Auc2Charge: An Online Auction Framework for Electric Vehicle Park-and-Charge

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Introduction

Electric Vehicles(EV)

- Crucial component of Intelligent Transportation System(ITS)
- Shift energy load from gasoline to electricity
- Cause high penetration of power grid
- Require large-scale deployment of *charging stations*

Various charging stations

Park-and-Charge

An up-and-coming mode for charging stations

- A parking lot equipped with Level 1 and Level 2 chargers
- EVs get charged during parking, e.g., a few hours
- Slow charging, inexpensive hardware and high utilization of space

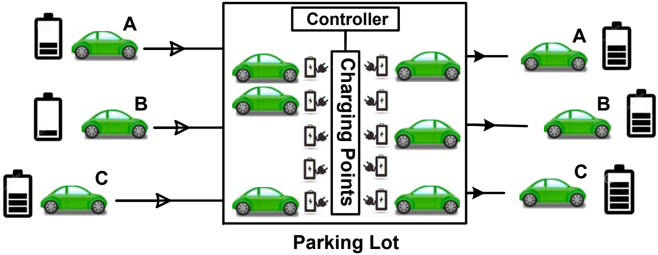


Figure: An illustration of park-and-charge

Current Field Deployment

- Workplace, airport, military base and etc.
- Pricing policies
  - Pay-per-use
  - Flat rate

Boston University

Seattle-Tacoma Airport

Sources: *bu.edu* and *plugincars.com*

Pay-Per-Use and Flat-Rate Pricing

Advantages

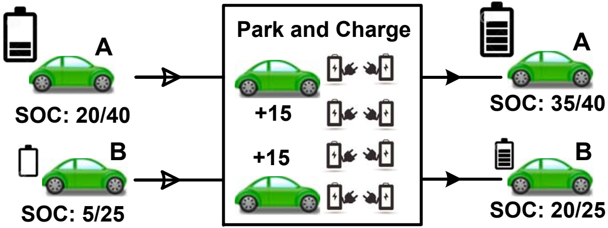
- Simple and straightforward
- Helpful for early market expanding

Limitations

- Overpricing and underpricing
- Undermined social welfare i.e., sum of station revenue and user utilities

Social Welfare in Park-and-Charge: An Example

Pay-per-use and flat-rate: allocate 15kWh to each EV



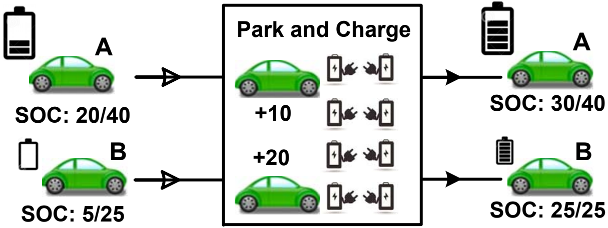
However,

- Marginal utilities of EVs are different
- Lower arriving SOC $\rightarrow$ Higher marginal utility
- Ignorance of such difference $\rightarrow$ Undermined social welfare

Social Welfare in Park-and-Charge: An Example

To maximize social welfare:

- Allocate electricity to low SOC vehicle as much as possible



Pay-per-use and flat-rate focus on station revenue, not social welfare.

Motivation

Future market deployment of park-and-charge desires an **efficient market mechanism** to

- Avoid overpricing and underpricing
- Maximize social welfare

Our Focus

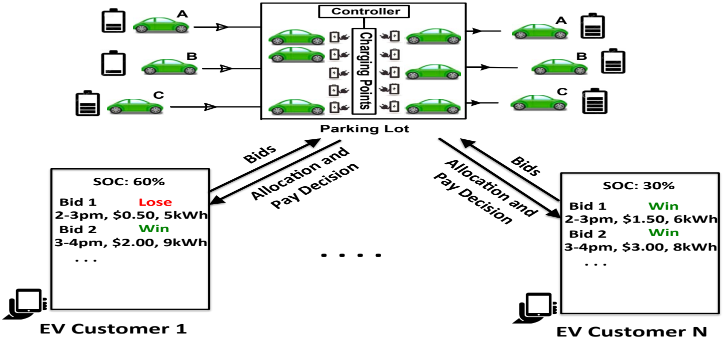
Our Focus

- Investigate auction as market mechanism for park-and-charge
- *Auc2Charge*: an online auction framework
- Understanding system benefits via numerical simulation

