Overview of Control Research & Robust Broadcast-Communication Control of Electric Vehicle Charging

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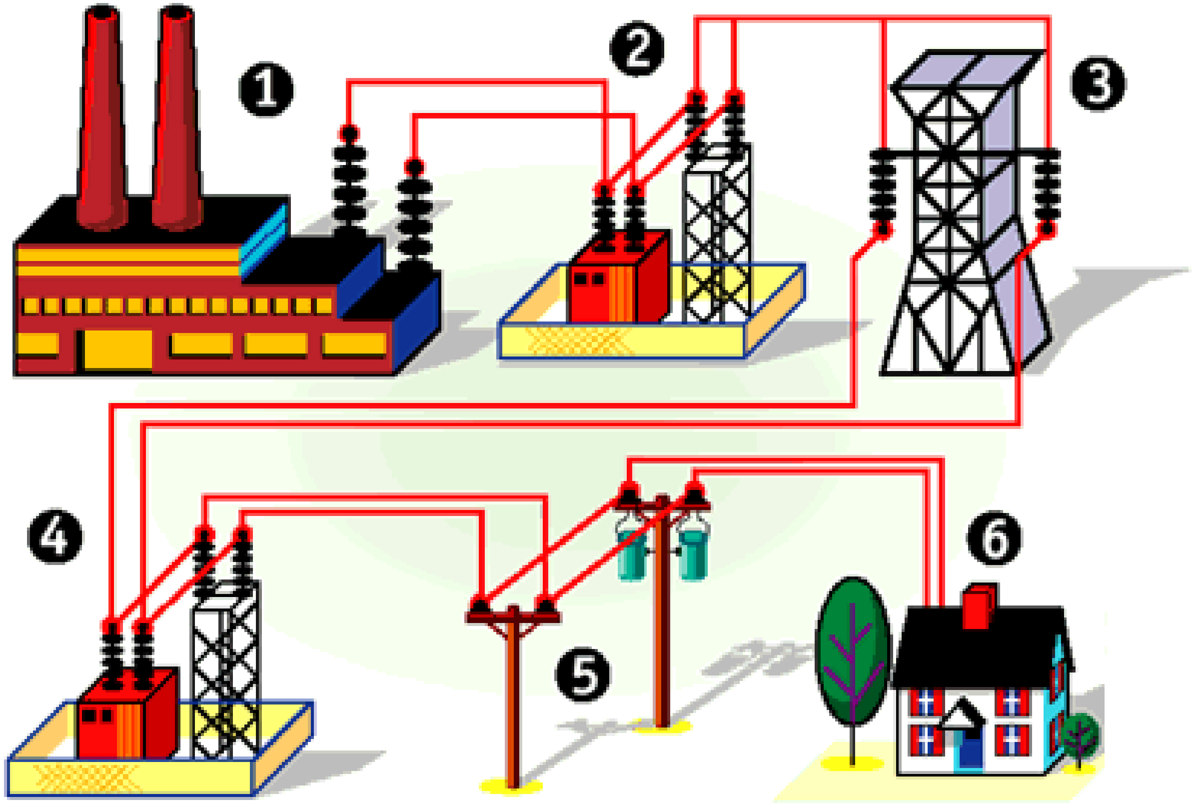
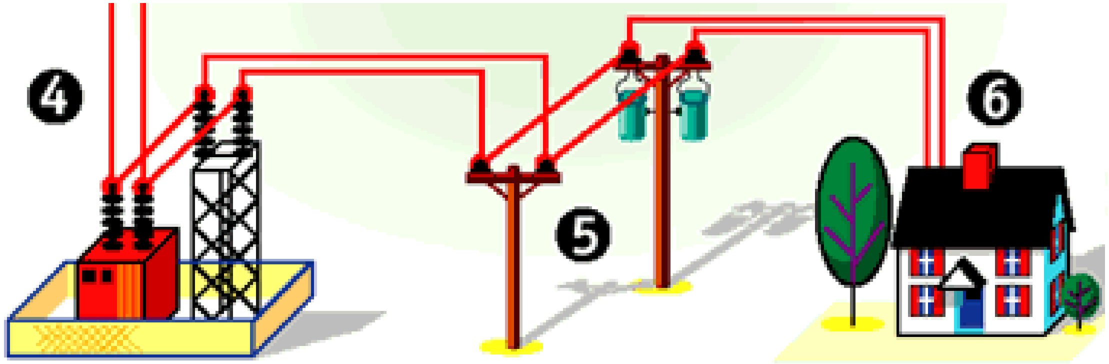
Electrical Grid Hierarchy



