Introduction to the Issue on Signal and Information Processing for Critical Infrastructures

CRITICAL infrastructures such as the smart electric power grid, gas and water utility networks, transportation networks, and communication networks are crucially supporting quality of life and economic growth. Future critical infrastructures are envisioned to integrate sensory data acquisition, communication and computation technologies, and signal processing to offer improved services to their end-users. Such an integration promises to have profound effects in improving societal welfare by enabling more efficient, open, consumer-centric, environmentally-friendly and resilient modern critical infrastructures. Thus, the design mantra for the evolution of critical infrastructures can be described, in part, as *knowledge is power*.

At the heart of many technological challenges underlying the vision of evolved critical infrastructures is the need for signal and information processing. For instance, new problems in smart power grids require the use of distributed signal processing and big data analytics to process continuous streams of information from a variety of sources including phasor measurement units, smart meters, smart building sensors, and electric vehicle systems. Moreover, the increased penetration of renewable sources, distributed storage, controllable loads such as plug-in electric vehicles, calls for novel optimal resource management methods that provide security and privacy while yielding system-wide benefits. The relationship of smart grid systems to related critical infrastructures such as transportation and water must be addressed from both cyber and physical perspectives. Classical signal and information processing problems are thus adapting to support dynamic system requirements and complex infrastructure dependencies with evolving characteristics.

The 17 papers in this special issue cover a wide range of topics at the nexus of optimization, estimation and detection theory, control, game-theory and machine learning and are categorized into four application areas.

I. Power System Monitoring

The issue starts with "A Robust Generalized-Maximum-Likelihood Unscented Kalman Filter for Power System Dynamic State Estimation" by Zhao and Mili. Here, observation and innovation outliers in power measurements are suppressed via noise filtering. The authors create a batch-mode regression from the simultaneous processing of both predictions and observations. The resulting robust estimator minimizes a convex Huber cost function using weights from projection statistics. Next, in "Power System State Estimation under Model Uncertainty" by Sihag and Tajer, the authors address when the power system model is only partially known and employ alternatives for the system model such that the state estimator needs to detect whether the model has deviated, and if so *isolate* the actual model. The paper studies the interplay between detection, isolation, and estimation.

Focused on PMU-based estimation, "Decentralized PMU-assisted Power System State Estimation with Reduced Inter-Area Communication" by Kashyap *et al.* develops a multi-area power system state estimation scheme that relies on network gossiping with reduced information exchanges among areas. Measurements from PMUs and legacy SCADA devices are combined based on the premise of separating the state vector into PMU observable and PMU unobservable parts, and estimating the former using PMU measurements alone.

In contrast, "Multi-Channel Hankel Matrix Completion through Nonconvex Optimization" by Zhang *et al.* studies the multi-channel missing date recovery problem when the measurements come from a dynamical system. They propose a model to characterize the low-dimensional structures in multi-channel time series such as measurements from multiple PMUs. The problem is formulated as a nonconvex optimization; two algorithms are developed with linear convergence rates. The number of required observations is significantly reduced compared to other low-rank completion methods. Finally, the paper "Estimation of Deterioration Levels of Transmission Towers via Deep Learning Maximizing Canonical Correlation between Heterogeneous Features" by Keisuke Maeda *et al.* studies deterioration levels of transmission towers using a deep extreme learning machine, which uses projections obtained by maximizing the canonical correlation as weight parameters of the hidden layer, thereby simplifying the computational complexity of the estimator.

II. Energy Management in Smart Power Grids

Several papers of this special issue are devoted to energy management. The first, "Scheduling and Pricing of Load Flexibility in Power Systems" by Khatami *et al.* uses an optimal control model to co-optimize the continuous-time flexibility of loads and the operation of the generation units. There is a reduction in the dimension of the problem and the parameter trajectories by a finite-order function space converting the problem into a mixed-integer linear one. The paper "Joint Energy Procurement and Demand Response towards Optimal Deployment of Renewables" by X. Cao *et al.* formulates a two-stage stochastic optimization problem with the objective of maximizing the profit of a power system operator. The first-stage

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decision is the optimal investment in renewable energy capacity, while second-stage decisions include energy purchase from the spot market and pricing schemes for the end-users. A low-complexity algorithm is developed to solve the problem.

