Robust Broadcast-Communication Control of Electric Vehicle Charging

Konstantin Turitsyn[1]

Nikolai Sinitsyn[1]

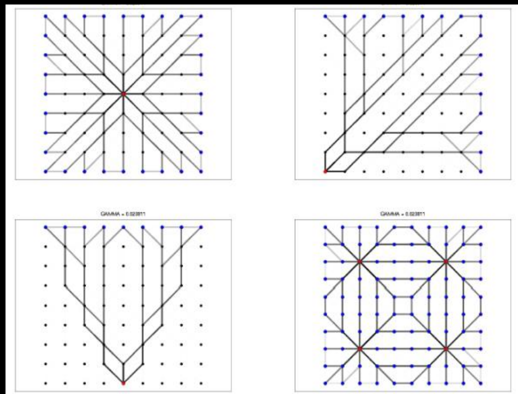
Scott Backhaus[2]

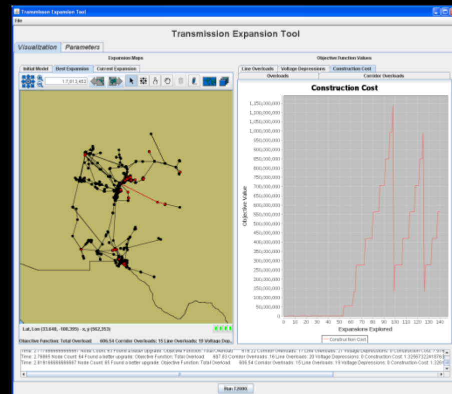
Michael Chertkov[1]

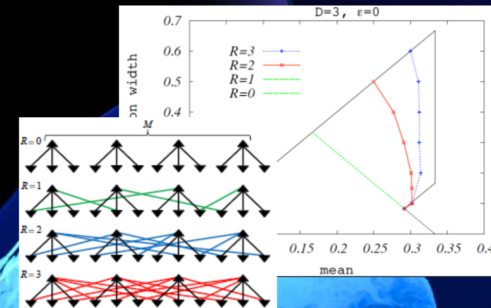
[1]Theoretical Division, Los Alamos National Laboratory

[2] Materials, Physics and Applications Division, Los Alamos National Laboratory

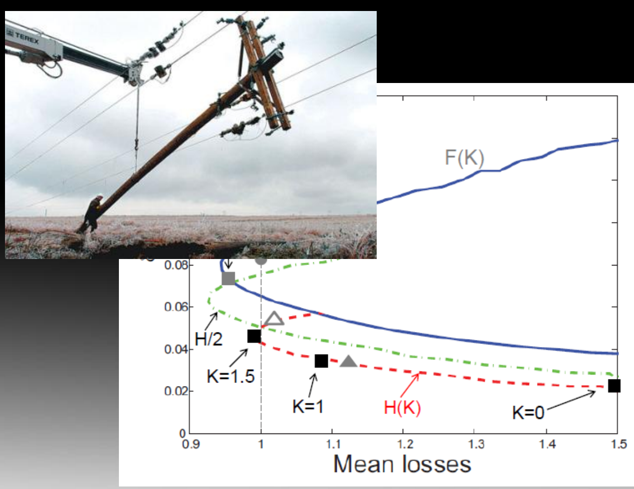
LANL LDRD DR (FY09-11): Optimization & Control Theory for Smart Grids