This part of our control research focuses on the distribution system

Electrical Distribution System



- Designed to handle peak loads with some margin
- Deliver real power from the substation to the loads (one way)
- Ensure voltage regulation by control of reactive power (centralized utility control)

<u>We will be asking the grid to do things it was not designed to do</u>

Some of the New Technology in the Distribution System

- **Distributed generation—Utility scale and consumer scale**
  - **Photovoltaic—US**
  - Small wind generation—mostly Europe
- **Demand response**
  - **Electric vehicles**
  - HVAC -Air conditioning systems-Electric heaters
- **Storage**
  - Utility-scale at the substation
  - Community Energy Storage
  - Individual consumer—coupled with distributed generation
  - Electric vehicles
- **Controls—Distribution Automation—Reliability—Integration of DER**
  - **Distributed control—fast—inexpensive—secure?**
  - Centralized control—slower—costly—cyber vulnerable?
  - **Voltage regulation—reactive dispatch**—control coordination
  - **Capacity constraints**—DG/**Load curtailment**—real-time switching

Bold=this year's focus

Red=next year's direction

Need for Control with New Technologies

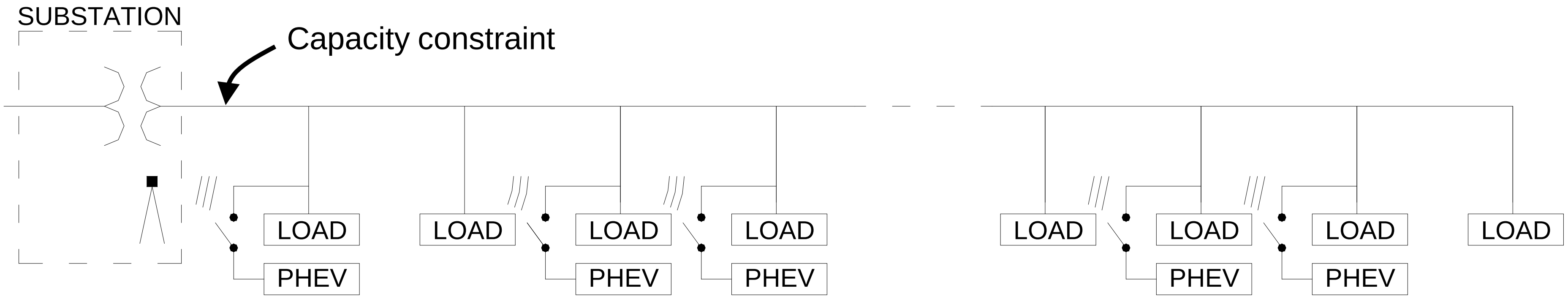
- **Electric vehicle charging is a significant new load**
  - Type 2 charging rates ~ 7-10 kW
  - Uncontrolled charging—peak load during evening hours
  - Coincident with the existing peak on many residential distribution circuits
  - Could easily double the peak load resulting in circuit overloads
  - *Need a robust and fair way to control EV charging*

- **High-penetration distributed photovoltaic generation**
  - Rapidly fluctuating real power flows during partly cloudy days
  - Large voltage swings and loss of regulation and power quality
  - Existing utility-scale equipment is too slow to compensate
  - Latent reactive power capability of the PV inverters can leveraged
  - *Need a fast, distributed algorithm to dispatch PV inverter reactive power*

