CRII: CPS: Internet-Inspired Autonomous Electric Vehicle (EV) Charging

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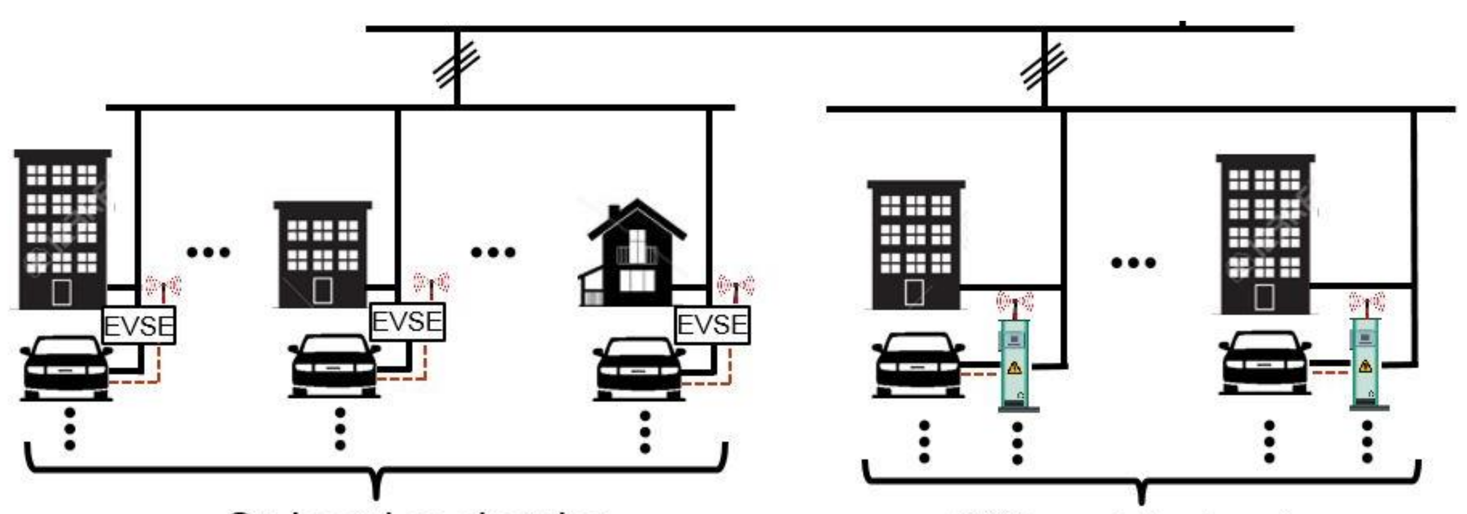
Introduction

