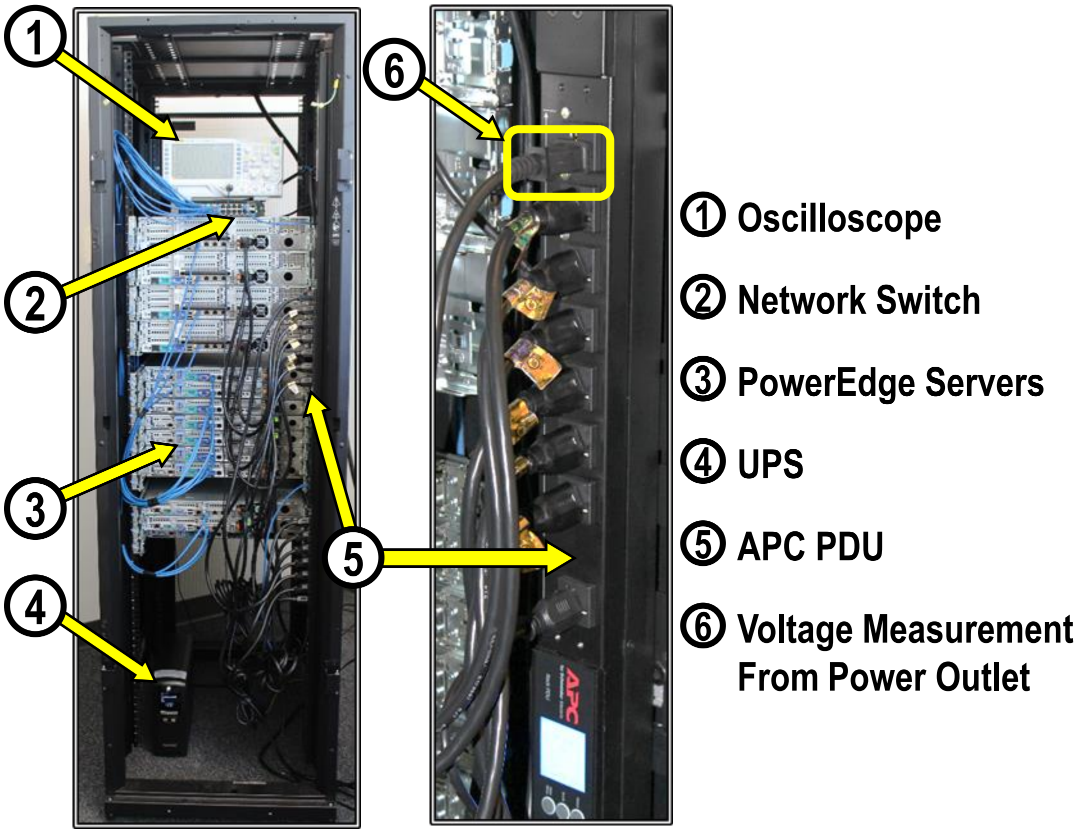
Can we estimate the power load based on frequency spikes?

Our intuition says "yes"!

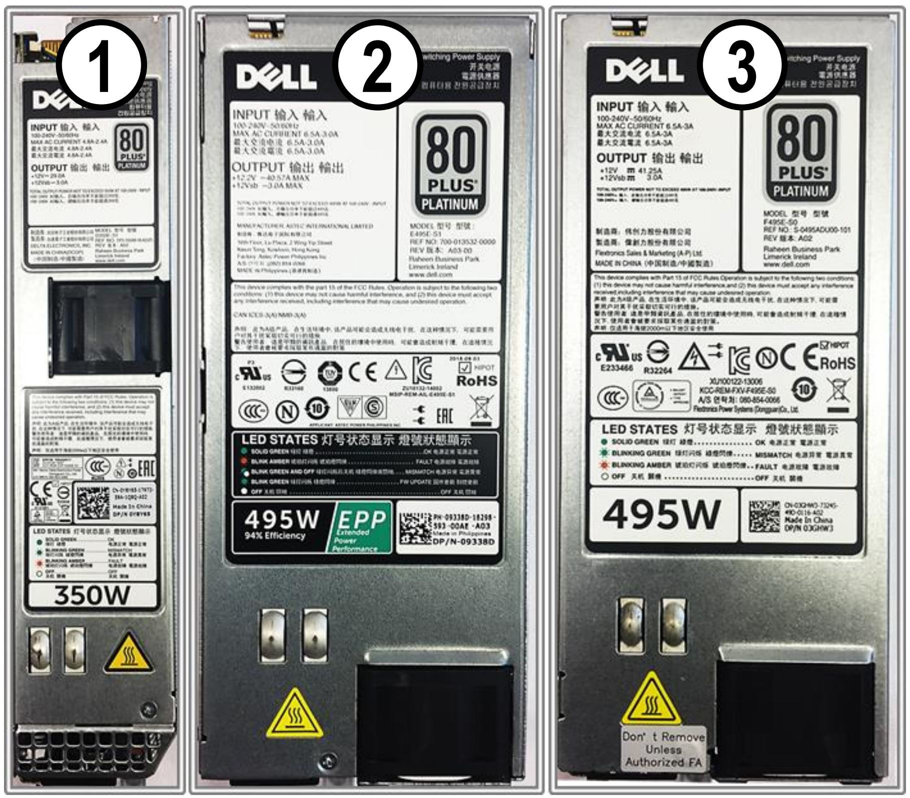
Given a higher current, the ripples need to rise up more during each cycle.

Experiment

- **13 Dell PowerEdge servers**
- **3 different server configurations**
- **3 different types of power supply units**



Power supplies

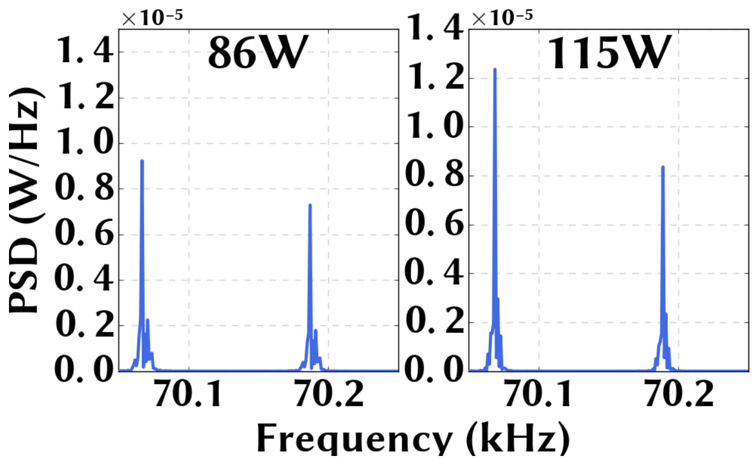


① 350W, PFC Switching ~63kHz
Model: D35E-S1
Manufacturer: Delta Electronics Inc.

② 495W, PFC Switching ~66kHz
Model: F495E-S0
Manufacturer: Astec Intl. Ltd.

③ 495W, PFC Switching ~70kHz
Model: E495E-S1
Manufacturer: Flextronics Intl. Ltd.