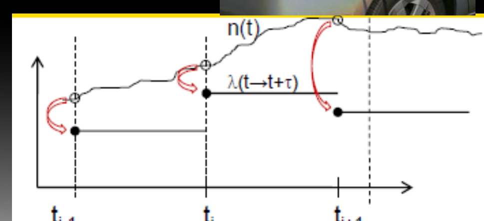


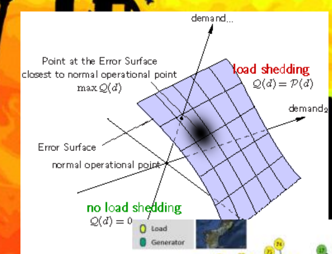


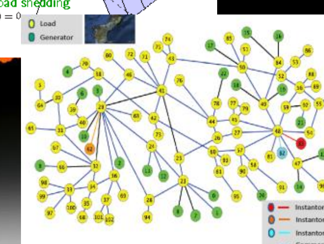


- grid planning









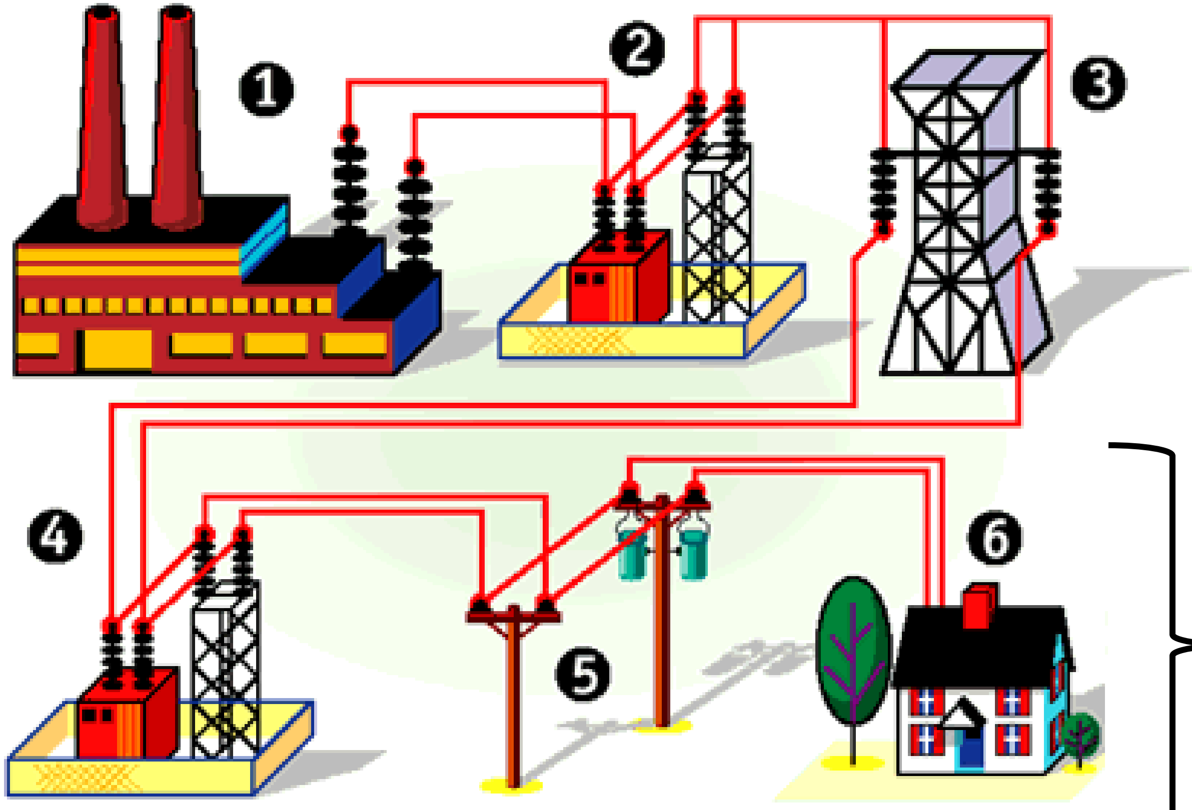
- grid control

- grid stability

Los Alamos NATIONAL LABORATORY EST.1943

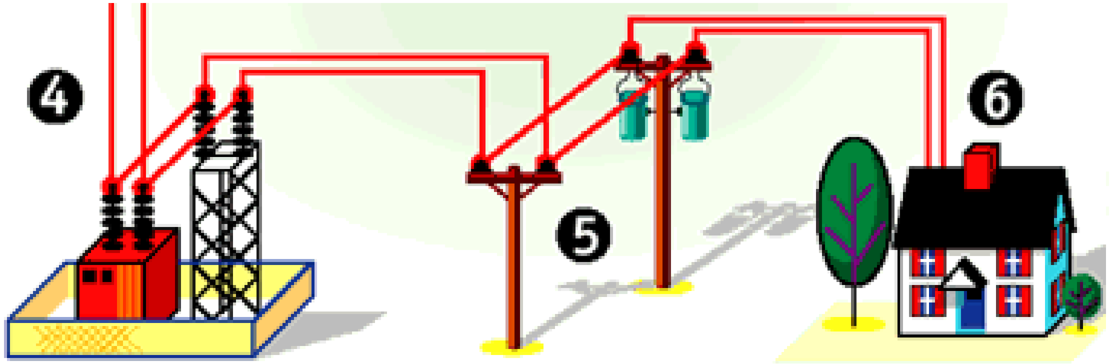
http://cnls.lanl.gov/~chertkov/SmarterGrids/