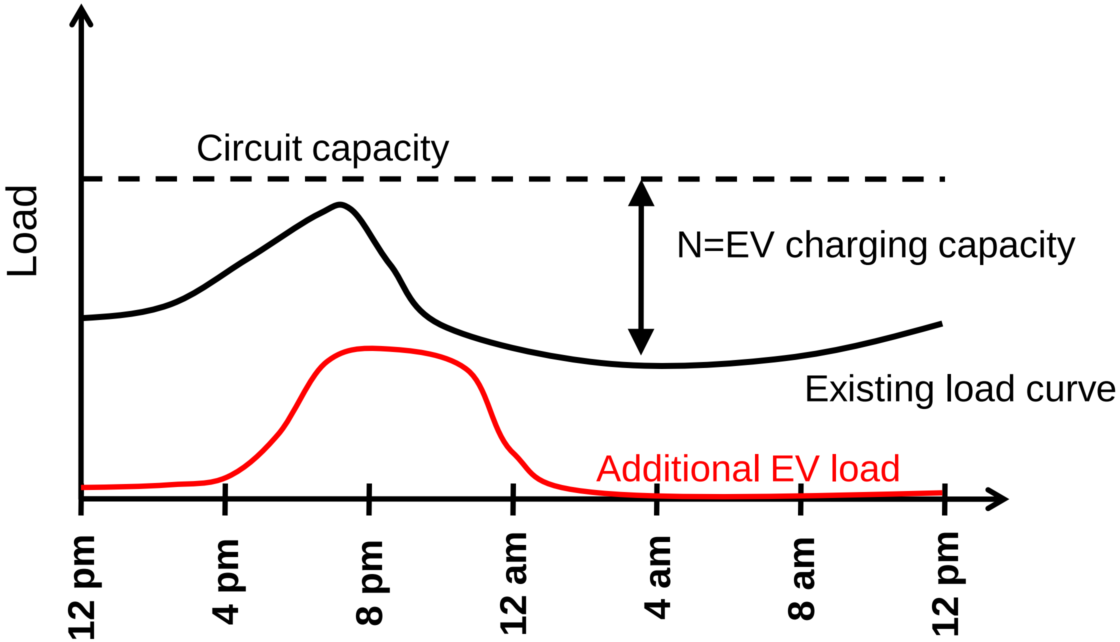
EV Charging—Objectives / Outline

- **Distribution circuits with a high penetration of uncontrolled EV charging may…**
  - experience large EV charging load in the evening…. Resulting in….
  - a coincidence with existing peak loads…..Causing…
  - potential circuit overloads, breaker operation, equipment damage…..
- **We seek to control circuit loading by spreading out EV charging via regulation of the rate of random charging start times because…**
  - it only requires one-way broadcast communication (less expensive), and
  - only requires periodic updating of the connection rate, and
  - customers treated equally.
- **Control of circuit loading also allows….**
  - maximum utilization of existing utility assets, but
  - analysis and engineering judgment are required to determine loading limits.
- **Questions we will try to (at least partially) answer:**
  - Is broadcast communication sufficient to control EV charging?
  - How does the control performance depend on communication rate?
  - How many EVs can be integrated into a circuit?