Related Work

- Auctions has been widely studied in Internet Adwords, cloud computing and smart grid.
  - Social welfare maximization
  - Truthfulness and individual rationality
- What enables *Auc2Charge*?
  - Budget-constrained online auction and randomized auction theory
- *Auc2Charge* can be extended to other operation modes of charging stations, e.g., fast charging reservation.

System Settings and Problem Formulation



- EVs arrive, park-and-charge, and leave
- Users send bids on how much to charge, when to charge and how much to pay, i.e., $\{b_j^k(t), c_j^k(t)\}$, to the charging station
- Auctions are conducted every time slot, and users get notified
- Users can adjust future bids anytime during parking,

A Binary Programming Formulation

$$\textbf{PNC}: \quad \text{maximize} \quad \sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{k=1}^{K} b_j^k(t)y_j^k(t) \qquad \textbf{Social Welfare}$$

subject to

$$\sum_{k=1}^{K}\sum_{t=1}^{T} b_j^k(t)y_j^k(t) \le B_j, \qquad \forall j, \qquad \textbf{Users Budget}$$

$$\sum_{j=1}^{M}\sum_{k=1}^{K} c_j^k(t)y_j^k(t) \le R(t), \qquad \forall t, \qquad \textbf{Station Supply}$$

$$\sum_{k=1}^{K} y_j^k(t) \le 1, \qquad \forall j \text{ and } t, \qquad \textbf{No Double Wins}$$

$$\sum_{k=1}^{K} c_j^k(t)y_j^k(t) \le C_j(t), \qquad \forall j \text{ and } t, \qquad \textbf{Unit-Time Charging Capacity}$$

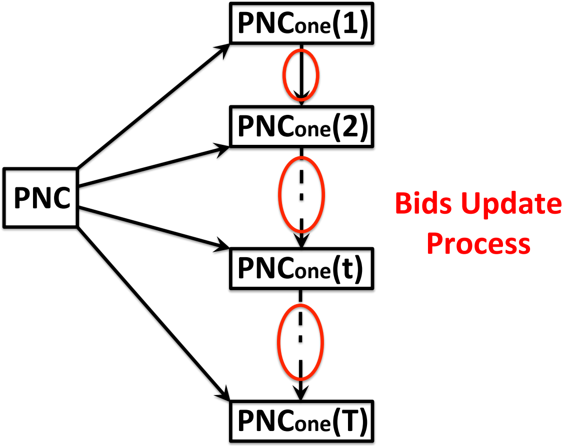
$$y_j^k(t) \in \{0,1\}, \qquad \forall j,\ k \text{ and } t. \qquad \textbf{Winning Indication}$$

Challenges

- **PNC** is NP-hard
  $\rightarrow$ The auction must be computationally efficient
- **PNC** is stochastic
  $\rightarrow$ The auction must be online
- Users may bid strategically
  $\rightarrow$ The autcion must be truthful and individual rational

Auc2Charge in a Nutshell

1. Decompose **PNC** into smaller auctions via bids update process.



Auc2Charge in a Nutshell

Bids Update Process:

- Originally proposed in budget-constrained online Adwords auction[1], and extended to resource auction in cloud computing.[2]
- **Intuition**: adjust reported valuation in $\mathbf{PNC_{one}(t)}$ based on the results from $\mathbf{PNC_{one}(t-1)}$
  - Users not getting electricity in $t-1$
    $\rightarrow$ No adjust in t
  - Users getting electricity in $t-1$
    $\rightarrow$ Reduce reported valuation in t based on remaining budget
- **Rationale**: avoid user depleting budget fast without fully charged
- **Result**: the overall budget constraint is dropped.

