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PERFORMANCE EVALUATION ON CYBER-PHYSICAL SYSTEMS

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Abstract. *Cyber-Physical Systems (CPSs) are made of composition of computer nodes and computing elements, such as sensors and actuators, which monitor and control physical processes. These physical processes impose to sensors and actuators a time behavior completely different of the one of the conventional computer nodes. Also, these systems can be deployed in a large scale, as, for instance, a large industrial plant, or even a large supervisory facility that control several industrial plants. Combining such very distinct kind of components, with distinct quality of services, CPS can be modeled as a hybrid and dynamic distributed system. In this paper, it is presented requirements for CPS and a brief discussion on performance evaluation techniques for these environments.*

Keywords: Cyber-Physical Systems, Smart grids, Performance evaluation

1. **Introduction.** Nowadays, Cyber-Physical Systems (CPSs) represent the next step forward in computing. These systems are integrations of computation with physical processes. That is, these systems rely on computer-based control loops, where commercial off-the-shelf components can be combined and used to monitor and control physical processes [1].

That is, CPSs are composed of computer nodes and computing elements, such as sensors and actuators, which monitor and control physical processes. Components that interact directly with physical processes follow response times that are directly related to the nature of such physical processes; otherwise, computer nodes follow a timely behavior that may be orders of magnitude faster than that. Also, these systems can be deployed in a large scale, as, for instance, a large industrial plant, or even a large supervisory facility that control several industrial plants. So, in CPS, distinct parts of the system have distinct characteristics that may vary dynamically following availability of computing resources and system failures (e.g., temporary network disconnection or a simple loss of quality-of-service). In some cases, some parts of the distributed CPS are interconnected by a real-time network whereas others are deployed over an Intranet facility or even across the Internet.

Designing CPS requires to combine requirements from computer nodes and from computing elements that interact with physical processes. This is a great challenge, in face that timeliness emerges unpredictable in such systems. In order for a proper design of CPS, we must use evaluation techniques adapted to the nature of those systems. For instance, using prototypes as a CPS testbed platform, as in [2], may result in complex evaluation plants. This can be undesirable in earlier stages of designing. A pure analytical model approach implies in combining such different nature of models, as automatas for computer node behavior and differential equations for physical processes behavior and its interaction with computing elements.

This paper shows up a brief analysis of the performance evaluation techniques for CPS and presents an approach for design and evaluate such systems.

2. **Requirements for Designing Cyber-Physical Systems.** CPSs do not operate in a controlled environment, once they interact with physical processes – as, for instance, smart grids based on computer systems that monitor and control power grids. So, those systems should be robust to deal with unexpected conditions [1]. That robustness may not be achieved at the microeletronics level. Higher levels may combine software and hardware components, abstracting details from lower levels and providing robustness through techniques as component replication.

Microeletronics that deal with physical processes may require concurrent behavior, but, in general, even Real-Time Operating Systems (RTOSs) do not deal properly with concurrent orchestration in the way that orchestration occurs on CPS. RTOS hides timing details and provides a Worst Cost Time Execution (WCET) approach [1], coarsing timing behavior, in order to assure timing primitives that allows, for example, control and monitor physical processes. Also, embedded sub-systems of CPS rely mostly on specialized networks, e.g., CAN buses in manufacturing systems, that allows advanced time synchronization across networks [3]. These parts may have to interact with computer nodes that use conventional networks, such as switched Ethernet or even Internet. Thus, designing Cyber-Physical Systems requires combining components with different levels of abstraction, and different requirements of QoS.

Some of these components may impose real-time behavior, due to physical processes, and others may work at a best-effort approach. Real-time networks, and synchronizing and prioritization primitives may be combined with conventional networks, to provide the whole complex computer system that is a CPS. Components in a Cyber-Physical System usually may be distributed across that networks, and then we can model CPS as a Distributed System.

CPSs are a distributed computing orchestration, that is, a CPS compounds a distributed system where computer nodes and computing elements, as processes, communicate each other through communication channels (as an abstraction for the whole hardware and software communication facilities).

However, CPSs are not adequately represented by classical asynchronous or synchronous distributed system models. CPS can be deployed in a large scale and distinct parts of the system may have distinct characteristics that may vary dynamically following availability of computing resources and system failures (e.g., temporary network disconnection or a simple loss of quality-of-service). In some cases, some parts of the distributed CPS are interconnected by a real-time network whereas others are deployed over the Internet.