PSD vs. server power



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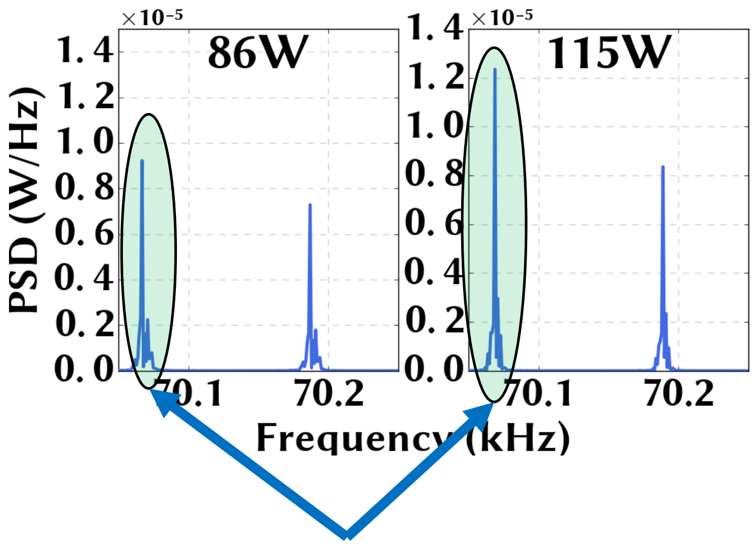
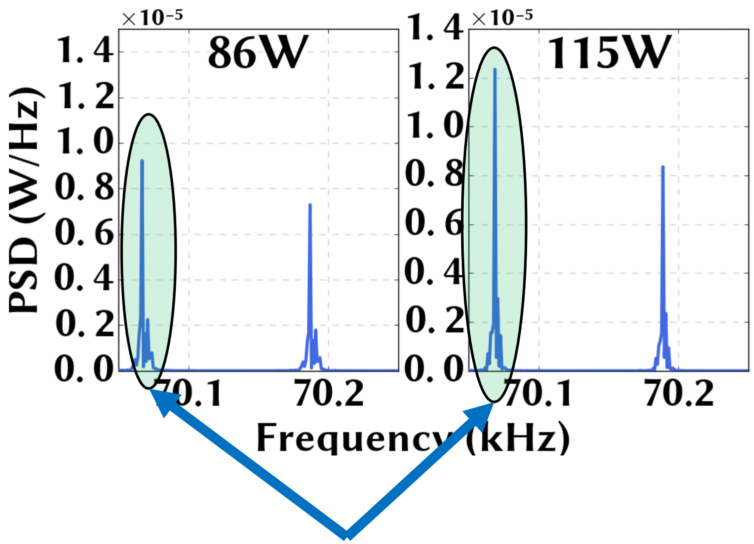
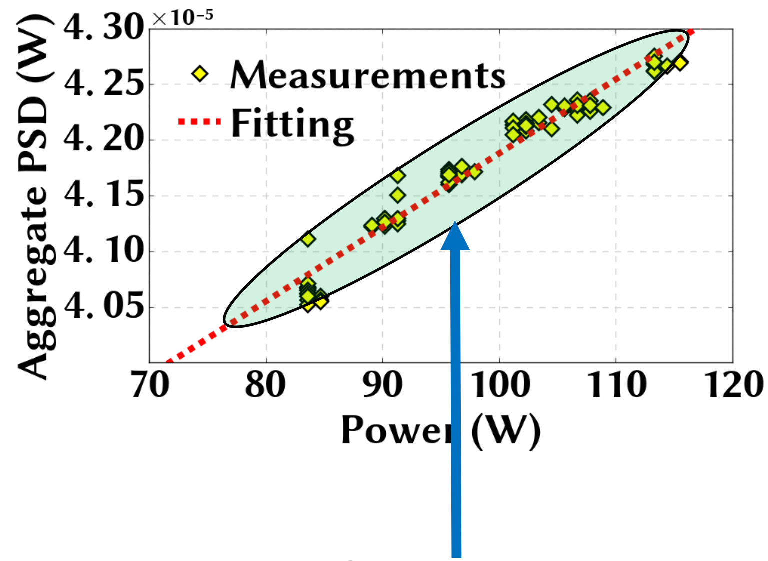