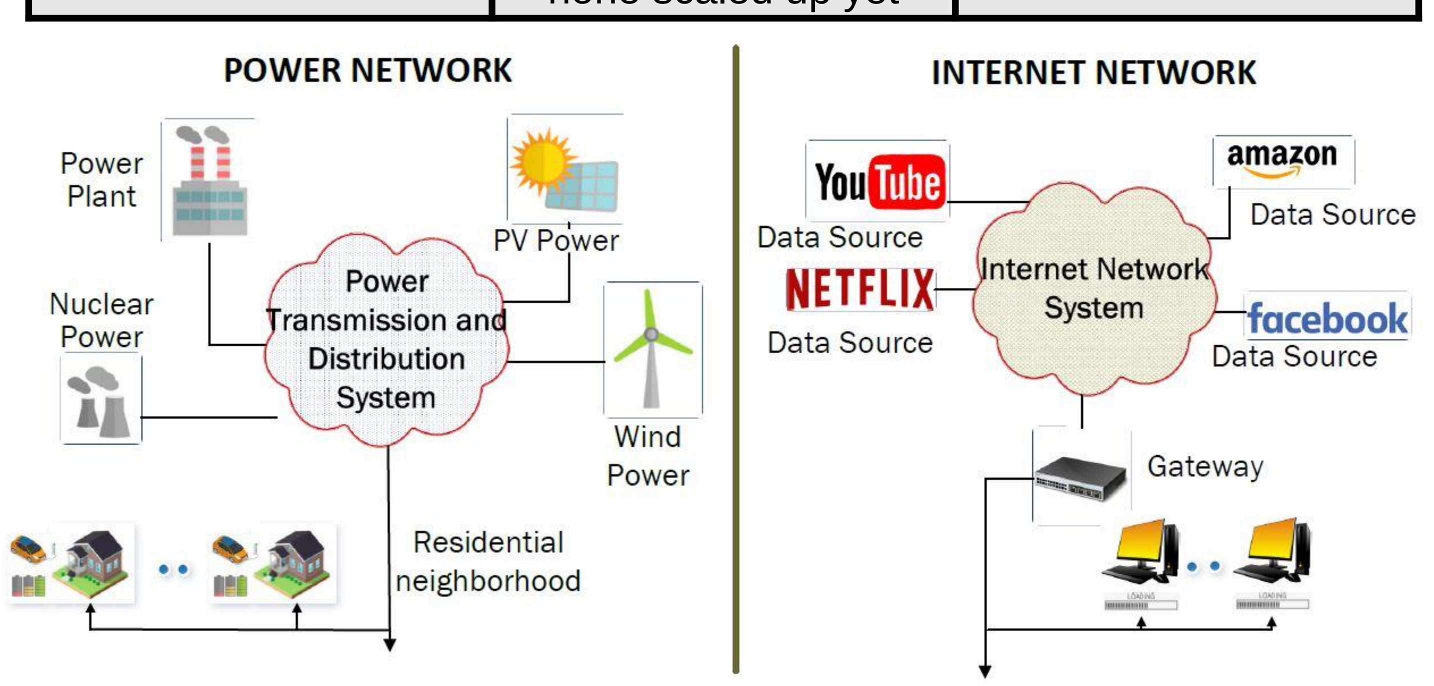
EV transition and low-cost renewable energy generation are putting power grid under a challenging transformation. Number of power electronics based actuators connected to the grid are increasing, and the legacy control methods employed on the grid are not responsive to this growing demand. Inspired by their similar historical development and social structure, in this study, we investigate two very complex networks: Internet and power grid in the context of on-board EV charging problem.



On-board ac charging Off-board dc charging

Internet Network vs. EV Charging Network Similarity

	EV Charging	Internet Operation
Transfer parameter	Power	Data
	Power congestion	Network congestion
	Cost of charging power	Cost of data transfer
	Charging rate	Download rate
	Node voltage	Round-trip-time (RTT)
Time scale	minutes to hours	miliseconds to seconds
Performance	State of charge (SOC)	Quality of service (QoS)
Fairness	No policy yet	Proportional fair
Control	Various proposed, none scaled up yet	AIMD



Additive Increase and Multiplicative Decrease Algorithm (AIMD)

- Internet's congestion avoidance control algorithm
- Proven to be stable and easily scalable
- Fully decentralized and autonomous plug-and-play, end-point solution
- Straightforward to implement, yet still manages to establish fair allocation of available capacity

$$w_i(t+1) = \begin{cases} w_i(t) + \alpha_i & \text{if there is no congestion} \\ w_i(t) \times \beta_i & \text{if congestion occurs} \end{cases}$$

w_i: i^{th} user's share
$\alpha > 0$: increase parameter
$0 < \beta < 1$: decrease parameter

- Linear model

$$w_i(k+1) = \beta_i \cdot w_i(k) + \alpha_i \cdot D(k)$$

$k \epsilon N$: k^{th} congestion event
$D(k) = t_{k+1} - t_k$: time between two congestion events

- Solution of linear model as $k \to n$

$$w_i(n) = \beta_i^n \cdot \left(w_i(0) - \frac{\alpha_i}{1-\beta_i} \right) + \frac{\alpha_i \cdot d}{1-\beta_i}$$

transient term steady-state term

$w_i(0)$: i^{th} user's initial share
$d = \widetilde{D}(k)$: average of D(k)