Electrical Grid Hierarchy



This talk 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** **– focus of this talks**
  - 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**
  - Distributed control—fast—inexpensive—secure?
  - Centralized control—slower—costly—cyber vulnerable?
  - Voltage regulation—reactive dispatch—control coordination
  - Capacity constraints—Load curtailment—real-time switching

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*

this talk

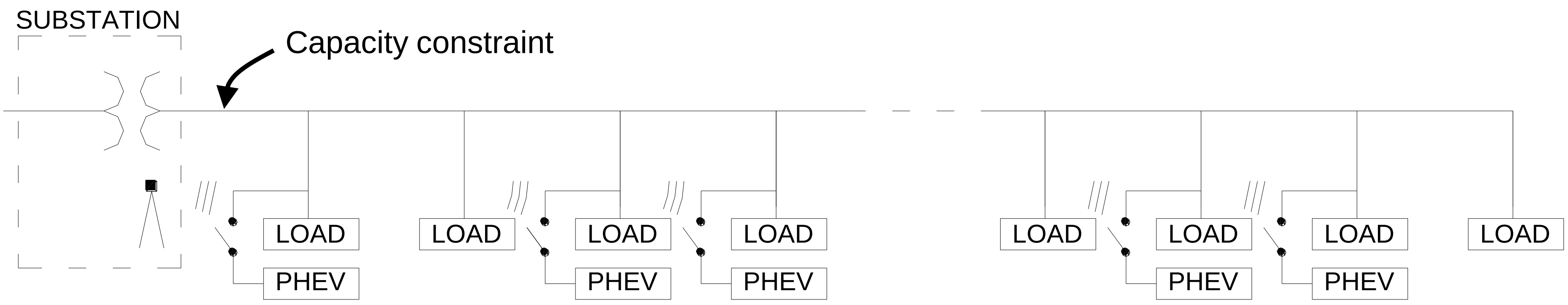
- **High-penetration distributed photovoltaic generation**
  - Rapidly fluctuating real power flows during partly cloudy days
  - Large voltage swings and loss of regulation and power quality
  - Existing utility-scale equipment is too slow to compensate
  - Latent reactive power capability of the PV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

yesterday talk

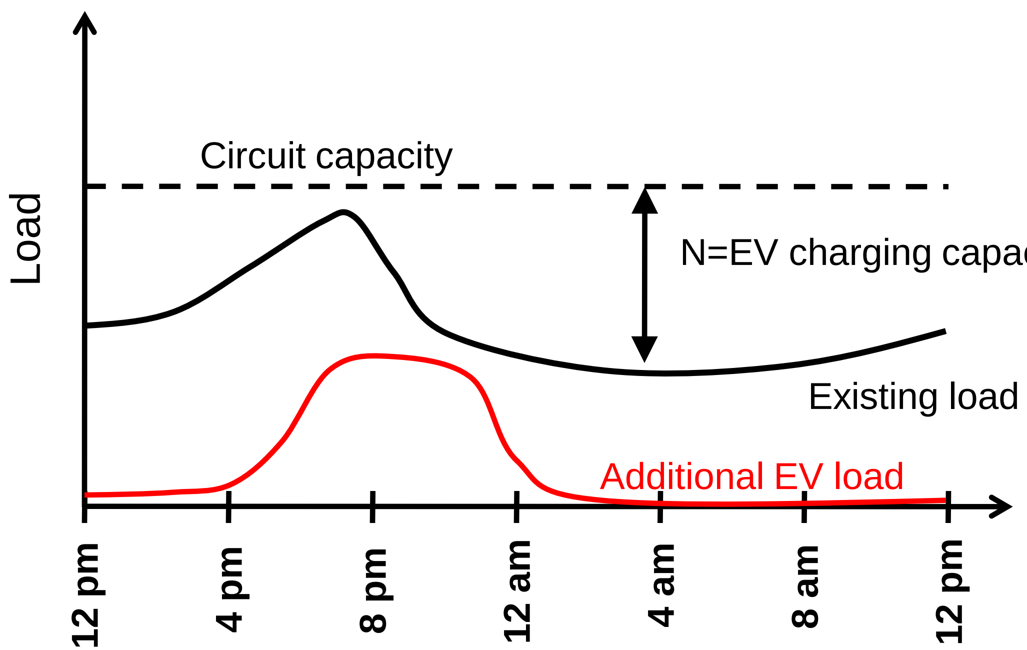
EV Charging—Objectives / Outline

- **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.
- **<u>Questions we will try to (at least partially) answer:</u>**
  - 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?

