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.

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.

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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.

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.

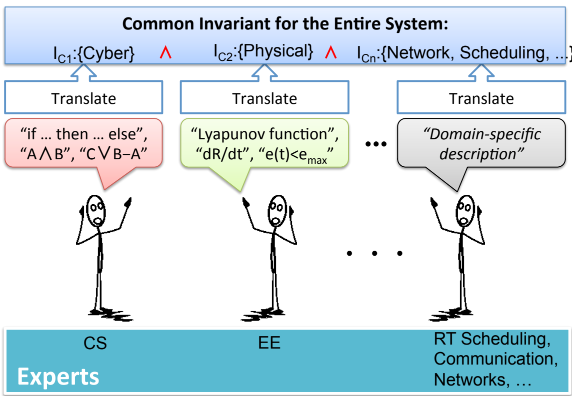

Figure 1: Overview of invariant-based approach

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 3. Section 4 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. SYSTEM MODEL AND ASSUMPTIONS

Power Management Architecture. Figure 2 shows the architecture of a future generation smart grid (SmartGrid) [23]. The system is essentially a microgrid consisting of energy storage devices (DESD), energy resources (DRER) and LOADs. Each node is potentially owned and located in a residence or business and the basic idea is to share power among nodes in order to benefit the overall system. Intelligent flow controllers (nodes) contain Solid State Transformers (SSTs), that are physical actuators controlling power flow to and from a shared electrical bus under the direction of co-operating Distributed Grid Intelligence (DGI) processes.

The DGI processes are cyber algorithms that choose, negotiate and manage power transfers among nodes based on local information and information about the states of other nodes that is periodically exchanged among nodes. In the current work, we assume that all nodes are synchronized, for the sake of simplicity. Nodes periodically exchange state information with each other in a state collection phase. Next, a negotiation phase is performed in which nodes conduct negotiations to identify which power transfers need to be performed among nodes. The identified power transfers between pairs of nodes are then performed in a power transfer phase. One cycle is depicted in Figure3, with one or more negotiation and power transfer phase pairs after a state collection phase. This entire cycle of state collection, negotiation and power transfer phases is repeated.

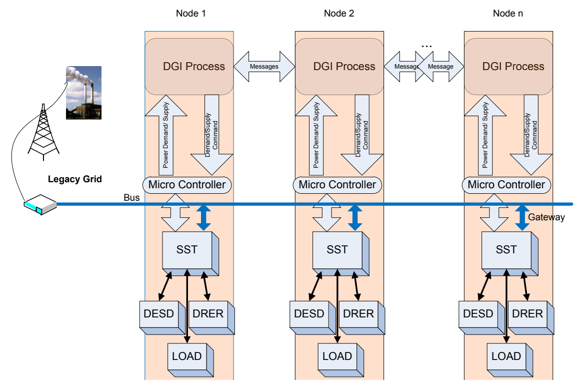

Figure 2: Smart Grid Power Management Architecture

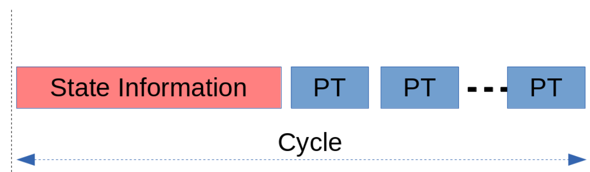

Figure 3: A single cycle of collecting state information followed by many negotiation and power transfer phases (PT)

Power Transfer Model. Power transfers within one phase are performed as a series of (periodic) power migrations, each transferring a given quantum (say δ) of power. The cyber algorithm on the source (sender) node sends appropriate control signals to the local physical actuators to add a quantum of power to the electrical bus and sends a power migration message to the destination (receiver) node signalling this. Upon receiving this power migration message, the destination node sends control signals to its local physical actuators to remove a quantum of power from the electrical bus and sends an acknowledgement message to the source node.

Physical System Model. The physical system is a finite inertia microgrid, that is, a power system with a small number of generators and loads that acts independently of the grid. There is a relatively small rotating generator, whose inertia dominates the dynamics as described in the next section. There are some number of controllable nodes that participate in the power management by acting as either loads or generators. Nodes with excess generating capacity transfer power to nodes that have excess load.

Communication Model. Each node in the network runs an adaptive message scheduling algorithm that schedules power migrate messages in any given topology, based on the observed communication latencies at a given node.