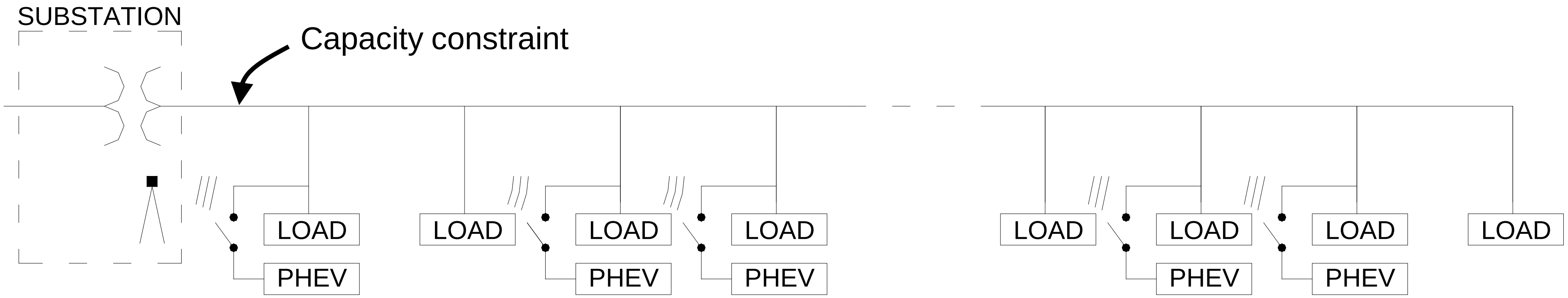
Simplified Physical Model

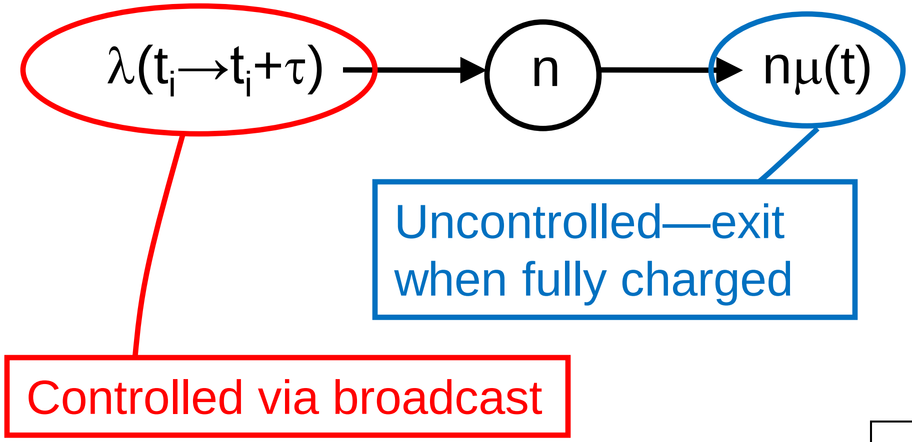


- **Single branch circuit**
- **EVs randomly distributed**
- **May need to consider clustering in multi-branch circuits**
- **Power flow modeled as capacity**
- **No voltage effects**



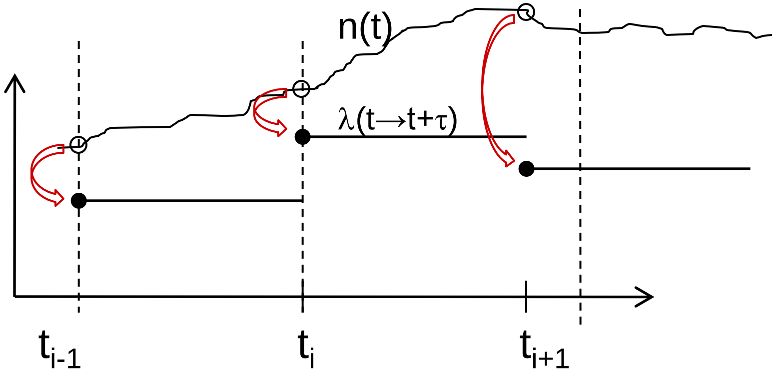
Broadcast Communication and Distributed Control Model





Uncontrolled—exit when fully charged

Controlled via broadcast



Poisson processes in each interval τ

Determine $\lambda(t_i \rightarrow t_{i+1}) = F[k(t_i)]$ such that $E(n)$ ♎ N, but $\pi_{n>N}$ is minimized.

Maximum circuit utilization with small chance of an overload

Some Math—Determination of Control Function

Evolution of π_n from t_{i-1} to t_i

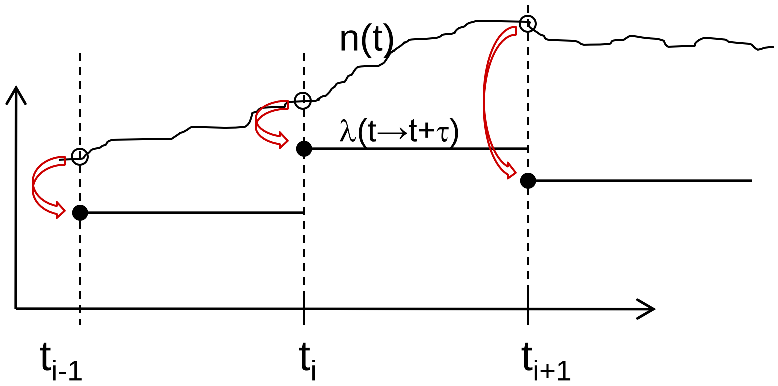
$$\pi_n^i = \sum_m W_{nm}(\lambda(m)\tau)\pi_m^{i-1}$$

Probability of an overload

$$P_N = \sum_{n<N,m\geq N} W_{mn}(\lambda(n)\tau)\pi_n^{i-1}$$

Control function $\lambda(n)$ to cap P_N

$$\sum_{m\geq N} W_{mn}(\lambda(n)\tau) = P_N^* \ll 1$$



$$W_{nm}(\lambda\tau) = \exp(-q)\sum_{k=0}^{n} \frac{n!q^{n-k}\epsilon^{m-k}(1-\epsilon)^k}{k!(n-k)!(m-k)!}$$

where $\epsilon = 1 - \exp(-\mu\tau)$ and $q = \lambda\epsilon/\mu$.