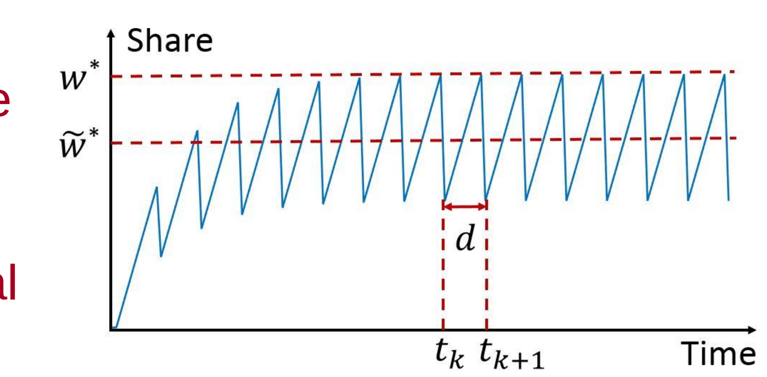
- As $n \to \infty$, $\beta^n \to 0$ (exponential convergence)

$$\lim_{n\to\infty} w_i(n) = w_i^* = \frac{\alpha_i \cdot d}{1-\beta_i}$$

w^*: final share

$$\widetilde{w}_i^* = \alpha_i \cdot \frac{(1+\beta_i)}{2(1-\beta_i)} \cdot d$$

$\widetilde{w}^*$: average final share



Proposed EV Charging Algorithm

- AIMD is adopted for EV charging.
- Charging current is the user share.
- *Congestion detection is done based on local voltage measurements.*
- It detects congestion when local voltage drops below a voltage threshold.
- This threshold can be dynamically learned by means of local voltage measurements on the fly.

Algorithm 1 AIMD algorithm for EV charging network

Input: Previous charging current: $I_i(t)$
Output: New charging current: $I_i(t+1)$
Parameter: Increase parameter: $\alpha(t) > 0$
Parameter: Decrease parameter: $0 < \beta(t) < 1$

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1: if V(t) > V_th and V(t) > V_min then
2:     I_i(t+1) = I_i(t) + α_i
3: else
4:     I_i(t+1) = β_i × I_i(t)
5: end if
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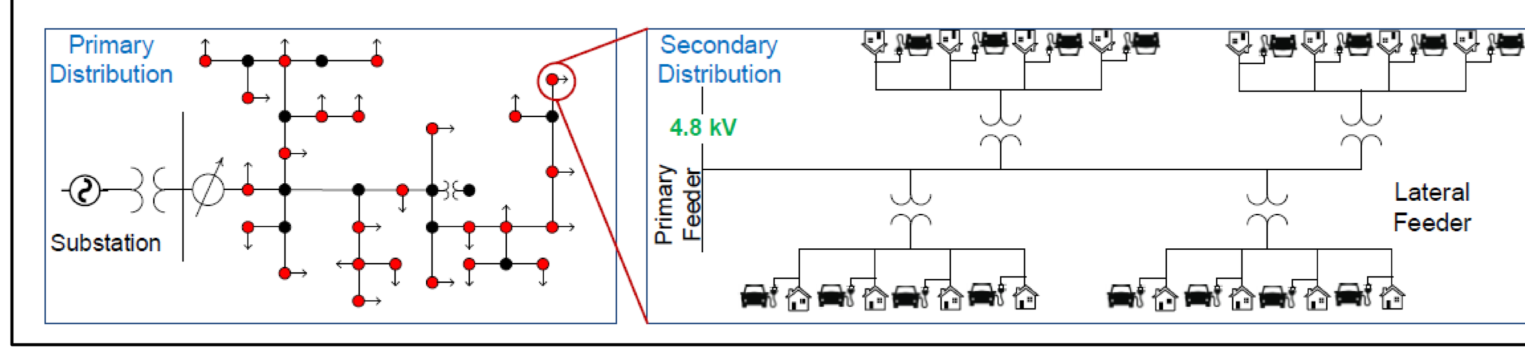
$$V_{th}(t+1) = AvgV(t+1) - 4 \cdot StdV(t+1)$$
$$AvgV(t+1) = \lambda \cdot V(t) + (1-\lambda) \cdot AvgV(t)$$
$$StdV(t+1) = \omega \cdot |AvgV(t) - V(t)| + (1-\omega) \cdot StdV(t)$$

