# A Sample *ACM* SIG Proceedings Paper in LaTeX Format[*]

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## ABSTRACT

Cyber-Physical Systems (CPS) consist of computational components interconnected by computer networks that monitor and control switched physical entities interconnected by physical infrastructures. To ensure a tight integration among the components in CPS we employ a novel approach that composes the correctness of components instead of their functionality using conjunction of non-interfering logical invariants. Our distributed algorithm developed for smart power grid nodes uses this approach to adaptively schedule power migrations in such a way that the stability of both the computer network and the physical system are maintained. In this paper we mainly focus on network congestion and explore a well known Explicit Congestion Notification (ECN) scheme from CPS context and demonstrate the significant improvement in overall CPS efficiency and stability. Experimentation results show how the power transfers between smart grid nodes are unaffected if nodes are allowed to exploit ECN scheme while also taking necessary actions to reduce network congestion.

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†Dr. Trovato insisted his name be first.

‡The secretary disavows any knowledge of this author's actions.

§This author is the one who did all the really hard work.



## 1. INTRODUCTION

Smart Power Grid [23] is a prime example of Cyber-Physical System (CPS) where the goal is to have embedded computing devices monitor and control distributed generation, storage and transfer of power in a safe, reliable, efficient and secure manner. Ensuring stability and correctness (both logical and temporal) of the system as a whole is a major challenge in CPS design. Any incorrectness or instability in one component can impact the same features of other components. For example, an action in the physical domain could affect the network domain and vice-versa, thus making correct scheduling of these actions paramount to overall system stability. The fundamental challenge in developing a design framework that unifies the various components is the heterogeneity of the component types, resulting in semantic gaps that must be bridged.

Existing papers largely consider the stability of one or two components in isolation. For example, network delays affect system stability and considerable work focusses on determining system stability bounds as a function of injected delay [20]. Results from switched-systems theory [15] model the stability of the plant. Hybrid automata [19] and timed I/O automata [5] represent a simultaneous mix of continuous and discrete states in the verification process [11, 43]. Real-time scheduling is traditionally a function of *a priori* time bounds [29]. To consider components individually, or in pairs, requires that they be very stable such that the composition of the components into a CPS is stable.

In our work, we employ a fundamentally different approach that composes correctness instead of functionality. The basic idea, depicted in Figure 1, is to express the stability and correctness constraints of all components in the form of logical *invariants* and ensure that system actions are performed only if and when they are guaranteed not to violate the conjunction of these invariants. This approach is not only limited to smart power grid design but can also be generalized to different cyber-physical systems with different functionalities.

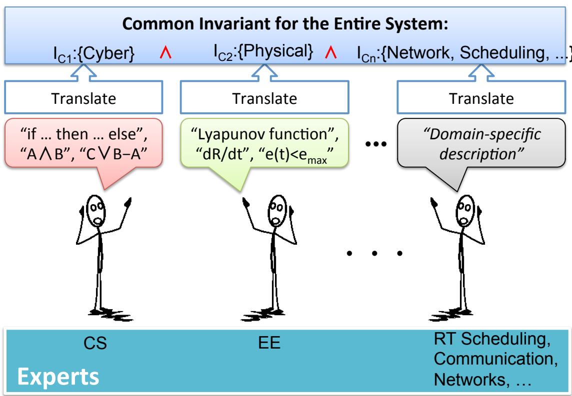


**Figure 1: Overview of invariant-based approach**

The state of the physical system and, hence, its stability, is dependent on power transfers (series of power migrations) initiated by the cyber algorithm within each node in the system and by the state of the communication network that carries messages between the cyber nodes to signal initiation and acknowledgement of physical power migrations. The state and stability of the communication network is in turn affected by the number of migration messages in transit at any given time. In recent work[*****cite COMPSAC], we developed a scheduling invariant for our distributed, adaptive algorithm for scheduling power migrations between nodes in a smart grid and demonstrate that conjunction of such a scheduling invariant and an invariant for physical system state is necessary to maintain overall system stability. In contrast to traditional real-time scheduling, *correct* scheduling in our context refers to initiating actions at appropriate times in a way that system stability is maintained rather than insisting that every action is initiated at a pre-defined time and must adhere to a pre-defined deadline. In order to improve efficiency along with stability, components in CPS must have certain amount of inter-component information. In the current paper, we focus on improving the efficiency while also maintaining the stability of smart grid nodes by exploiting the network congestion information obtained from Early Congestion Notification (ECN) scheme, wherein packets are marked indicating impending congestion, instead of dropping them[16, 36, 37]. We allow the smart grid nodes to sense the possible upcoming network congestion and change the amount of power being transferred with every power migrate message in order to compensate for reduced rate of power transfers. As of our knowledge, this is the first work that explore ECN scheme from CPS context for the benefit of physical system efficiency as well as take necessary action to reduce network congestion.