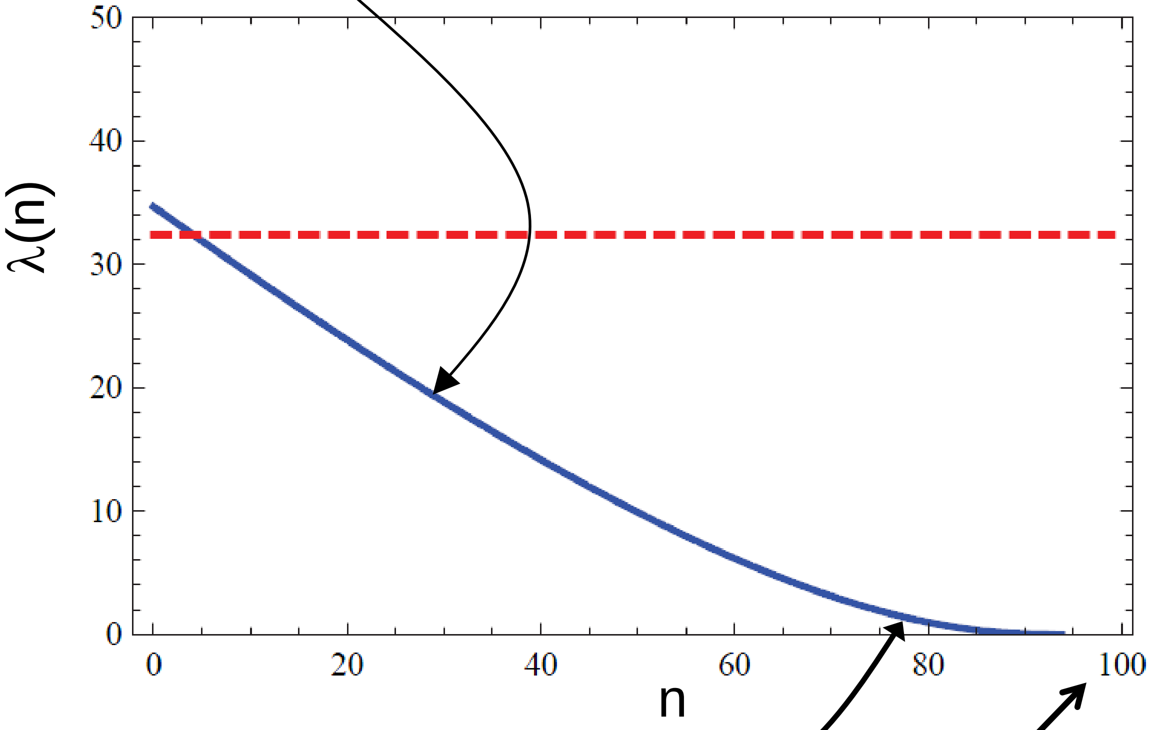
Determination of Control Function

$P_N=10^{-10}$

$\mu\tau=10^{-3}$

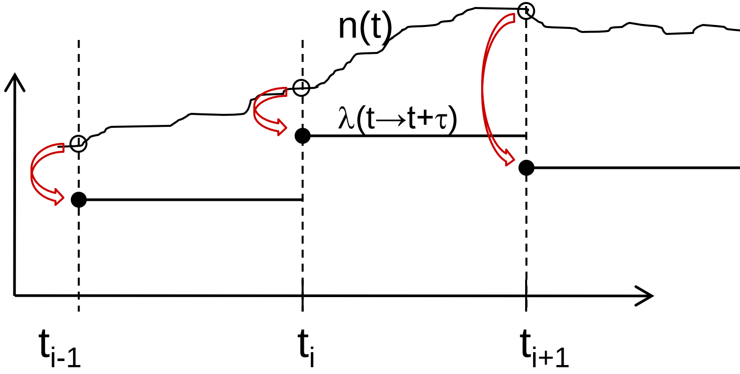
1 overload/10 years

τ=15 seconds for $1/\mu$~4 hours



Shape in this region is important

N=100



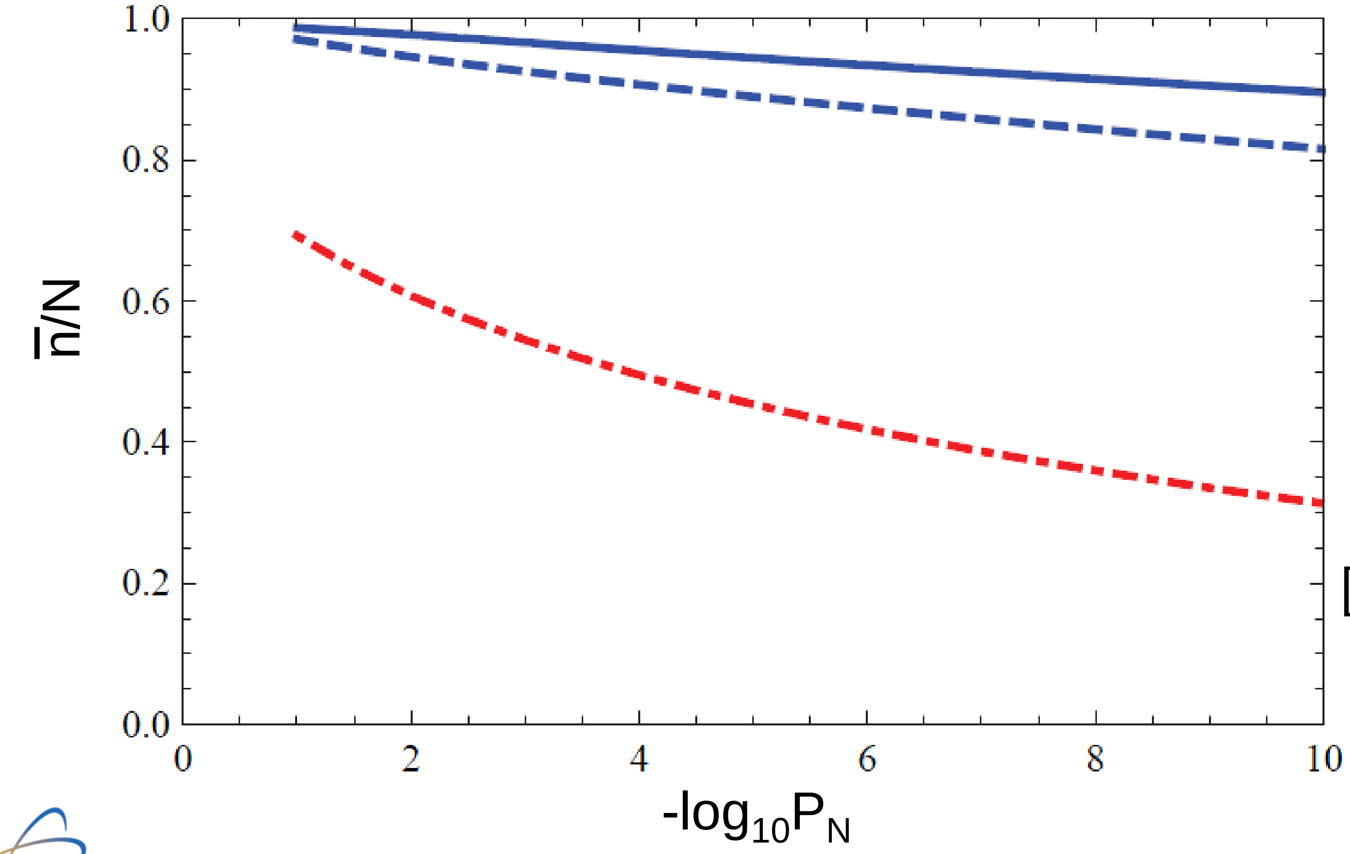
In steady state: $\overline{\tau\lambda(n)} = \tau\mu\overline{n}$

$$\overline{n} = \overline{\lambda(n)} / \mu > \lambda(\overline{n}) / \mu$$

Steady-State Performance vs. Communication Rate, N=100

$$\bar{n} = \overline{\lambda(n)} / \mu > \lambda(\bar{n}) / \mu$$

A little bit of communication goes a long way



$\mu\tau=10^{-3}$ [15 sec]