Higher power creates taller frequency spikes

PSD vs. server power

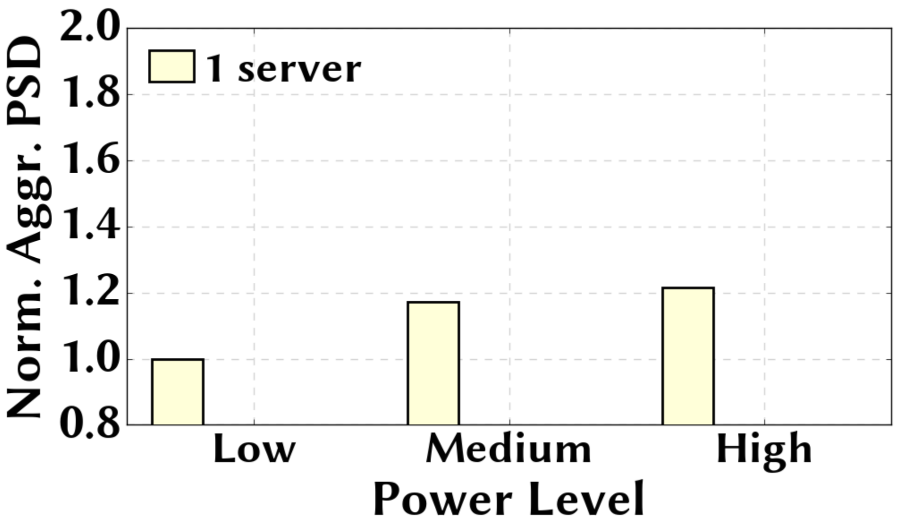




Higher power creates taller frequency spikes

Aggregate PSD monotonically increases with server power

PSD vs. server power



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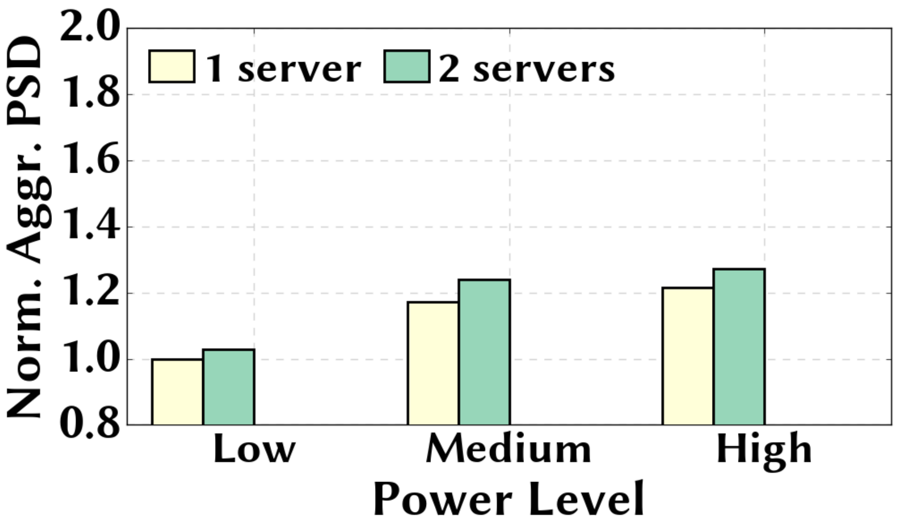
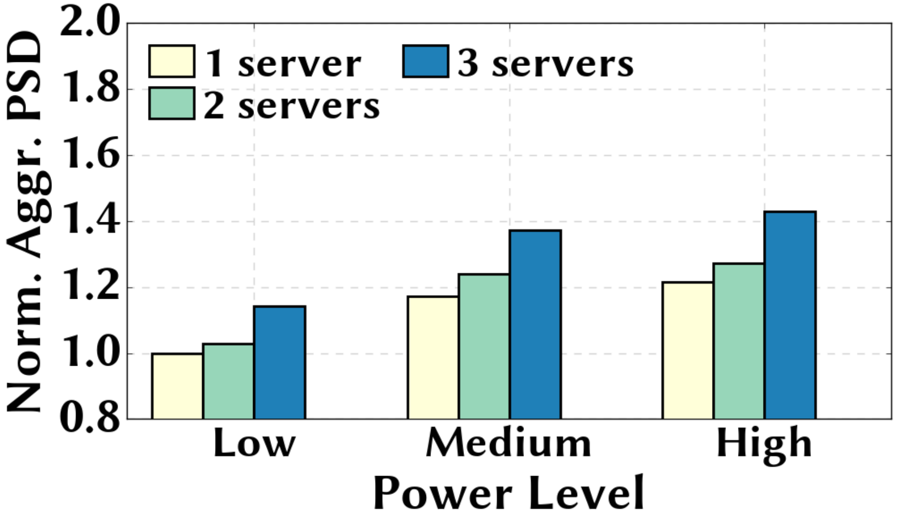
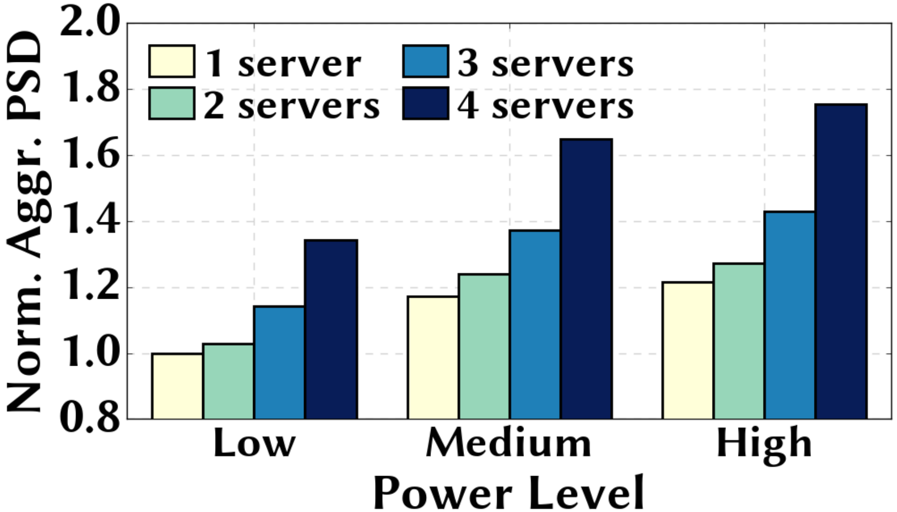