4. SYSTEM ANALYSIS AND INVARIANT FORMATION

4.1 Physical System Analysis

The physical system must satisfy one out of several criteria in order to be stable. The criteria are derived from an analysis of the continuous-time dynamics of the system, which are modeled as

$$\frac{d\omega}{dt} = -\frac{V_1 V_2}{J\omega X} sin(\theta - \theta_0) - \frac{D}{J}(\omega - \omega_0) + \frac{P_{imb}}{J\omega} - \frac{kP^2}{J\omega},$$
$$\frac{d\theta}{dt} = \omega - \omega_0, \tag{1}$$

where ω is the frequency, θ is the phase angle of the generator voltage, ω_0 and θ_0 are their nominal values, P_{imb} is the net power imbalance due to outstanding messages, and the other terms are various physical parameters. The error energy, given by

$$V(\omega, \theta) = \frac{J}{2}(\omega - \omega_0)^2 + \frac{V_1 V_2}{\omega X}(1 - cos(\theta - \theta_0)). \tag{2}$$

is a Lyapunov function (that is, a positive-definite function with a non-positive time derivative) if the system satisfies I_{P1}, given by

$$\left\{ \begin{array}{c} I_{P1} : (\omega - \omega_0)^2 \, (D\omega + m) \\ +(\omega - \omega_0)(kP^2) > \delta K(\omega - \omega_0) \end{array} \right\} \tag{3}$$

With other factors, I_{P1} ultimately imposes a limit on $\delta * K$, where δ is the quantum of power migrated with each message and K is the number of outstanding messages.

In general, if a Lyapunov function exists for a particular physical system, then the system is stable. However, there are other conditions that also ensure stability for a switched system, which is a continuous-time system that is subject to external switching events. A *Lyapunov-like* function [9, 46, 47] is similar to a Lyapunov function in that it must be positive-definite, but its value may increase under some conditions. If the value of the Lyapunov-like function decreases at each switching event, then the system is stable. A final option is that the error may not decay to zero, but is bounded.

Physical System Invariant(I_P). Combining the three conditions, a single invariant may be found,

$$\{I_P : I_{P1} \vee (V(\omega, \theta) < V_{bound}) \vee (V(t) \leq V(t_x))\} \tag{4}$$

where V_{bound} is the maximum allowable value of V, $V(t)$ is the value of $V(\omega, \theta)$ at the present time and $V(t_x)$ is its value at the most recent previous violation of I_{P1} due to a large value of K. Prior work [33, 32] has demonstrated that the system can be stable for certain combinations of steady-state power imbalance and droop constants in the SST controllers.

4.2 Network And Scheduling Analysis

As mentioned earlier, physical system stability at any point of time depends on the product of outstanding messages in the communication channel and the quantum of power migration, δ. Stability of network depends on the number of outstanding messages K, where K is also a function of the rate(s) of power migration of source node(s) and transfer times for messages over the communication network. To ensure safe and stable operation, an upper bound for maximum outstanding messages $Kmax_{global}$ is established prior to power transfer phase based on physical and network restrictions. $Kmax_{global}$ is distributed among the communicating nodes as in Figure4 so that each node i is given a limit, $Kmax_i$, on the number of outstanding messages it can have in the system. For example, $Kmax_{global}$ can be distributed among the n nodes in proportion to the excess power that nodes have at the end of the state collection phase, as shown in equation below, where P_s is the excess power of node s.

$$Kmax_s = \lfloor (\frac{P_s}{\sum_{i=1}^{n} P_i}) * Kmax_{global} \rfloor \tag{5}$$

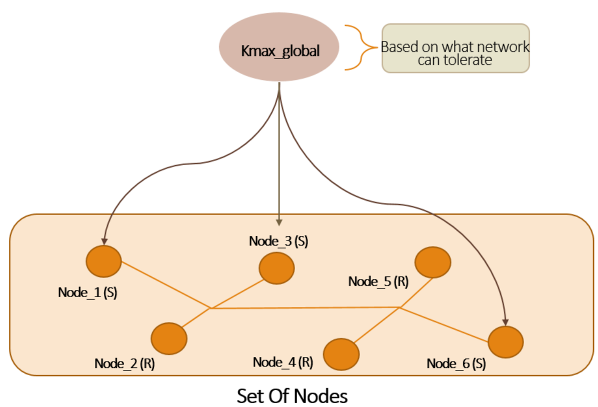

Figure 4: $Kmax_{global}$ Distribution Among Sender Nodes

The message scheduling algorithm running at node s, adapts the power message migration rate r_s or, inversely, the period p_s such that the number of outstanding messages of node s at any given time, namely K_s ($\sum_{i=1}^{n} K_i = K$), never exceeds its maximum allowed outstanding messages $Kmax_s$.