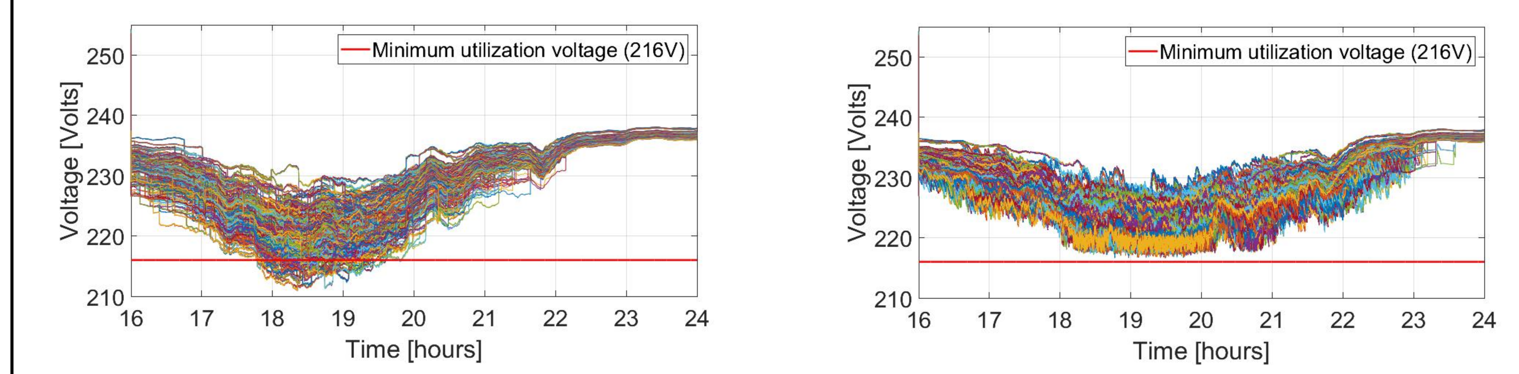
$V_{th}(t)$: voltage threshold
$AvgV(t)$: moving average of voltage
$StdV(t)$: moving standard deviation of voltage