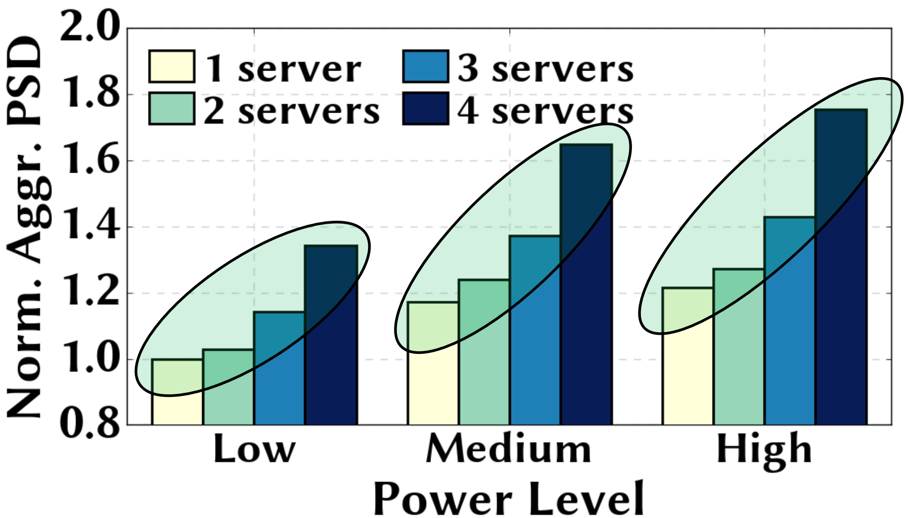
PSD vs. server power



PSD vs. server power

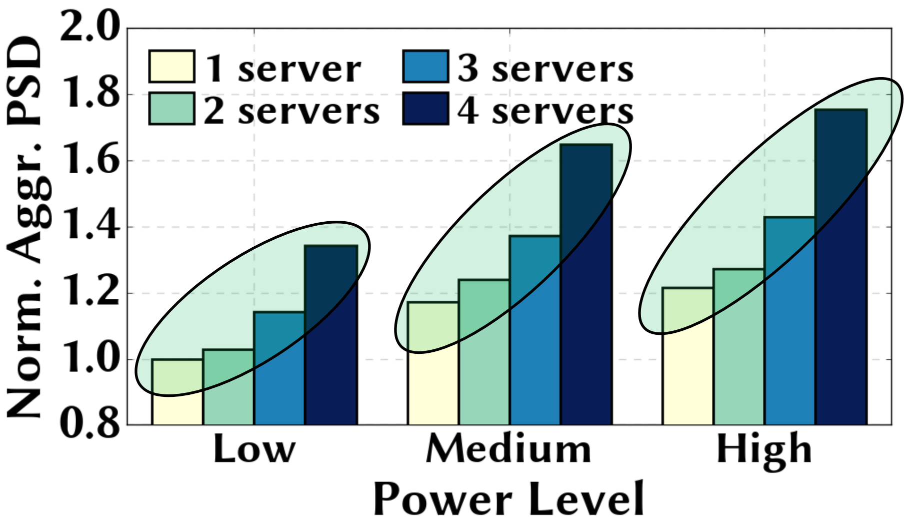


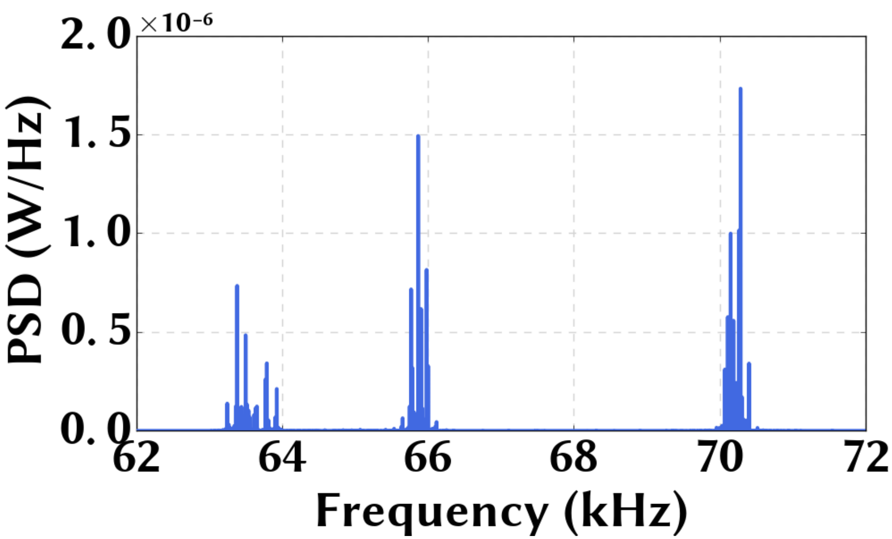
PSD vs. server power



Aggregate PSD is additive for multiple servers with similar PFC frequencies

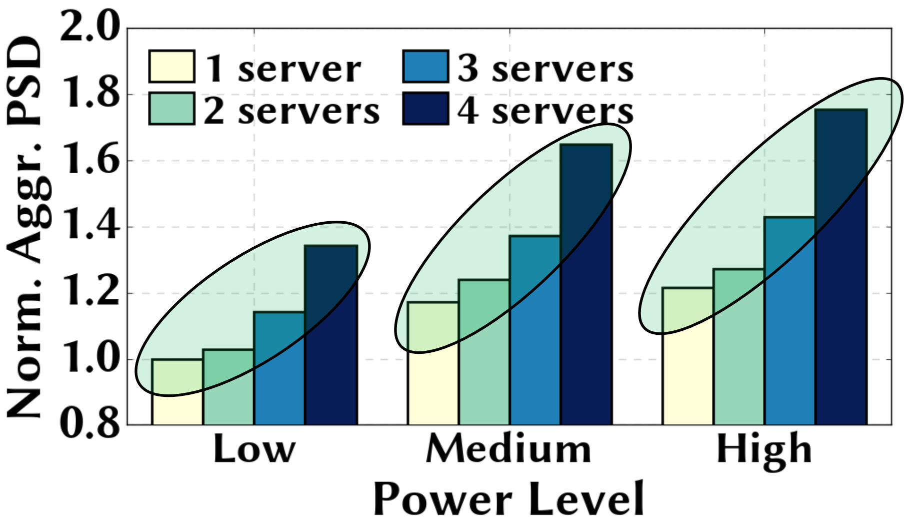
PSD vs. server power



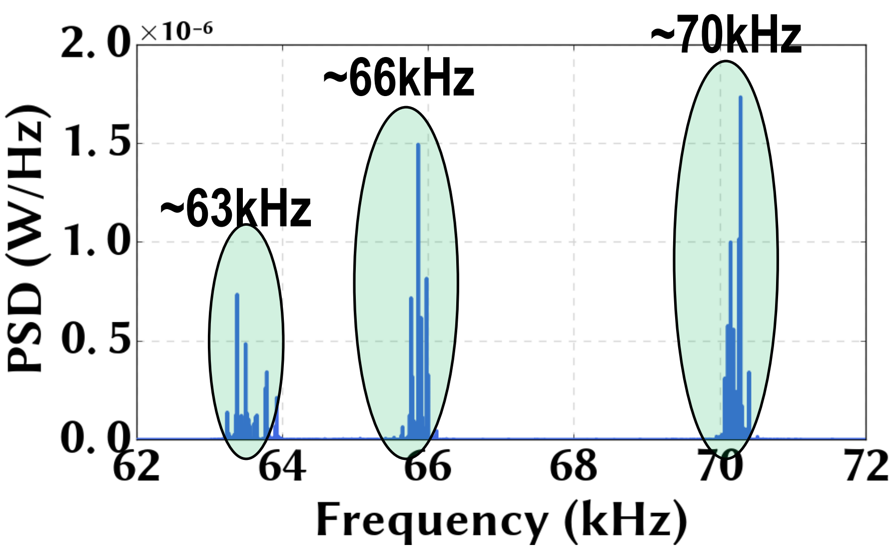


Aggregate PSD is additive for multiple servers with similar PFC frequencies

PSD vs. server power

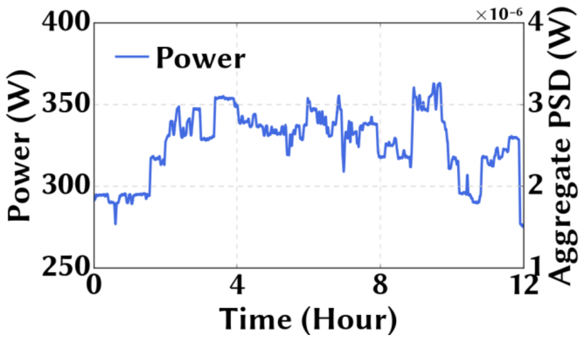


Aggregate PSD is additive for multiple servers with similar PFC frequencies

