

Sensor Placement in Energy Systems Based on Residual Uncertainty

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Summary:

This work investigates the measurement requirements in energy systems from an information-centric viewpoint. The framework models an energy system as a hierarchy of aggregated nodes, represented as the sum of known and unknown load components. The mismatch between measured node power and the estimated system state defines a residual that represents the remaining information uncertainty and serves as the basis of a greedy sensor selection process. The sensor placement task is formulated as an optimization problem, where sensors are selected to minimize the residual-based uncertainty.

Keywords: sensor placement, observability, energy systems, residual uncertainty, greedy optimization

Introduction

Modern energy systems are increasingly characterized by distributed generation, heterogeneous loads, and multi-level system structures. From individual households and buildings to district energy systems and large-scale grids, the number of interacting components continues to grow. Reliable monitoring of these systems is essential for energy management, forecasting, and control [1], [2], [3]. In practice, however, energy systems are only partially instrumented. Installing sensors at every possible point is typically infeasible due to cost, communication constraints, and system complexity. Energy management systems must therefore operate with incomplete information about the underlying system state and rely on state estimation techniques to reconstruct the system state from available measurements [4]. This leads to a central design question: which sensors provide the greatest information value for observing the system? In this work, we focus on optimizing an existing energy system that is modeled as a hierarchy of aggregated nodes. Based on this representation, sensor placement is formulated as an optimization problem, where the goal is to select measurement points that reduce the remaining information uncertainty as efficiently as possible. To evaluate our study, the simulation-based sensor placement method is evaluated using stochastic realizations.

Description of the New Method

The energy system is modeled as a set of aggregated nodes, each representing a local power balance. The balance can be categorized into measured loads (A), modeled loads (B) and unknown loads (C), representing a realistic scenario. The difference between measured node power and estimated power defines a residual $R(t)$, which represents the remaining information uncertainty. The effects of the variability and the maximum deviation of the residual are combined into a single score, referred to as the observability score shown in (1). Adding a sensor reduces the score by transferring loads from modeled to measured, thereby decreasing the residual uncertainty.

$$Score(\mathcal{S}) = Var(R(t)) + w_{peak} \cdot \max |R(t)|^2 \quad (1)$$

The variance of the residual $Var(R(t))$ of the residual captures overall fluctuations, while the maximum deviation reflects critical peak events. The sensor placement problem is defined over a set of candidate sensors, from which a subset is selected to minimize the observability score. To archive this, a greedy algorithm is applied, iteratively selecting the sensor that provides the largest reduction in uncertainty. This allows an efficient approximation of the optimal sensor configuration without evaluating all possible combinations.

Results

The method is evaluated using stochastic simulations with 50 different random seeds of a representative node with multiple heterogeneous electrical loads. As shown in Fig. 1, the observability score decreases rapidly with the first few sensors, indicating that a small number of measurements already captures most of the relevant information. The shaded areas indicate the variability across the realizations.

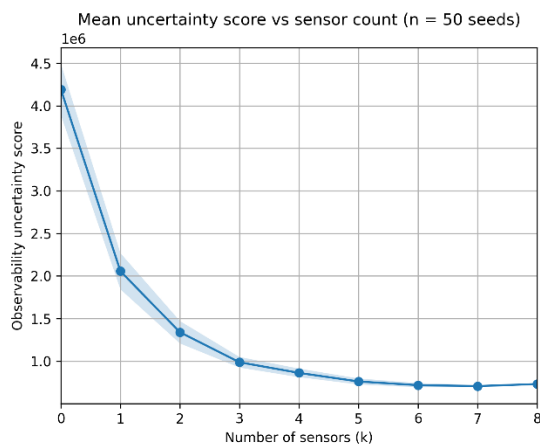


Fig. 1. Mean Observability score as a function of the number of sensors

Consistent with this, Fig. 2 shows that the marginal information gain decreases with each additional sensor, confirming the presence of diminishing returns. The first sensor provides the largest improvement, while later sensors contribute only minor reductions.

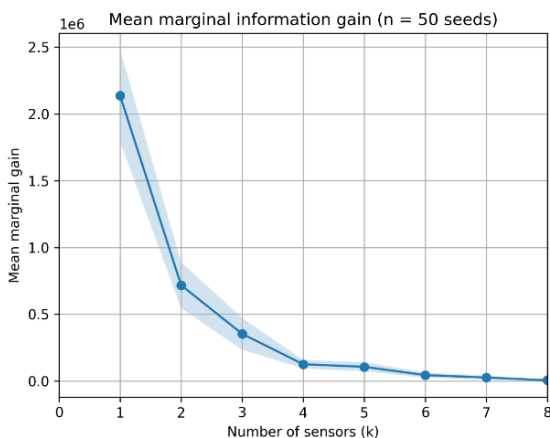


Fig. 2. Mean marginal information gain

The stability analysis in Fig. 3 demonstrates that the selection order of sensors is largely consistent across different stochastic realizations. This indicates that the proposed metric captures meaningful structural properties of the system. It also suggests that the dominant sources of uncertainty are identified consistently across different realizations.

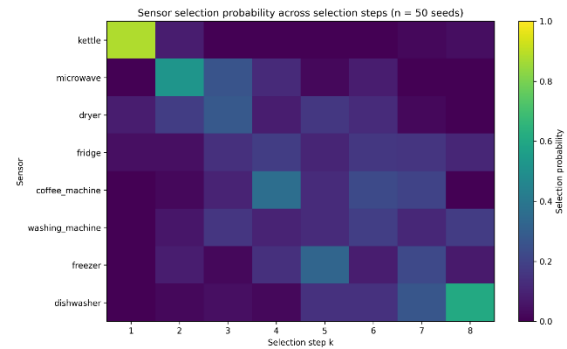


Fig. 3. Sensor selection probability heatmap

Conclusion

The proposed observability metric and greedy sensor placement method provide an effective approach for identifying informative sensors in partially observed energy systems. The framework links sensor placement directly to the reduction of residual information uncertainty at the node level. The simulation experiments show that a small number of strategically placed sensors already reduces the majority of the information uncertainty. Additional sensors lead to progressively smaller improvements, indicating diminishing returns in sensor placement. The stability analysis shows consistent sensor prioritization across realizations, indicating meaningful structural properties. While the present study focuses on the active power balance of a single node, the proposed framework is designed to scale to hierarchical energy systems consisting of multiple interconnected subsystems. Future work may therefore extend the model to incorporate additional system variables such as voltage, reactive power, and environmental inputs, as well as investigate sensor placement strategies in larger multi-node systems. Furthermore, the proposed approach could be applied to other sensor placement problems.

References

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