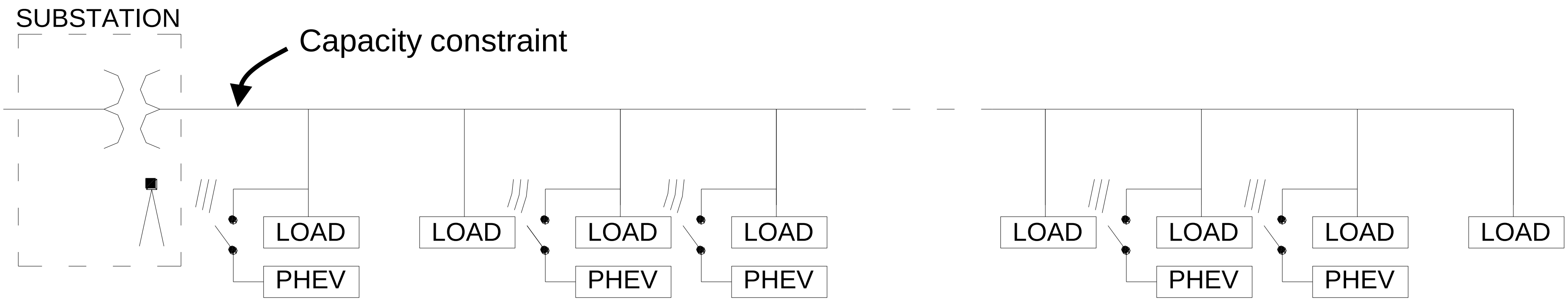
Simplified Physical Model

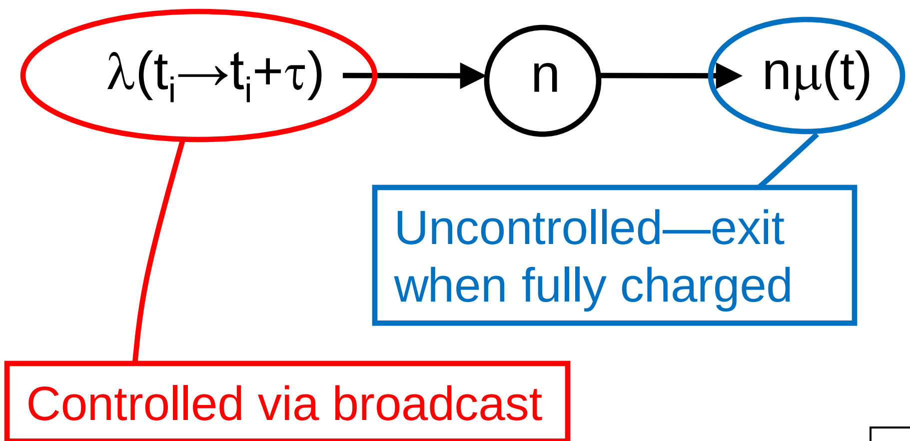


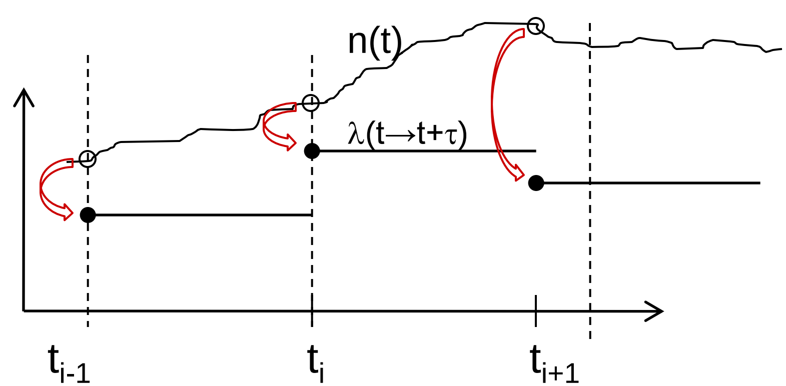
- Single branch circuit
- EVs randomly distributed
- May need to consider clustering in multi-branch circuits
- Power flow modeled as capacity
- No voltage effects