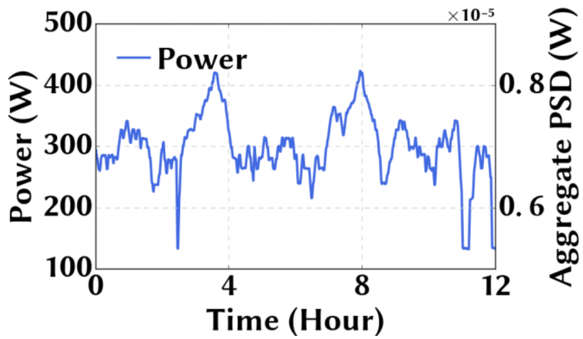


Frequency spikes are separated for different types of power supply units

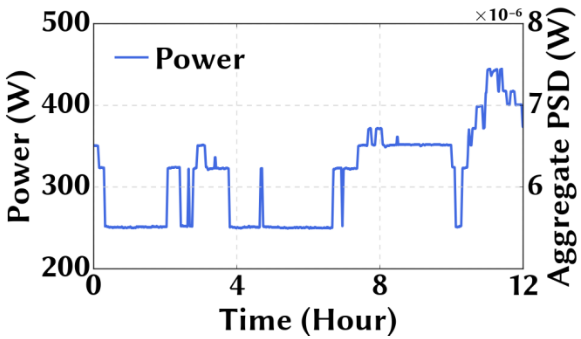
Accuracy of the voltage side channel



Tenant #1

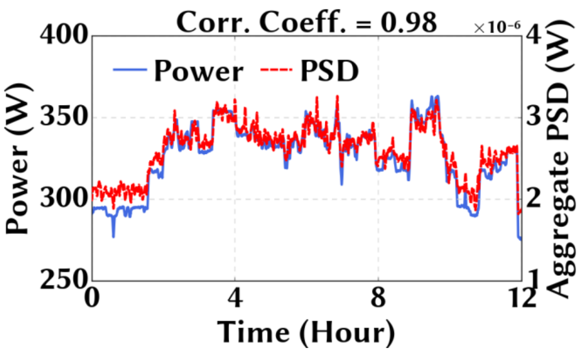


Tenant #2

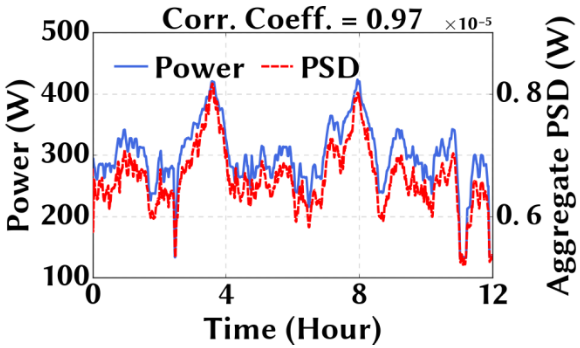


Tenant #3

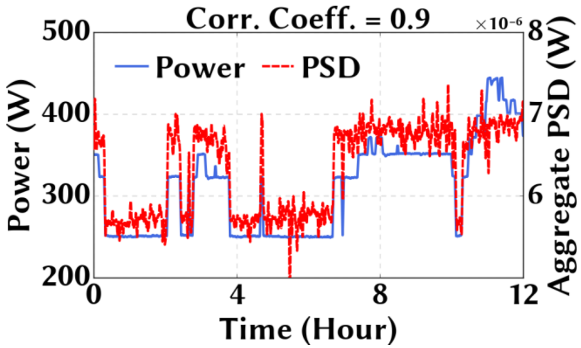
Accuracy of the voltage side channel



Tenant #1



Tenant #2

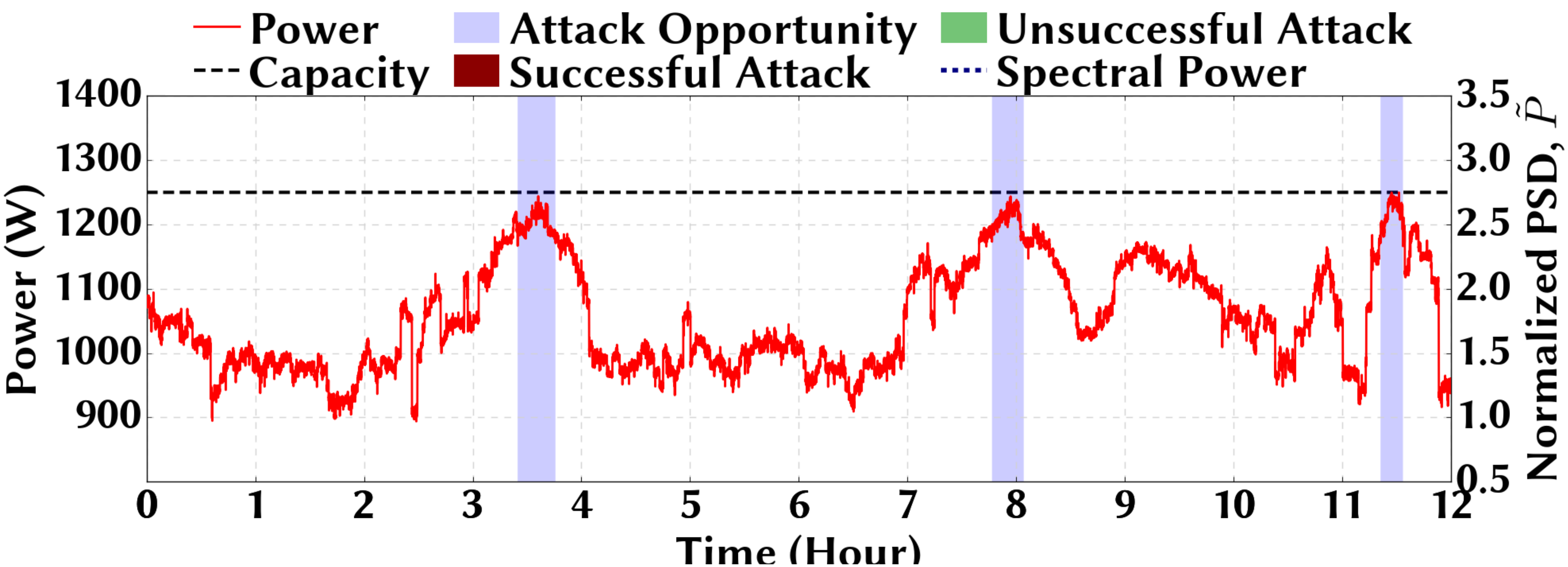


Tenant #3

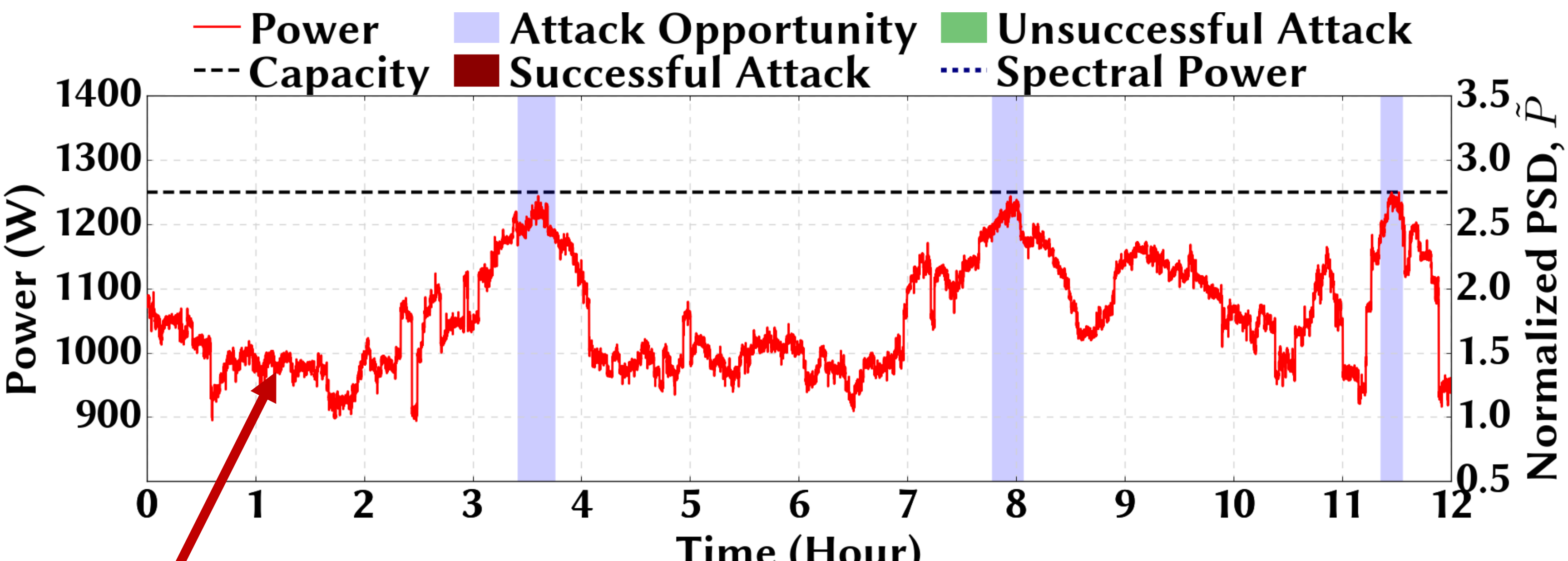
Estimating power loads with a high accuracy!