Once, the Quality of Service (QoS) may change from one CPS component to another – that is, some CPS components may present determinist real-time behavior (timely) and others not–, and there are either distinct QoS between communication channels – once, for instance, several kinds of network infrastructure may be used, from CAN buses, from dedicated switched-Ethernet to Internet.

Several distributed system models may be used to represent models with dynamic or hybrid QoS behavior [4, 5], allowing to be possible to use the advantage of available synchronous behavior, even there is not in the whole system components or for the whole execution. Herein, we assume a simple generic hybrid and dynamic distributed system model: processes are said *timely* if they execute steps within known time bounds, and *untimely* otherwise; also, communication channels are also said *timely* if the sending/receiving of messages is realized within known time bounds, and *untimely* otherwise.

Any hybrid and dynamic distributed system DS may be made of arbitrary compositions of *timely* and *untimely* components (processes and channels), and that timeliness behavior can change during system execution. Finally, each component can be associated to distinct fault models. This level of abstraction reduces the evaluation of CPS to an evaluation of a distributed system, where the behavior emerges from interaction of system components with distinct QoS.

3. **Performance Evaluation on CPS.** Any computer system can be evaluated by analytical methods, simulation, or measurements [6]. CPSs are a special kind of computer system. They rely on a special combination of software, hardware, and firmware, once computing elements, as sensors and actuators play an important role in these systems, through the interaction with physical processes. That orchestration is a distributed system with a hybrid configuration of QoS components that may change over execution time. Once, CPS can be viewed as hybrid and dynamic distributed systems, performance evaluation on these scenarios should observe such requirements.

Measurements on scenarios with configurations that change dynamically, may not be easy to deploy. Measurements on CPS should require to evaluate execution of large industrial plants, including interaction with physical processes, and even measurements on prototyping can require a large effort. Analytical approaches are adequate to estimate asymptotic behavior and worst-case scenarios. That approach may not be useful to estimate average cases, due to complexity present on CPS systems to represent interaction of distributed components, including hybrid and dynamic behavior. That may result in strongly complex queuing systems, indeed if parameters change arbitrary across the time.

Simulations are based on characterizing the behavior of each computer system component as an algorithmic model, that runs the analytical model associated to the component. The interaction between the components is achieved through a simulation environment, representing system execution flow. Simulation combines best of two worlds: as in measurements, execution of all system components provides the whole computer system execution; and, as in analytical methods, the behavior of each component is modeled through a mathematical model, that is an algorithmic model that runs on simulation environment. So, simulation is more appropriate to those hybrid and dynamic systems, especially for the average cases.

A great number of network and distributed system simulators have been proposed, each of them with a specific set of goals [7]. For instance, in [8] is presented HDDSS, that stands for 'Hybrid and Dynamic Distributed System Simulator', a simulation framework that allows to characterize hybrid and dynamic behavior to each component of a distributed system, implementing performance evaluation of the presented generic distributed system model and offering a proper abstraction level for evaluating CPS.

4. **Smart Grids as Cyber-Physical System.** The smart grids represent a vision of a future electricity grid, radically different to those currently deployed [9]. Smart grids are decentralized, intelligent, autonomic, critical and needs real-time requirements. In this section, smart grids will be presented and mapped as Hybrid and Dynamic Distributed Cyber-Physical Systems.

4.1. **Smart grids – A study case in distribution.** The current power system is a set of power plants, substations, transmission lines, devices and other equipment which are part of three major parts: (*i*) Generation – The electricity generation is a process which transforms natural resources as gas, coal, solar or wind, into electrical energy through power plants. The tension level in this phase is established between 12kV-24kV; (*ii*) Transmission – This phase is responsible in transport of electricity at high voltages until the distribution phase, usually with voltages set between 138kV-765kV; (*iii*) Distribution – In distribution, the electricity is conduced from power plants to consumers, usually voltage set between 4.16kV-34.5kV.

In general, the actual power system is composed of control centers that received measurements from sensors that interact with distinct devices (transmission lines, relay, transformers and others) [10]. The intelligence is centralized in a control center that received an information set of sensors and transmitted to actuators to implement changes on field devices in function of administrator decision.

In [10] is presented as simple generic control loop to an electric system and the relationship between physical system and control center (Figure 1). This generic control loop is composed by: (*i*) Actuators and Sensors; (*ii*) Control Center – In this local, the algorithms running to make operational decisions in the energy management system; (*iii*) Messages – The measurements[1] from sensors ($y_i(t)$) and control ($u_i(t)$) messages are transmitted to received information and transmitted decisions, respectively.