Message Scheduling Invariant (I_S).

For a given power transfer phase and based on above $Kmax_s$, p_s constraints, following scheduling invariant I_s can be formed, shown in Equations 6 - 9.

$$\{I_S = I_k \wedge I_c \wedge I_p\} \tag{6}$$

$$I_k : K_s < Kmax_s \tag{7}$$

$$I_c : RT_s^{ex} \leq PT - t \tag{8}$$

$$I_p : t - LT(s) \geq p_s \tag{9}$$

Here, PT is the end time of the power transfer phase, t is the time at which the invariant is evaluated and $LT(s)$ is the time at which the last power migration message was initiated by node s. Work done in [**?**] shows the importance of composing system correctness through conjunction of physical I_p and scheduling I_s invariants in order to maintain system stability.

5. ADAPTIVE SCHEDULING WITH EARLY CONGESTION NOTIFICATION

In this section, we propose modifications required for adaptive power scheduling algorithm[******cite COMPSAC] to support Early Congestion Notification (ECN) obtained from the ECN capable transport. We overview adaptive scheduling algorithm in 5.1, explain ECN mechanism in 5.2 and then propose the integration of ECN in scheduling algorithm.

5.1 Adaptive Scheduling Overview

Every power migration message is assigned a relative deadline D_s based on the current expected response time (RT_s^{ex}) for messages initiated by node s. The expected response time is calculated as the average of a given number of previously observed response times. A "deadline miss" for any given message indicates longer network latencies than expected due to potential congestion in the network. In this situation, the algorithm increases its expected response time by a pre-defined margin ($RTMargin$) and calculates a new, larger period and larger relative deadline for power migration messages in an effort to reduce congestion. In the worst case, this may result in a migration message being initiated only after acknowledgements for all previous messages have been received. If, on the other hand, acknowledgements are received earlier than expected for a given number, say $CtrMax$, of consecutive messages, the algorithm decreases its expected response time and calculates a new, smaller period and smaller relative deadline for power migrations that can still maintain network and physical system stability. Note that $RTMargin$ and $CtrMax$ are configurable system parameters that are assumed to be constant for all nodes in a given power transfer phase.

5.2 Early Congestion Notification Mechanism

Congestion detection and avoidance for TCP through ECN (Early Congestion Notification) was proposed in [16]. Essentially, ECN mechanism is implemented by maintaining two bits in IP header making four possible combinations as in Figure5. If ECT, CE are $0, 0$ then the transport(Sender, Receiver, Network) is considered to be not ECN-capable. If ECT, CE are $0, 1$ or $1, 0$ then the transport is ECN-capable and if ECT, CE are $1, 1$ then the transport is ECN-capable but also the packet into consideration has experienced congestion.

Gateways, in the network maintain Q_{min} and Q_{max} thresholds for average queue size, Q_{avg} for every outgoing port.

ECN FIELD		
ECT	CE	Codepoint
0	0	Not-ECT
0	1	ECT(1)
1	0	ECT(0)
1	1	CE

RFC 3168: ECN field in IP

Figure 5: ECN Field In IP Header

When a packet arrives at the gateway, one among the following actions is taken,

IF $Q_{min} \geq Q_{avg} \leq Q_{max}$: Set ECN_CE bit.

IF $Q_{avg} < Q_{min}$: Take no action.

IF $Q_{avg} > Q_{max}$: Drop packet.

Receiver, upon arrival of packet marked with ECN_CE(Congestion experienced), sets a flag in the acknowledgment packet header and send it back to Sender. **Sender,** when receives this acknowledgment reduces the rate of transmission in order to avoid possible upcoming congestion. For example, in TCP, sender reduces the transmission rate by reducing its congestion window size and slow start threshold. This mechanism avoids the unnecessary packet drops during mild congestion.

Although there are modifications made to ECN as in [49]

6. CONCLUSIONS

Conclusion goes here.

Acknowledgments

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APPENDIX

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