Attack only when the estimated power load is sufficiently high

Power attack

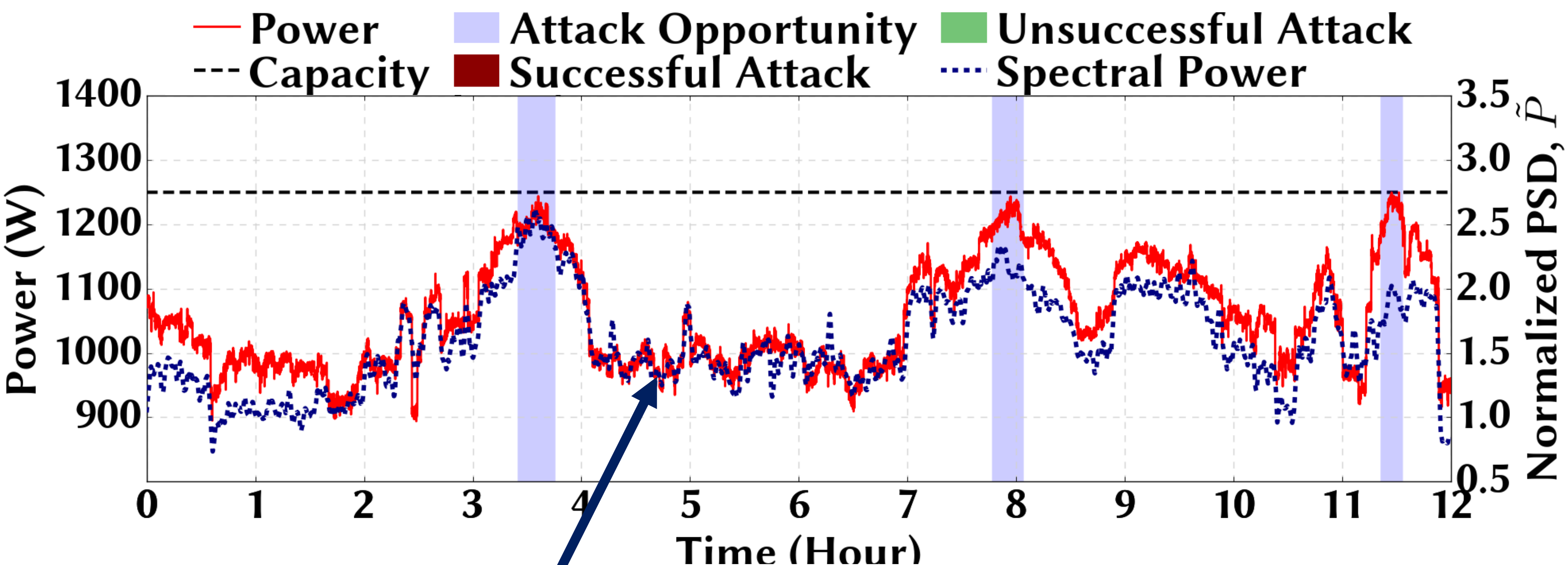


Power attack



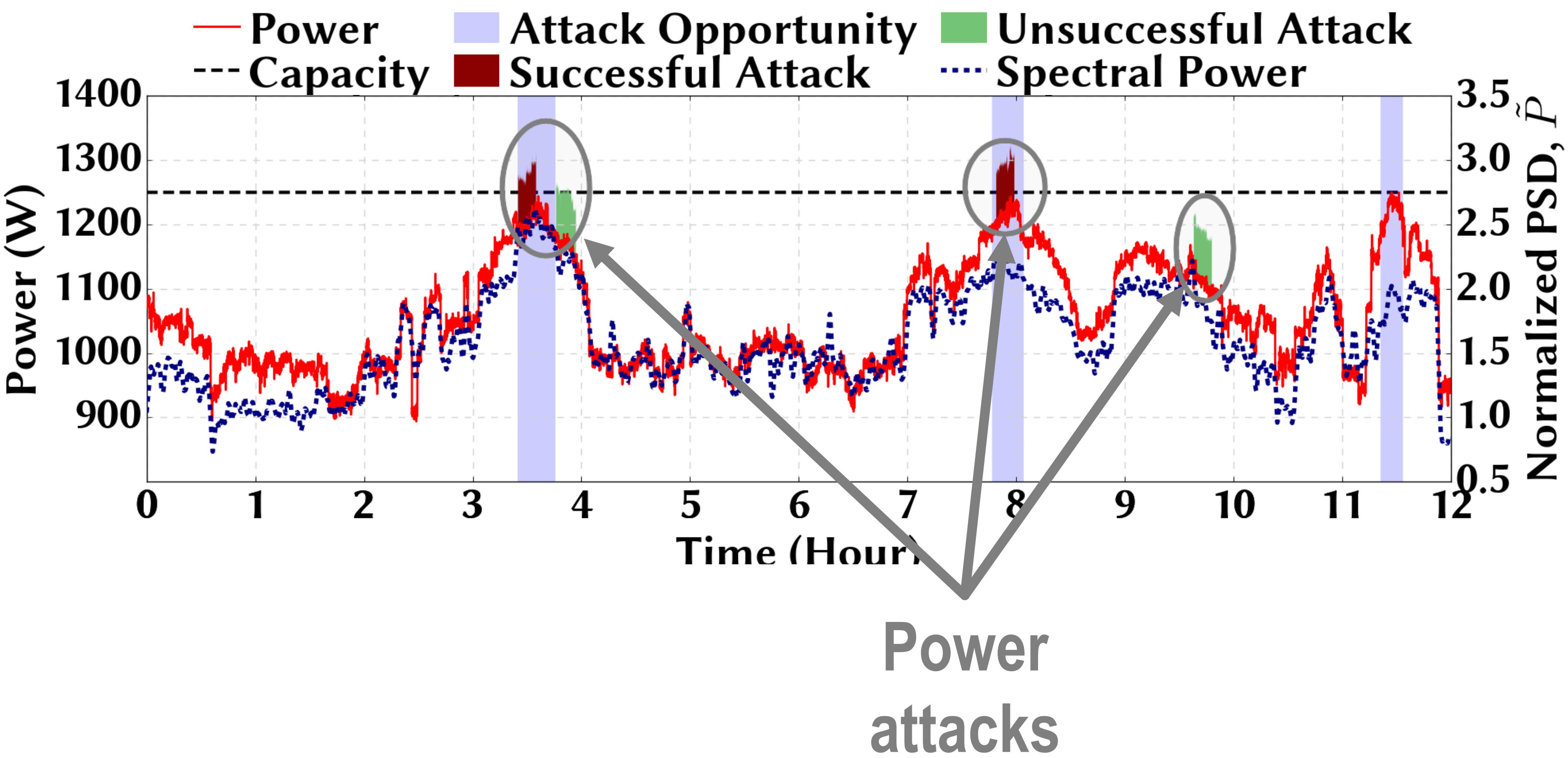
Tenants' total power

Power attack

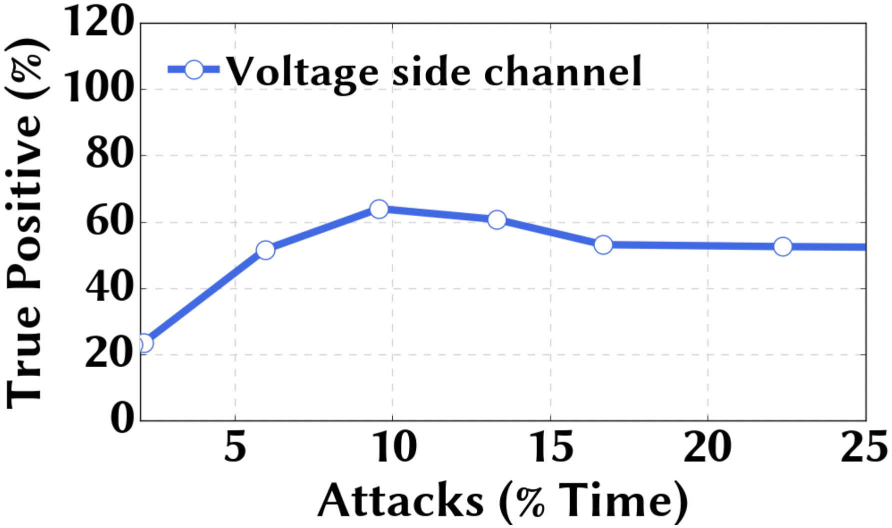


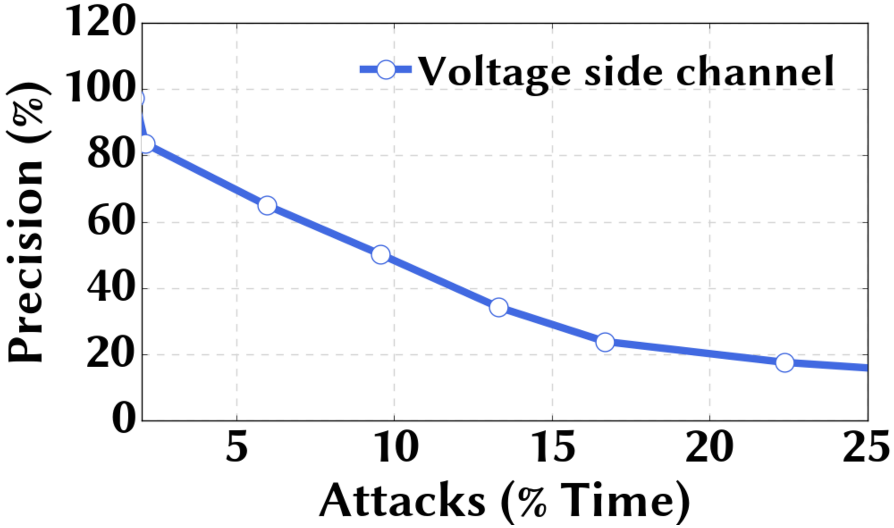
Estimated power loads

Power attack

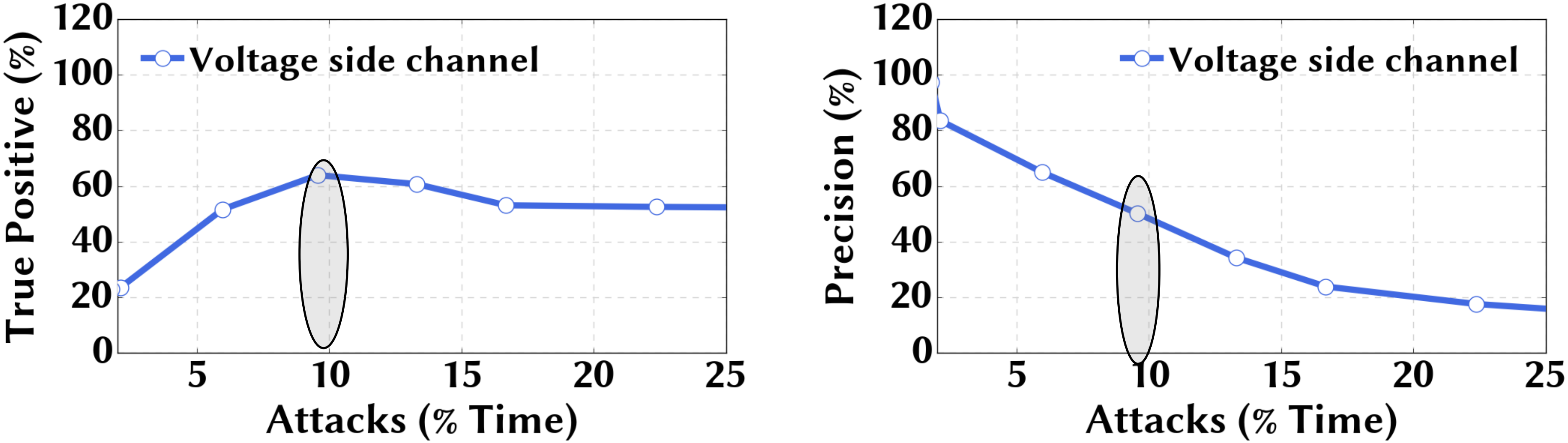


Timing accuracy