[1] Buchbinder, Niv, *et al.* "Online primal-dual algorithms for maximizing ad-auctions revenue." Algorithms-ESA 2007.

[2] Shi, Weijie, *et al.* "An online auction framework for dynamic resource provisioning in cloud computing." ACM SIGMETRICS 2014.

A Binary Programming Model without Budget Constraint

$$\mathbf{PNC_{one}(t)}: \quad \text{maximize} \quad p(t) = \sum_{j=1}^{M}\sum_{k=1}^{K}\omega_j^k(t)y_j^k(t), \qquad \textbf{Social Welfare}$$

subject to

$$\sum_{j=1}^{M}\sum_{k=1}^{K} c_j^k(t)y_j^k(t) \leq R(t), \qquad \textbf{Station Supply}$$

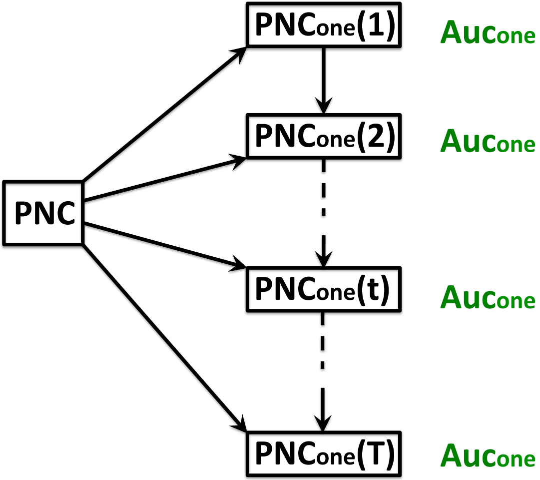
$$\sum_{k=1}^{K} y_j^k(t) \leq 1, \quad \forall j \qquad \textbf{No Double Wins}$$

$$\sum_{k=1}^{K} c_j^k(t)y_j^k(t) \leq C_j(t), \quad \forall j \qquad \textbf{Unit-Time Charging Capacity}$$

$$y_j^k(t) \in \{0,1\}, \quad \forall j \text{ and } k. \qquad \textbf{Winning Indication}$$

Auc2Charge in a Nutshell

2. Execute randomized auction for $\mathbf{PNC_{one}(t)}$



Auc2Charge in a Nutshell

Randomized Auction Auc_{one}

- **Basic idea**: design truthful mechanism via approximation algorithm[3]

1. Perform a fractional VCG auction for $\mathbf{PNC_{one}(t)}$
2. Decompose fractional solutions to $\mathbf{PNC_{one}(t)}$ into a polynomial number of feasible solutions
3. Randomly select one feasible solution as the allocation decision
4. Compute the corresponding pricing decision

[3] Lavi, Ron, *et al.* "Truthful and near-optimal mechanism design via linear programming." Journal of the ACM (JACM) 58.6 (2011): 25.

Auc2Charge in a Nutshell

How to find a polynomial number of feasible solutions?

- Use a greedy primal-dual approximation algorithm for $\mathbf{PNC_{one}(t)}$ as a separation oracle

Greedy approximation algorithm

- Drop bids exceeding the unit-charging capacity
- Select the bid with highest unit-value, one at a time, while supply and demand lasts

Theorem

The greedy algorithm provides a close-form approximation ratio of α and an integrality gap of α to problem $\mathbf{PNC_{one}}(t)$ in polynomial time.[a]

[a] $\alpha = 1 + \epsilon(e-1)\frac{\theta}{\theta-1}$.

Properties of Auc2Charge

Theorem

Auc_{one} is computationally efficient, truthful, individual rational, and $\alpha(1 + R_{max})$-competitive in the one-shot auction of Auc2Charge online auction framework.[a]

[a] R_{max}: the maximal per-timeslot bid-to-budget ratio.

Theorem

Using Auc_{one} as the one-shot auction, the Auc2Charge framework is truthful, individual rational, computationally efficient and $(1 + R_{max})(\alpha(1 + R_{max}) + \frac{1}{\varphi - 1})$-competitive on the social welfare for the EV park-and-charge system.[a]

[a] $\varphi = (1 + R_{max})^{\frac{1}{R_{max}}}$.

