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Learning and Optimization for Sustainability

Designing algorithms to promote efficiency and decarbonization in modern infrastructure systems

Led by Professor Mahnoosh Alizadeh, the main focus of the Smart Infrastructure Systems Lab is to design learning and control algorithms that promote responsible and efficient use of large-scale societal infrastructure systems. Consider the canonical example of modern transportation systems. Every day, we experience the societal impacts of poor coordination in how users make travel choices through traffic congestion, accidents, parking scarcity and increased air pollution. But, the mobility scene is changing rapidly as electric vehicle (EV) adoption rates increase in conjunction with the proliferation of ridesharing and connected and autonomous vehicle (CAV) technologies. These advancements hold great promise in improving efficiency and reducing travel delays, accidents, the need for new infrastructure, and the carbon footprint of our societal transportation needs. However, without proper coordination, pricing mechanisms, and infrastructure interoperability, this vision cannot be realized. Consider how EVs are advertised as an environmentally-friendly commute choice. If the battery charging of EVs is left uncontrolled, it is expected that EVs will result in major increases in peak load and generation capacity and require significant infrastructure upgrades, hence exerting significant strain on electric power systems and heavily reducing the environmental benefits of transportation electrification. Instead of renewable energy resources such as wind and solar providing battery charge, expensive and potentially environmentally unfriendly generators would have to be dispatched to meet the uncontrolled charging load. Furthermore, due to significant increases in peak load, capacity violations could occur in power distribution systems, requiring major and expensive upgrades in assets, or policy changes to prevent residents from charging their vehicles at home. This highlights the importance of the design of smart charging initiatives to guide EV owners toward greener charging patterns. Alternatively, consider the case of ridesharing platforms. We all have first-hand experience of the importance of good vehicle routing and ride pricing algorithms employed by the system operator in order to manage travel demand, ensure low wait times, and promote driver participation in the platform. Last but not least, by managing traffic flow and reducing intersection wait times using smart traffic lights that coordinate vehicles virtually, CAVs can significantly decrease travel times and reduce the need for building new infrastructure. But, these clearly require interventions that enable coordination and cooperation among vehicles and their owners.

All of the problems mentioned share the same interdisciplinary and interrelated challenges: How do we *control* a cyber-physical system such as the power grid when its operation is directly affected by the choices consumers make? How do we *incentivize* customers toward a more socially-optimal behavior that potentially conflicts with their personal gains? And, while we are *learning* the correct mechanisms to optimize customer behavior, how do we ensure that the physical and cyber safety requirements of our infrastructure systems are not violated (e.g., preventing capacity violations in power systems in order to avoid blackouts)? The Smart Infrastructure Systems Lab studies these questions through a mix of tools from stochastic control, distributed

"We use a mix of tools from stochastic control, distributed optimization, signal processing, machine learning, and game theory."

optimization, signal processing, machine learning and game theory. We will highlight a number of recent efforts next, ranging from theoretical questions to real-world demonstrations of research results.

With the explosion of real-time data from infrastructure systems, machine learning (ML) algorithms are gaining popularity in systems that were classically operated using entirely model-based schemes and under strict safety requirements. Hence, we ask the question: how do we adapt recent advances in learning theory for better data-enhanced decision making in such safety-constrained complex systems? We have been able to provide theoretical guarantees for this challenging problem in certain instances. We have also demonstrated the value of such safety-constrained ML techniques using price-responsive electricity demand data to learn the optimal retail prices to charge for electricity in order to incentivize customers to become more environmentally friendly. Ultimately, the goal is to guide customers who want to minimize their electricity bills to consume more electric energy when supply is abundant and less when supply is scarce, while considering the load's impact on the operations of electricity transmission and distribution networks. This is one of many ways that learning from data can aid with renewable energy integration efforts.

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In a related effort, the distributed and networked nature of coordination protocols to manage customer demand makes infrastructure systems susceptible to external influences and cyber-attacks which, if left untreated, can arbitrarily lower system efficiency. For example, price-responsive electricity customers may rely on automated home energy management systems, which can be hacked into by malicious agents. In our work, we design new control and optimization protocols to reduce the vulnerability of distributed multi-agent networks to external manipulation.

Last but not least, the Smart Infrastructure Systems Lab has been involved in multiple efforts to showcase the efficacy of our EV smart charging algorithms in real-world field demonstrations. In partnership with SLAC National Laboratory, Chargepoint Inc., and Google, we are implementing workplace charging protocols at the Google Mountain View campus and a new charging schedule for the EV bus fleet at Stanford University to showcase the benefits of smart charging in managing peak load, reducing local distribution system impacts, and developing methods to quantify value streams for EVs as a grid resource for renewable energy integration.

Smart Infrastructure System lab members (from right to left) Mahnoosh Alizadeh, Berkay Turan, and Nathaniel Tucker.