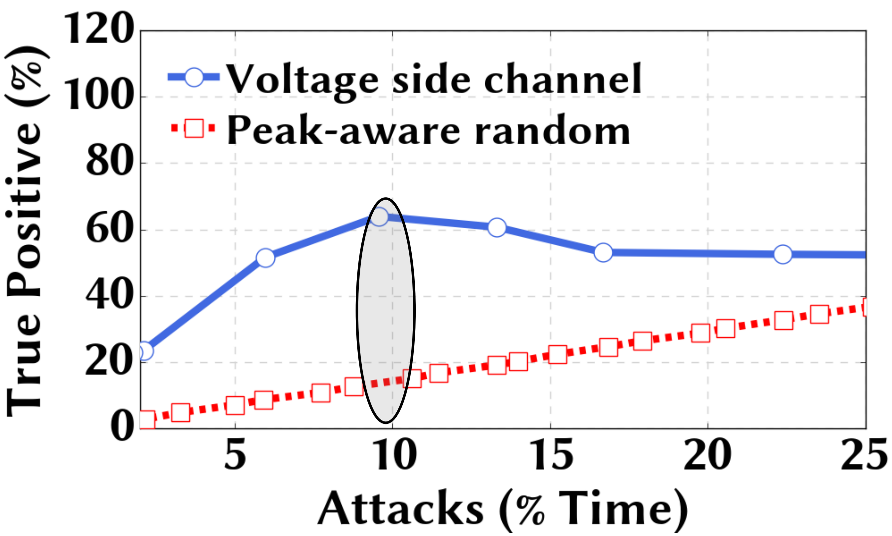


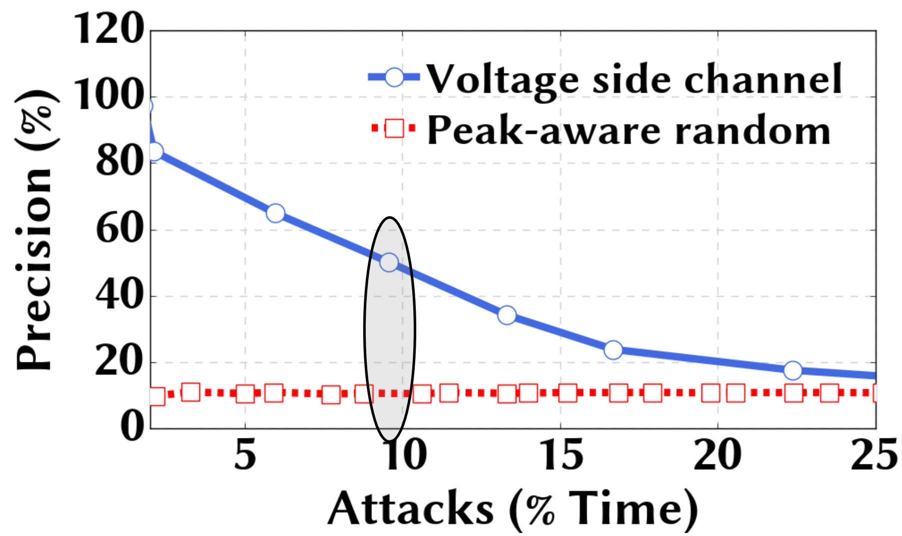
Timing accuracy



>50% true positive rate and precision for ~10% attack

Timing accuracy





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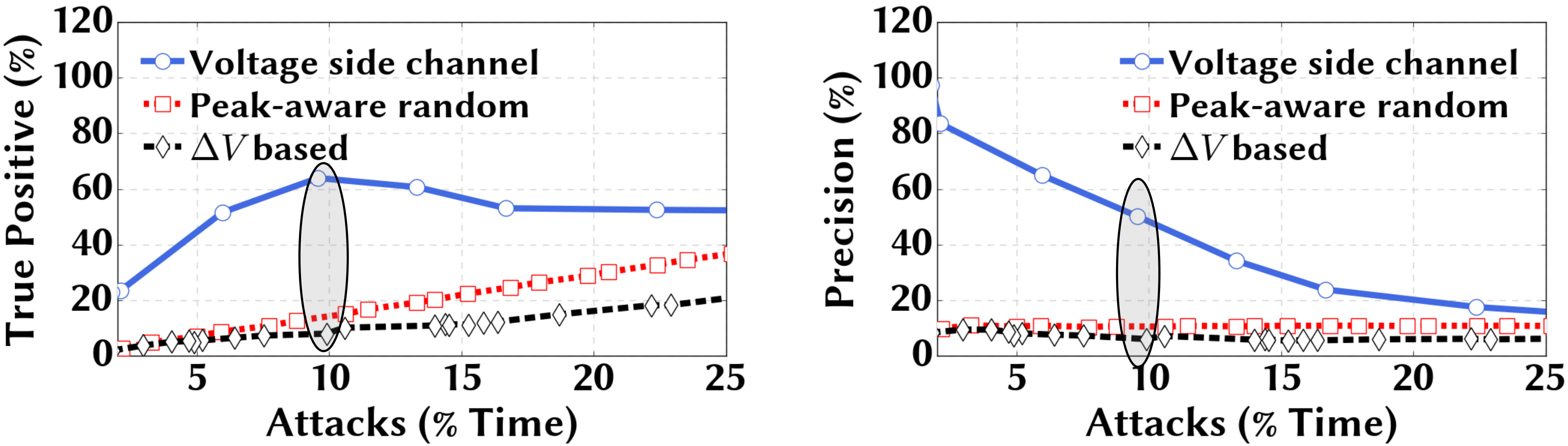

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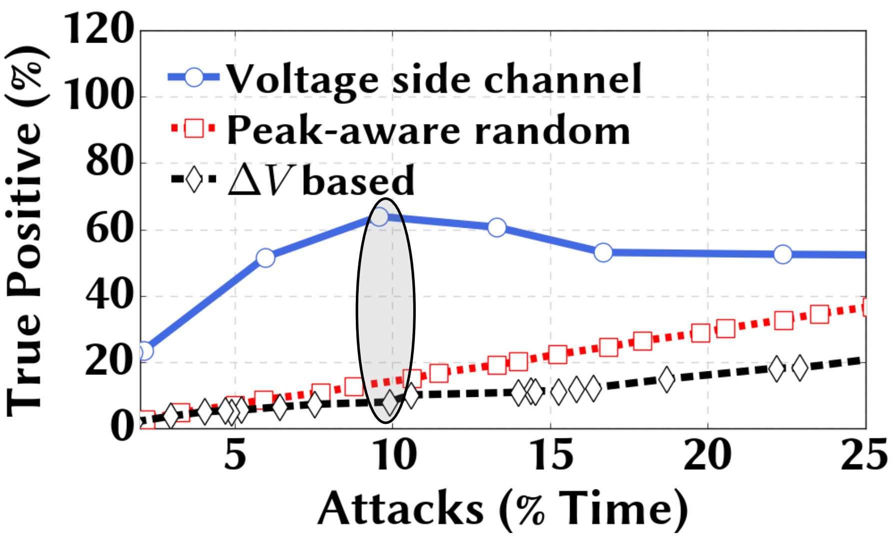
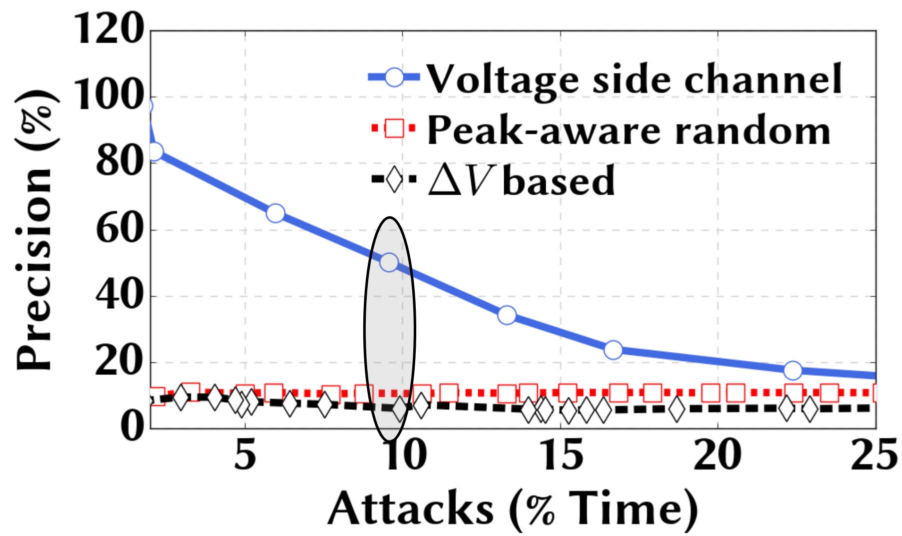
Timing accuracy