Simulation Settings

- Park-and-charge Facility: 500 spots
- EV battery capacity: 40kWh
- Arriving SOC $\in (0, 0.7]$
- Parking time $\in [2, 6]$ hours
- Budget: $\in [8, 12]$ dollars
- Number of bids/hour: ≤ 5
- Simulated time $T = 12, 18, 24$ hours
- Simulated scale $M = 100, 200, 300, 400, 500$ EVs

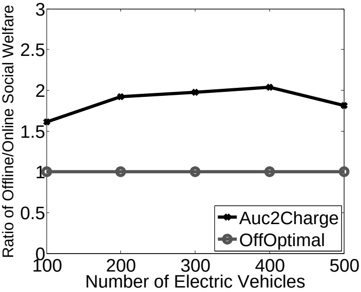
Simulation Settings

Metrics

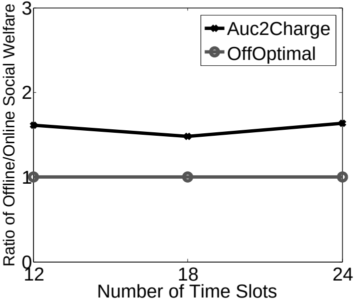
- Social Welfare
  - Approximation ratio over offline optimum
- User Satisfaction
  - User Satisfaction Ratio
  - Unit Charging Payment
  - Total Charging Payment
  - Budget Utilization Ratio

Evaluation Results

Approximation Ratio on Social Welfare



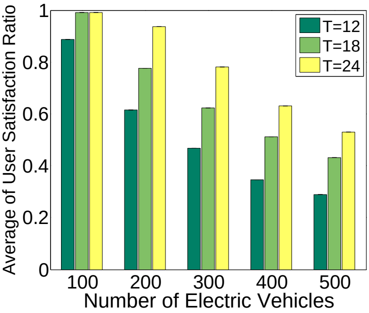
$T = 12$ Hours



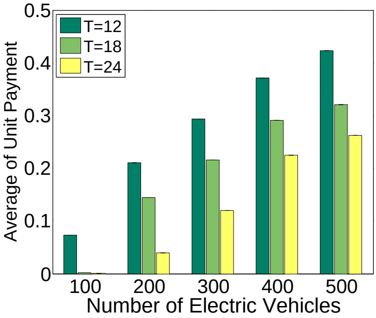
$M = 100$ Electric Vehicles

Evaluation Results

User Satisfaction



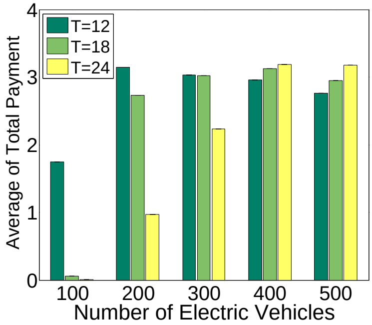
User Satisfaction Ratio



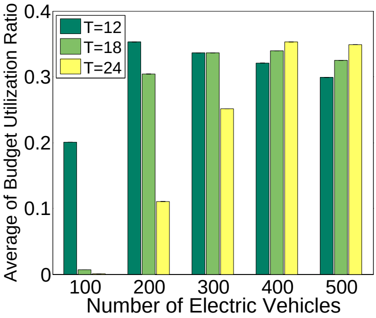
Unit Charging Payment

Evaluation Results

User Satisfaction - Cont'd



Total Charging Payment



Budget Utilization Ratio

Conclusion and Future Work

Conclusion

- Explore auctions as efficient market mechanisms for EV charging stations
- Propose *Auc2Charge*, an online auction framework for EV park-and-charge
- Demonstrate system benefits in terms of social welfare and user satisfaction

Future Work

- Include other realistic constraints, e.g., V2G transmission and ramp-up/down generation cost
- Investigate privacy-preserving auctions for EV charging