Broadcast Communication and Distributed Control Model







Poisson processes in each interval τ

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

Maximum circuit utilization with small chance of an overload

Determination of Control Function

Evolution of π_n from t_{i-1} to t_i

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

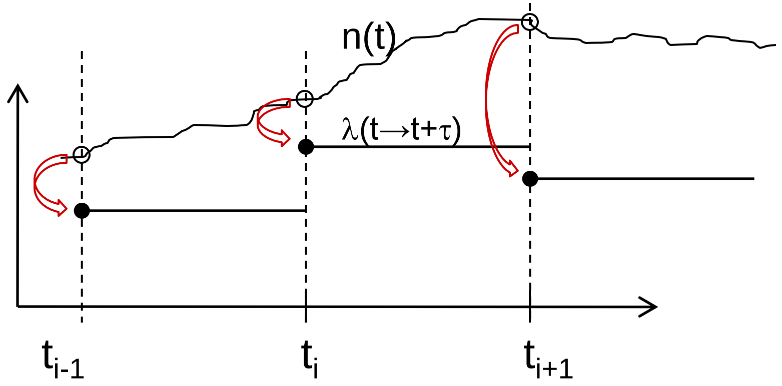
Probability of an overload

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

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

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

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



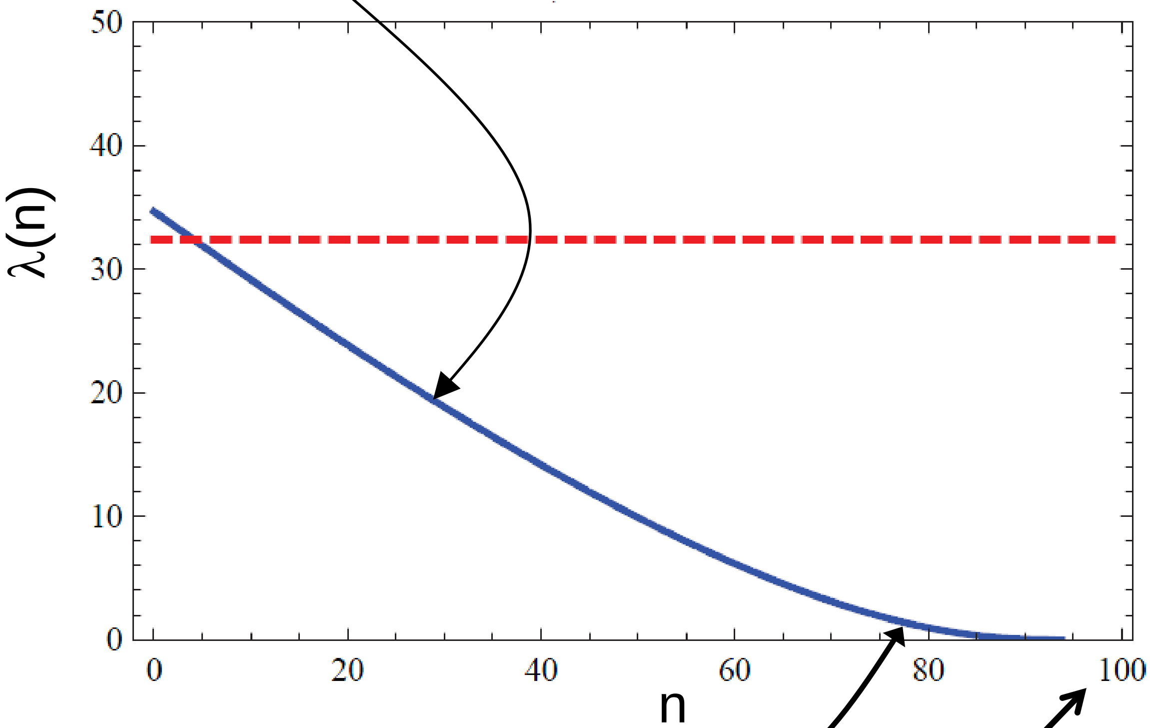
$$W_{nm}(\lambda\tau) = \exp(-q)\sum_{k=0}^{n} \frac{n! q^{n-k}\epsilon^{m-k}(1-\epsilon)^k}{k!(n-k)!(m-k)!}$$