The rest of this paper is organized as follows. Section 2 provides some background information and discusses related work. We present our system model and assumptions in Section **??**. Section **??** presents our physical system invariant and adaptive scheduling invariant. Section **??** presents our resulting power management algorithm. Our simulation setup is introduced in Section **??** and results are presented in Section **??**. Section **??** presents a brief discussion and conclusions are presented in Section **??**.

## 2. BACKGROUND AND RELATED WORK

CPSs, with few exceptions, are switched dynamic systems. A switched system is a fundamentally continuous-time system with changes that occur at discrete times [28]. Analysis and design of CPSs is a challenge as any process must simultaneously take into account cyber, physical, and network aspects. Some work is breaking through this barrier. Acumen [48] bridges the gap between analytic models and simulation codes. Interface automata [12] checks for compatibility of components in composition by showing that they do not *interfere* with each other. Recent work [26] proposes a performance verification technique for CPS. This work assumes the use of a communication network such as CAN, FlexRay, etc. and use the relatively structured properties of the networking infrastructure to tightly bound network delays and, hence, control performance. Invariants and predicate transformers on the state of CPS was explored for dynamical systems in [41] and more recently as a formalism for invariant interaction and incremental invariant composition [7] and run-time assurance of operational modes [6]. The interaction of invariants for purely cyber processes has its origins in [31] which affords composition of sequential proofs governed by the property of noninterference. Recently, there have been several attempts to create comprehensive models for design and analysis of CPSs (such as [13, 8, 1]) that use domain-specific ontologies and hybrid systems techniques.

Correct scheduling of actions affecting one or more subcomponents is key in such a CPS in order to maintain overall system stability. However, stability and scheduling are not *a-priori*, but must be adaptive based on events in the CPS. Mode-based real-time scheduling allows different modes of operation where different modes may have variation in their task set and/or task timing characteristics [39, 38, 18, 42], thereby allowing a degree of adaptation. However, existing approaches assume that mode parameters and mode change triggers are statically well-defined, allowing static analysis of individual modes and mode transitions, thus making them inapplicable in a CPS. Recent work proposes a technique for online reconfiguration of resource reservations using Constant Bandwidth Servers [27]. Elastic scheduling strategies [10] and feedback schedulers [45] allow for more dynamic adaptation, but adaptation is still typically performed at sporadic intervals, in contrast to the continuous adaptation needed in a CPS. Adaptive scheduling as in [14] dynamically changes the rates of task execution in response to system behavior, but would require complete abstraction of physical and network parameters, making its application to a CPS very challenging. Scheduling of power demands for optimal energy management in a smart grid has been proposed [25]. However, this work only considers instantaneous power in the physical system and does not consider network behavior. Considering all continuous and discrete dynamics along with dynamic behavior simultaneously results in state explosion. While verification is possible, it is extremely challenging.

[******add citations] Although protocols such as TCP are well known for reliability, TCP relies on packet drops caused due to overflow of queues at routers as an indication of network congestion. In smart grid context, every message is responsible for a small amount of power in grid therefore message loss is directly associated to the grid stability. TCP by controlling its transmission rate can effectively reduce packet drops if transport is capable of ECN. But, congestion information obtained from network is completely hidden from the application running over TCP. In order to know ECN in application, UDP protocol is a perfect choice. It is then application's responsibility to adapt according to network conditions and take necessary actions upon detection of congestion in network. [******end citations]

## 3. METHODOLOGY

Methodology goes here

## 4. CONCLUSIONS

Conclusion goes here.

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# APPENDIX

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