"Dynamic Power Distribution System Management with a Locally Connected Communication Network" by Zhang *et al.* proposes an innovative coordinated optimization and control approach for distribution systems to facilitate the integration of large numbers of distributed energy resources (DERs). Modeling and algorithm design to address weakly connected communication networks and DER heterogeneity and measurement mismatches are considered. Analysis and empirical results demonstrate the potential of the approach.

Finally, "Adaptive Contextual Learning for Unit Commitment in Microgrids with Renewable Energy Sources" by Jang-Won Lee *et al.* presents an adaptively partitioned contextual learning algorithm that learns the best unit commitment schedule and minimizes the total cost, while using estimates of the effects of system uncertainties considering contextual information strongly correlated with various system uncertainties.

III. Resource Allocation and Inference in Networked Infrastructures

Networked infrastructures are the focus of the next three papers. "A Virtual-Queue Based Algorithm for Constrained Online Convex Optimization with Applications to Data Center Resource Allocation," by Cao *et al.* studies an online convex optimization as applied to the dynamic resource allocation problem in data center networks. A novel algorithm based on virtual queues for a constrained online convex optimization is proposed. Analytic and empirical results demonstrate superior performance in many cases in comparison to existing work. The paper. Next, "Communication Complexity of Dual Decomposition Methods for Distributed Resource Allocation Optimization" by S. Magnússon *et al.* is concerned with coordination algorithms whereby a supplier allocates resources to multiple users via dual decomposition. The paper proposes complexity measures that characterize the trade-off between solution accuracy and the number of bits used for quantization of transmitted information in such coordination algorithms. Bounds on the complexity of different practical resource allocation algorithm variants are provided as well. Last, "Averting Cascading Failures in Networked Infrastructures: Poset-constrained Graph Algorithms" by P.Yu *et al.* studies the strategic placement of protection nodes in the networked infrastructure to mitigate cascading failures via stochastic optimization and exploits the concept of graph centroid in developing an algorithm to solve the problem.

IV. Detection and Mitigation of Cyber-Attacks

A number of cybersecurity related papers round the special issue. The paper "Requirements for Secure Clock Synchronization" by Narula and Humphreys establishes a fundamental theory of secure clock synchronization for a generic system model. The paper proposes a set of necessary conditions for secure two-way clock synchronization and specializes these conditions to design a secure PTP protocol.

In the realm of false data injection (FDI) attacks, "Reactance Perturbation for Detecting and Identifying FDI Attacks in Power System State Estimation" by Liu *et al.* analyzes and proposes a strategy to detect and identify FDI. The authors derive the conditions to mitigate attacks and design a secure reactance perturbation algorithm that maximizes detection and identification while minimizing power losses. The paper "Non-Circular Attacks on Phasor Measurement Units for State Estimation in Smart Grid" by Mohammadi and Plataniotis introduces a novel FDI attack on PMU measurements by manipulating the circularity of PMU readings. The paper also proposes attack detection methods for these non-circular attacks based on statistical tests.

The paper "Evaluating Detectors on Optimal Attack Vectors that enable Electricity Theft and DER Fraud" by Krishna *et al.* focuses on the emerging problem of smart meter fraud in the context of DERs and demonstrates how monetary incentive exists for electricity generators to over-report generation. The economic impact of cyberattacks of smart meters is addressed using real consumption data from Europe, Australia, and the USA. To round out the special issue, the article "Intelligent Soft Computing-based Security Control for Energy Management Architecture of Hybrid Emergency Power System for More-Electric Aircrafts" by M. B. Kamal *et al.* develops computational tools for enhancing the situational awareness of more-electric aircrafts. In particular, the paper proposes methods for detecting cyber-attacks on the aircraft's energy management system and for validating the integrity of its measured critical signals.

Lastly, thanks are in order for a number of people whose contributions and help made this special issue possible. We appreciate the insights, encouragement, and support of Shri Narayanan and the entire editorial board. Allison Fisher, the journal coordinator, provided very effective support throughout the reviewing process and kept us on track. Last but not least, we thank all the reviewers for their outstanding efforts in improving the quality of the manuscripts.

We hope that you will find the articles in this special issue interesting, stimulating, and useful for your own research.

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