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

Determination of Control Function

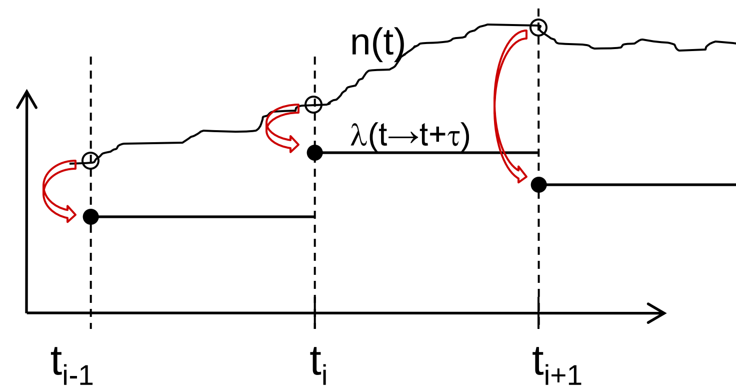
$P_N=10^{-10}$
$\mu\tau=10^{-3}$

1 overload/10 years
τ=15 seconds for $1/\mu$~4 hours



Shape in this region is important

N=100



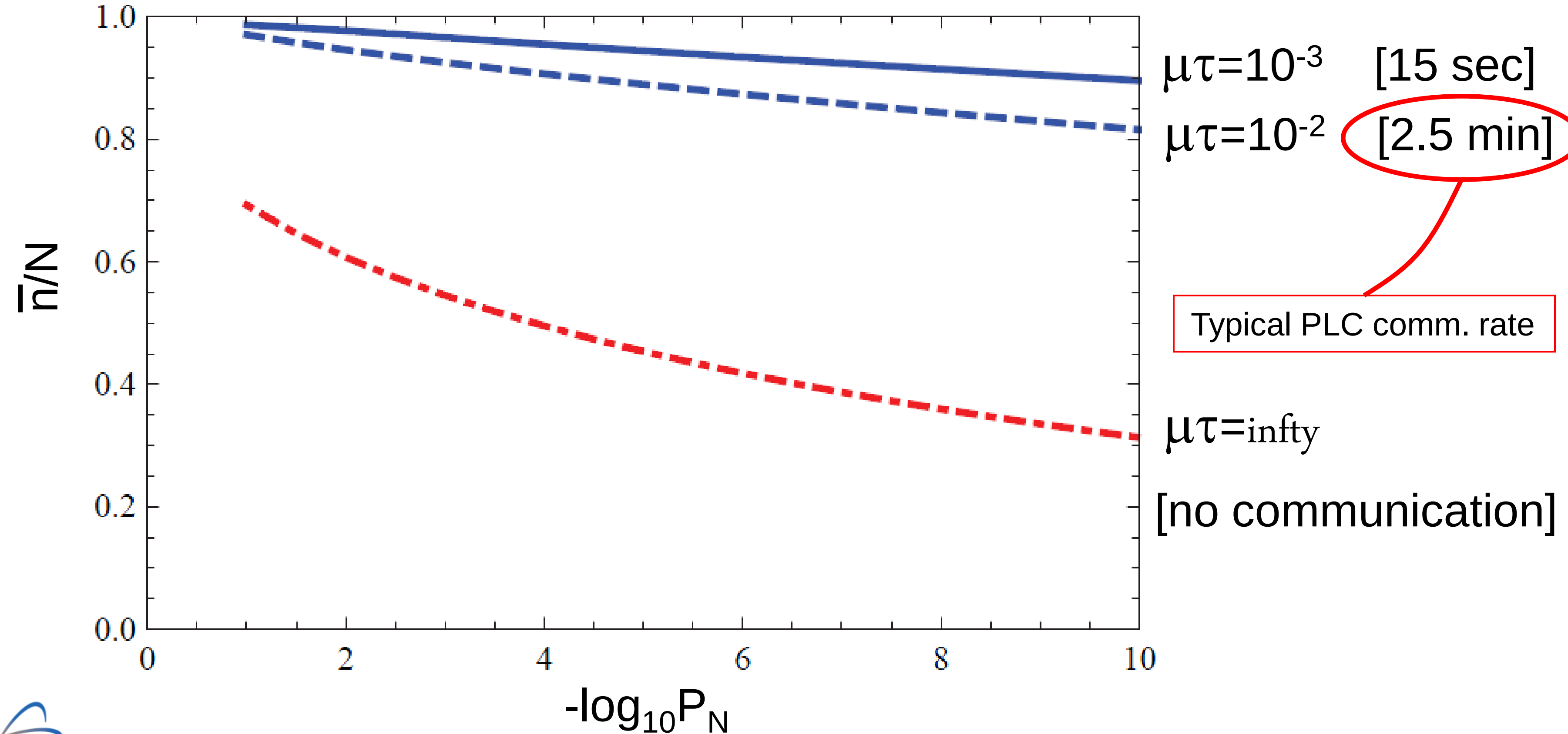
In steady state: $\overline{\tau\lambda(n)} = \tau\mu\bar{n}$