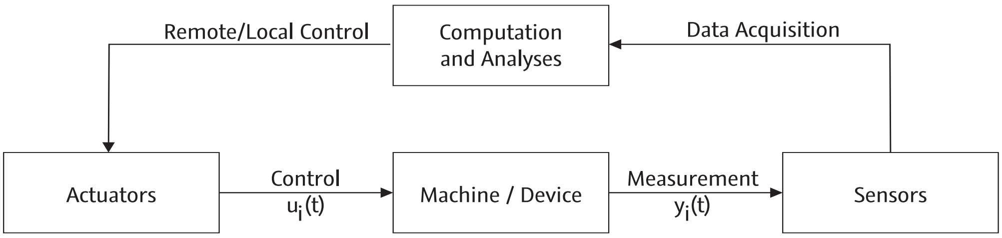

FIGURE 1. A typical power system control loop [10]

Currently the electric system is typically centralized in both generation/distribution of power and in decision-making. Already the smart grids are an ecosystem which will heavily rely in its basis on real-time monitoring (with measurements acquisition) and a decision making in management system. The smart grids are increasingly Cyber-Physical Systems dominated and Cyber-Physical Systems lie in the heart of the merging Smart Grid [11].

4.2. **Evaluation performance to smart grids context.** As mentioned earlier, the performance evaluation should observe system requirements and the simulation strategy is more appropriate to those hybrid and dynamic systems. Regarding evaluation performance in smart grids context, some challenges are found as: (*i*) Designing automation technologies for heterogeneous devices [9]; (*ii*) Developing simulation and prediction tools [9]; (*iii*) Developing the means by which the automated decisions are made [9]; (*iv*) The risk modeling methodology [10]. In smart grids will be essential to design simulation systems that can accurately represent both the grid and the reaction consumers to the system under a range of different conditions and worst-case scenarios.

4.3. **Modeling and simulation to distribution – A simple example.** The electrical distributed systems have many challenges that must be treated. The power system reconfiguration is difficult to deal due to its combinatorial nature [12] and mathematical formulation to fulfill the constraints is very complex. In [13] the distribution problem is defined in three points: (*i*) Minimize the number of switching operations while keeping the radial structure of the system (without rings); (*ii*) Reduce the energy loss; (*iii*) Maximize the system availability. In this article, we will present a proposal seen in [14] that makes balancing the participation of generators in the distribution lines. In case of failure in a generator, the impact on the distribution lines (consumers) can be more easily minimized.

This modeling and simulation were only possible because of the variety of packages used compiler (R compiler). The simulation allowed experimentation without actually changing the situation, i.e., for Smart Grids it is much safer to simulate than actually testing.

Problem Definition – Balance the participation of generators in all distribution lines.

Problem Representation – A distribution network can be represented using graph theory and can mathematically calculate the contribution of each generator in a distribution line [14].

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[1] Measurements from transmission lines, substations, transformers and others devic=es/machines

Problem Modeling and Simulation – The representation proposed in [14] was modeled using graph theory in [13] and contributions calculated by the R [15] with igraph package [16].

Given a connect graph $G = (V, E)$ and $(degree(v_i) \geq 1)$ without loops $(e_i = (v_i, v_i) \notin G)$ in which V corresponds to the set of vertices, $V = \{v_1, v_2, \ldots, v_n\}$, and E corresponds to the set of edges, $E = \{e_1, e_2, \ldots, e_n\}$, this may represent an infrastructure reconfiguration of power networks, as shown in Figure 2 as follows.