$\mu\tau=10^{-2}$ [2.5 min]

Typical PLC comm. rate

$\mu\tau=\infty$

[no communication]

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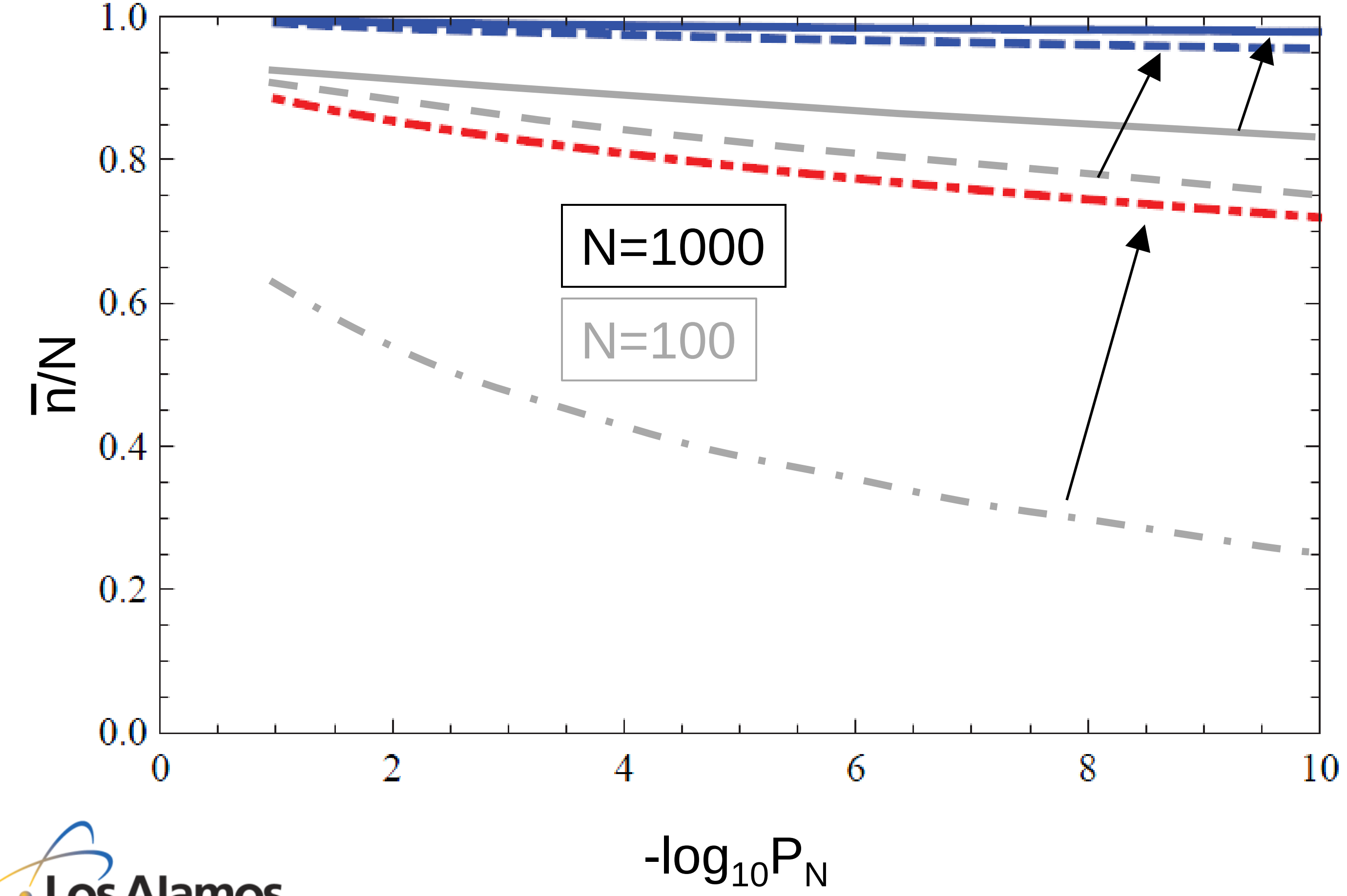
Steady-State Performance vs N