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

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

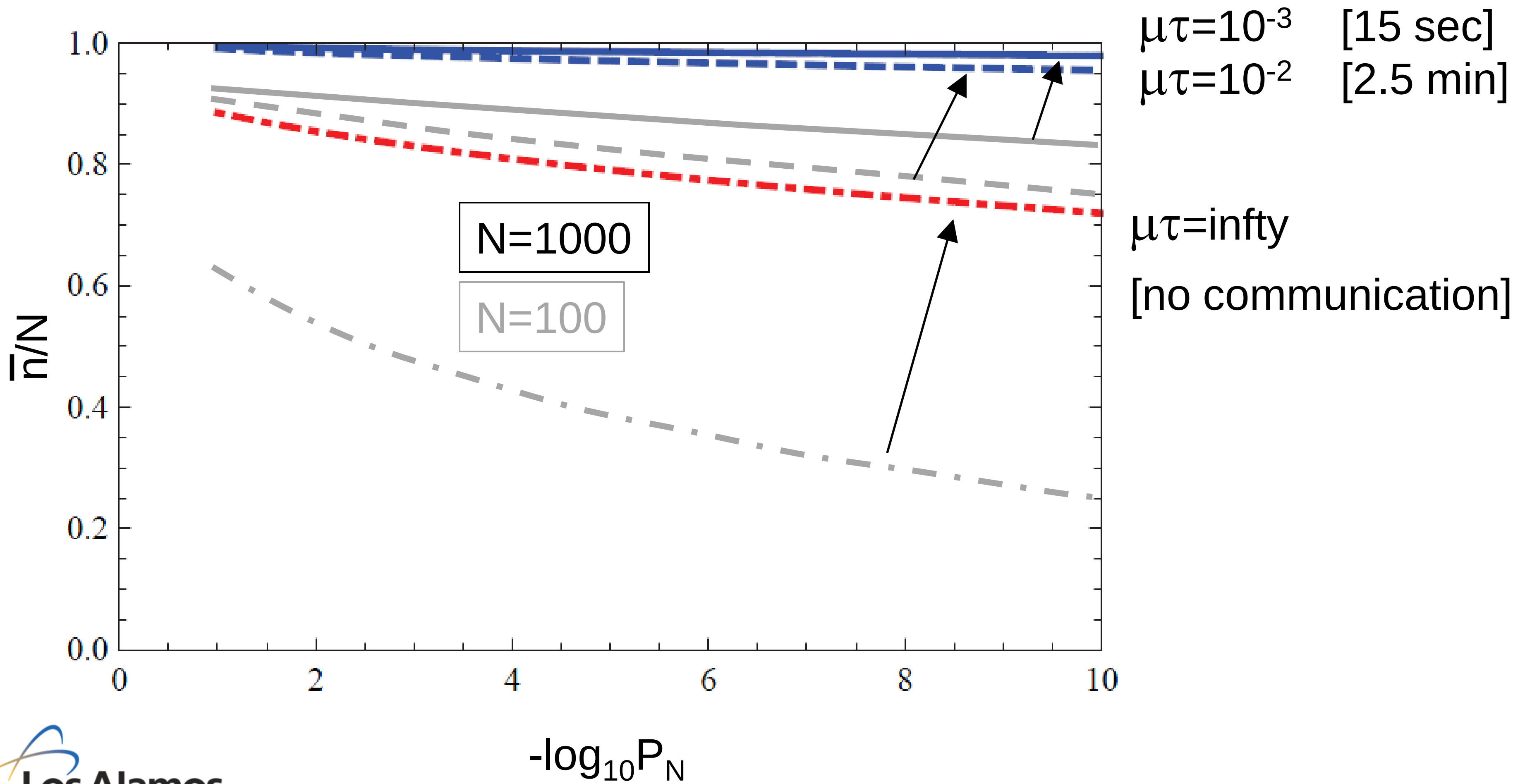
$$\bar{n} = \overline{\lambda(n)} / \mu > \lambda(\bar{n}) / \mu$$