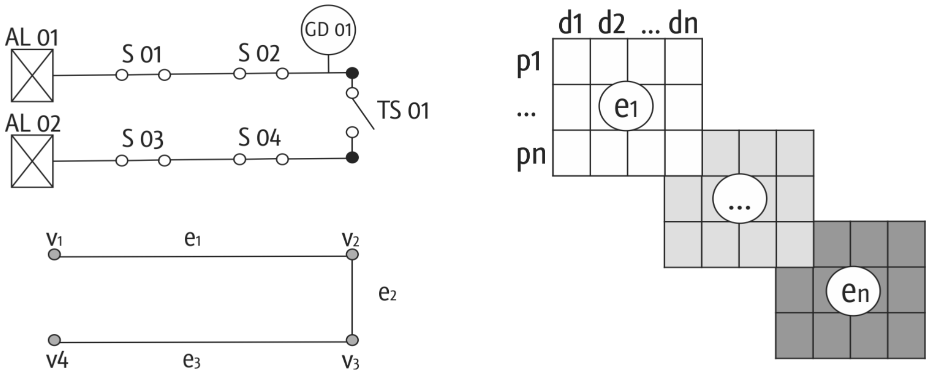

Figure 2. Mapping computational model of the power grid

- The set of vertices V represents the generator supplying (AL) and the intersections of the transmission lines.
- The set of edges E represents the transmission lines. Each edges e_i may contain a set of devices (such as circuit breakers and distributed generators) beyond the transmission line properties. The representation of these data is accomplished through a three-dimensional matrix $M = (d \times p \times e)$ (Figure 2), in which:
  - The line (d) represents the devices;
  - The column (p) stores the properties of the devices and the segment of the transmission line between the device and its predecessor;
  - Dimension (e) of the matrix (M) stores the devices (d) and its properties (p).

Table 1 shows the individuals contributions of each generator to the loads and the Load 5 receives 50% power from Generator B and 50% from Generator C, but its load does not receive any contribution of generator A.

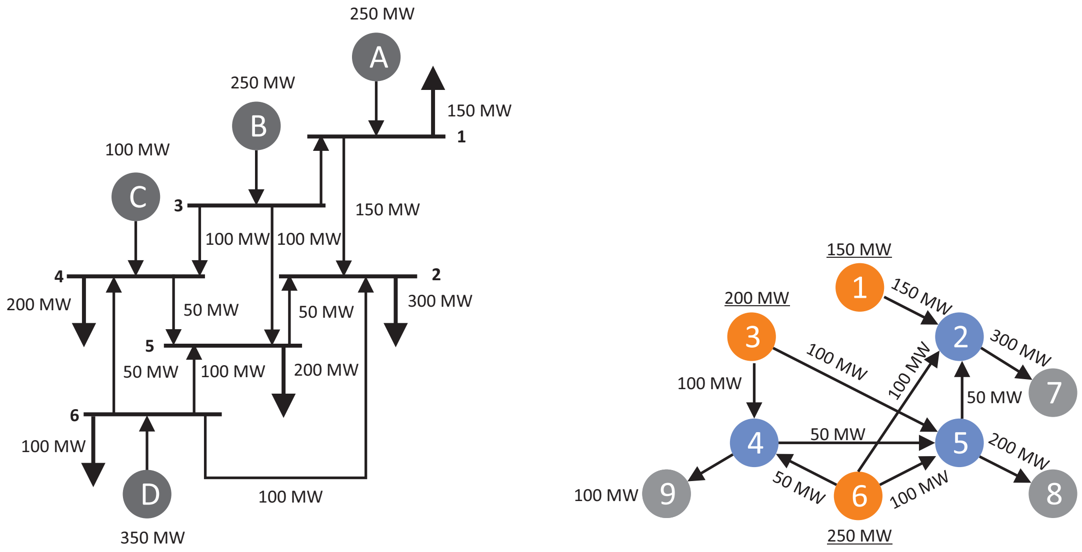

Figure 3. Example of IEEE 6-bus system and oriented graph modelling an IEEE 6-bus system

Table 1. Contribution of each generator to each load in the system

	Load 2	Load 4	Load 5
Generator A	0.3333	0.0000	0.0000
Generator B	0.2500	0.7500	0.5000
Generator C	0.4167	0.2500	0.5000

5. **Final Remarks.** Cyber-Physical Systems can be modeled as a distributed system, that combines components with distinct quality of service: from classic computer nodes to computing elements, such as sensors and actuators, which monitor and control physical processes. These components can be connected each other through a mix of network technologies: from a dedicated switched-Ethernet network to wireless connections, to the Internet. Those characteristics provide CPS to behave as a hybrid and dynamic distributed system model.

On designing solutions for the environments, often we must run performance evaluations. A proper performance evaluation based on real measurements requires prototypes for running physical processes and its interaction with computer nodes and computing elements, such as an industry pilot plant. On the other hand, that distinct quality of service implies on very complex mathematical models for using analytical model.

In this case, we show that simulation techniques can be feasible to evaluate CPS. An adequate simulation framework can combine distinct abstraction levels, providing the proper and required details to implement the CPS environment. We can also combine traces measurements from a pilot plan or use emulation to combine a simulation framework with prototypes of parts of the system. That can be a safe way to design and evaluate such systems.

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