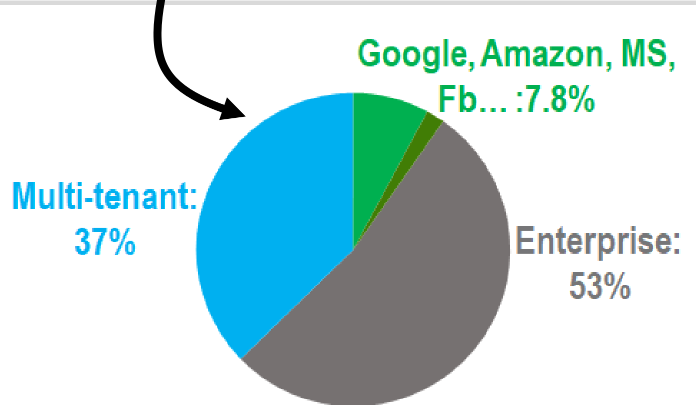




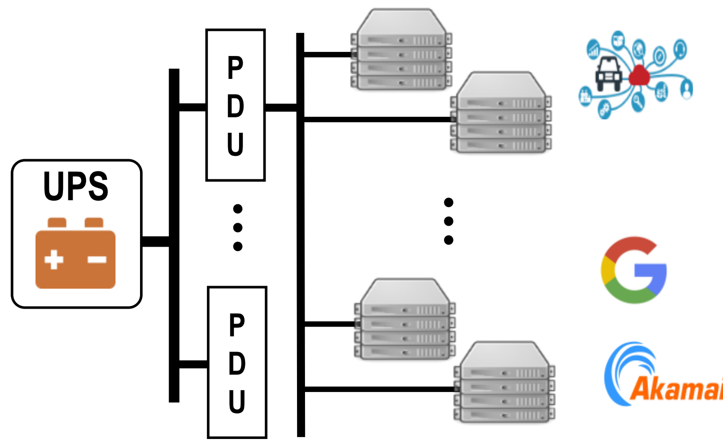
>50% true positive rate and precision for ~10% attack

Also works with UPS and three-phase power systems

Physical infrastructure sharing means everything but power security



Percentage of electricity usage by data center type (source: NRDC 2015)



Thanks!

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