A little bit of communication goes a long way



Steady-State Performance vs N

More loads allows for slower communication — smaller fluctuations



Approach to Steady State—Speed of Control

- no communications … slow

$$t_s \approx 1/\mu << \tau$$

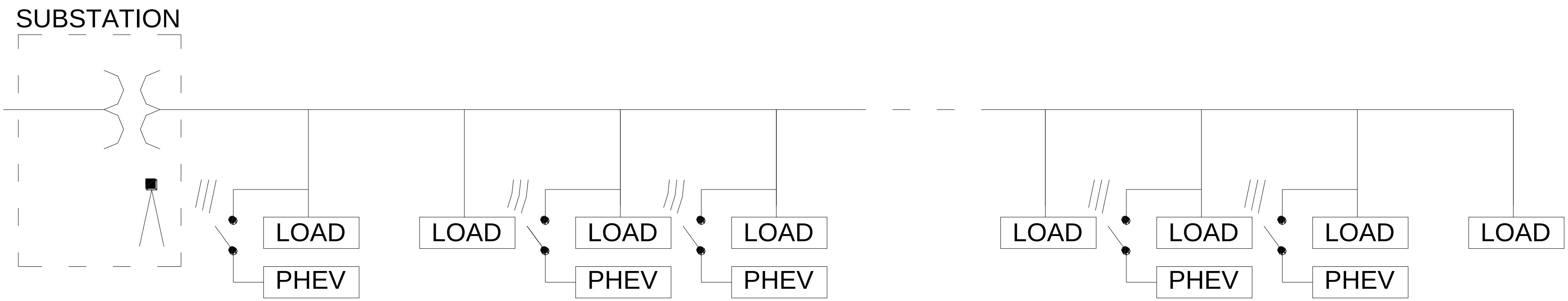
- with communications … much faster

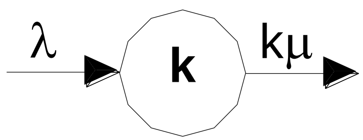
$$t_s \approx \tau[\log(-N\log(P_N))] \approx [a \ \ few]\tau$$

Conclusions

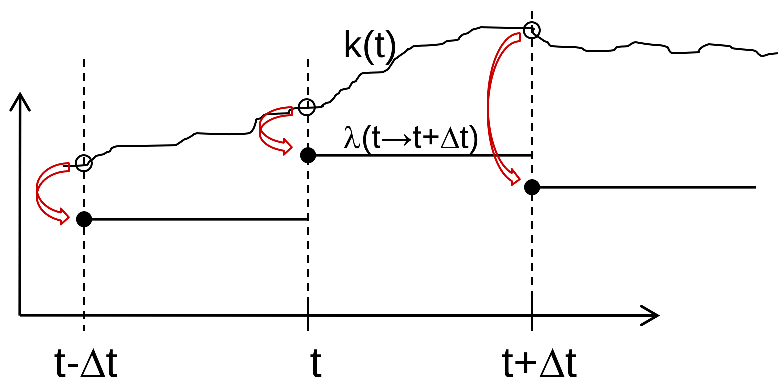
- **In distribution circuits with a high penetration of EVs where uncontrolled charging will lead to coincident peaks and overloads, excellent EV load management can be achieved by:**
  - Randomization of EV charging start times
  - Control of rate of EV connections by one-way broadcast communication.
- **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)
  - Speed of control (convergence) improves significantly
  - Subtle aspects to control function when n~N
- **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.

Control model with significant latency





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



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