More loads allows for slower communication — smaller fluctuations



$\mu\tau=10^{-3}$ [15 sec]

$\mu\tau=10^{-2}$ [2.5 min]

$\mu\tau=0$

[no communication]

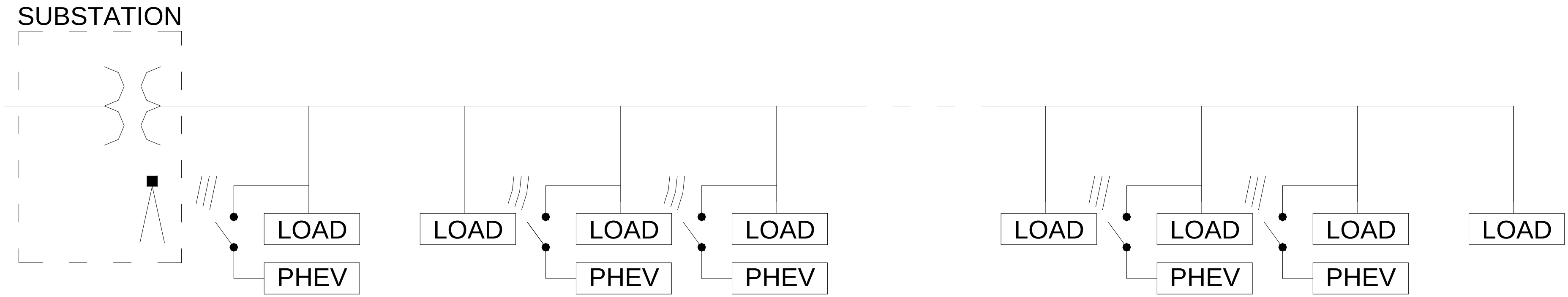
Conclusions

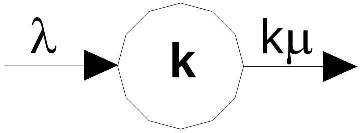
- **In distribution circuits with a high penetration of EVs where uncontrolled charging will lead to coincident peaks and overloads, excellent EV load management can be achieved by:**
  - Randomization of EV charging start times
  - Control of rate of EV connections by one-way broadcast communication.
- **Quality of control depends on the communication rate, but**
  - Modest communication rates can achieve high circuit utilization
  - Control gets better as the number of EV increases (for a fixed communication rate)
  - <u>Subtle aspects to control function when n~N</u>
- **How many EVs can be integrated into a circuit?**
  - Requires engineering judgment to balance cost versus performance, but….
  - Greater than 90% of excess circuit capacity can be utilized with modest communication requirements.

Approach to Steady State—Speed of Control

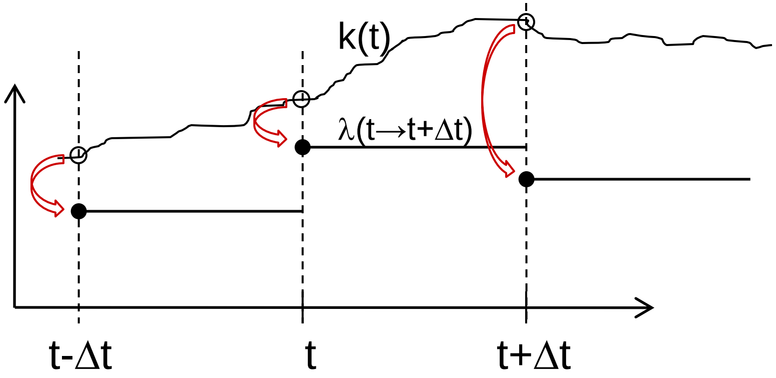
$$t_s \approx \tau[\log(-N\log(P_N))] \approx [a\ \ few]\tau$$

Control model with significant latency





Limited communication: $\lambda(t\rightarrow t+\Delta t)=F[k(t)]$



Include latency: $\lambda(t\rightarrow t+\Delta t)= G[k(t-\Delta t), \lambda(t-\Delta t)]$