Some Preliminary Results

Test distribution system with primary and secondary networks

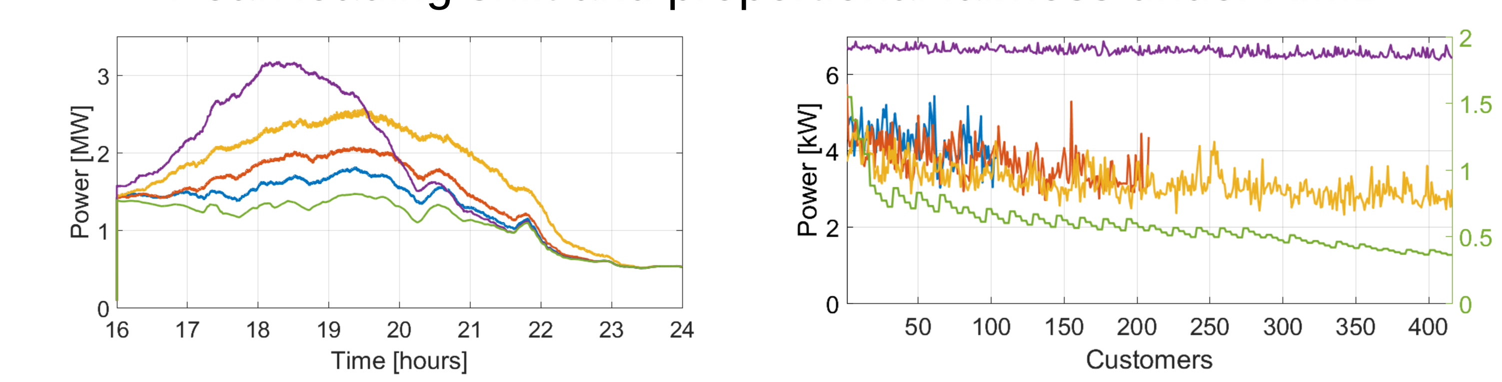


Voltage waveforms of houses under 100% EV penetration



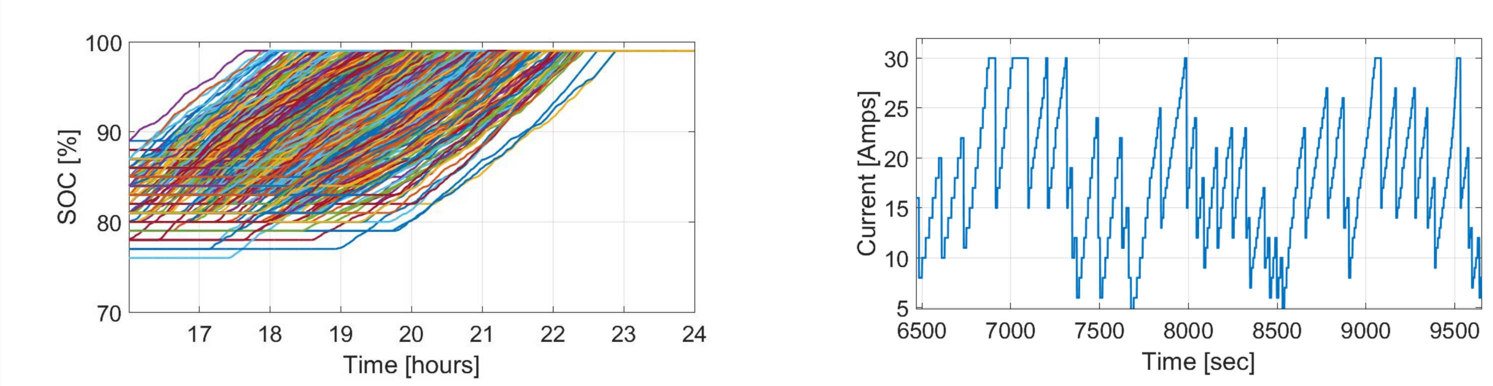
Uncontrolled EV charging AIMD-based EV Charging

Peak loading shift and proportional fairness under AIMD



Total loading of the system Average charging powers

SOC variations and sample charging current waveform



SOC variation Charging current under AIMD

Important Conclusions

- Internet's congestion control algorithm (AIMD) can be adapted for EV charging.
- Congestion events can be detected via local voltage measurements without requiring communication hardware.
- This solution provides utmost cyber security for on-board residential EV charging protecting the private information of users.
- We will collect more field data regarding voltage and frequency, and investigate a fully decentralized algorithm.

Published/Under review Papers:

1. E. Ucer, M. C. Kisacikoglu, and M. Yuksel, "Analysis of an internet inspired EV charging network in a distribution grid," in IEEE Transmiss. Distr. Conf., Apr 2018
2. E. Ucer, M. C. Kisacikoglu, and A. Gurbuz, "Learning EV integration impact on a low voltage distribution grid," in IEEE PES General Meeting, Aug 2018
3. E. Ucer, M. C. Kisacikoglu, M. Yuksel, and A. Gurbuz, "An internet-inspired proportional fair EV charging control method," IEEE Sys. J., under review, major revision.
4. E. Ucer, M. C. Kisacikoglu, and M. Yuksel, "AIMD-based electric vehicle charging," IEEE Internet Things J., under review.
5. E. Ucer, M. C. Kisacikoglu, and M. Yuksel, "Analysis of a decentralized AIMD-based EV charging control" submitted to IEEE PES General Meeting, 2019