Communications and Power Distribution Network Co-Simulation for Multidisciplinary Smart Grid Experimentations *

Martin Lévesque
Optical Zeitgeist Laboratory
INRS
Montréal, QC, Canada
levesquem@emt.inrs.ca

Da Qian Xu
Department of ECE
McGill University
Montréal, QC, Canada
da.xu@mail.mcgill.ca

Martin Maier
Optical Zeitgeist Laboratory
INRS
Montréal, QC, Canada
maier@emt.inrs.ca

Géza Joós
Department of ECE
McGill University
Montréal, QC, Canada
joos@ece.mcgill.ca

ABSTRACT
Multiple simulation tools have been built and studied independently in the communications and power system perspectives of IEEE P2030 to study new Smart Grid applications. However, very few studies have been done on co-simulation by combining both perspectives in a multidiciplinary manner. In this paper, we show implementation details of our novel communications and power distribution network co-simulator based on OMNeT++ and OpenDSS. We then demonstrate the novelty of our co-simulator by showing the impact of data rate-based and event-based sensors on reactive control algorithms of plug-in electric vehicles to reduce critical voltage durations.

Keywords
Co-Simulation, Smart Grid, Smart Grid Co-Simulator

1. INTRODUCTION
The world has become heavily dependent on oil through the widespread use of combustion engines in gasoline cars, resulting in climate change, massive transfers of wealth to oil-producing countries, and heightened geopolitical tensions. The advent of commercially available plug-in electric vehicles (PEVs) is expected to be a game changer that will shake things up in a fundamental manner. The upcoming exploitation of renewable energy resources such as photovoltaic and wind generators, where the energy produced depends on the climate and varies over time, has a big impact on the overall power systems operation and planning. Sophisticated two-way and end-to-end communications between all the power grid elements, including the consumer, must evolve to create a new power grid: the Smart Grid [7].

The vision of Smart Grid is all about controlling and sensing the electric power network by using a communications infrastructure. In [6], we recently introduced a fiber-wireless (FiWi) network infrastructure for smart distribution grids based on standardized and low-cost Ethernet passive optical network (EPON), WiMAX, and wireless mesh network technologies as well as an optical metropolitan area ring network. Multiple simulation tools have been built and studied independently in the communications and power system perspectives. However, very few studies have been done on co-simulation by combining both perspectives, which is an issue since Smart Grid should be studied in a multidiciplanary manner. In [9], the authors showed the benefit of using wireless communication links for the integration of distributed energy resources and energy storage units via co-simulation, but the event model is simply a single power interruption event. Lin *et al.* [3] combined Positive Sequence Load Flow (PSLF) and Network Simulation 2 (ns-2) to simulate a case study of an agent-based remote backup relay system. However, results focused only on the power system. In [5], the authors presented guidelines to synchronize the power grid simulator Modelica and ns-2. In this paper, however, we report on the implementation of our novel co-simulation platform to examine a reactive control algorithm with PEVs in a modified IEEE 13-Node power distribution network of 342 customer households with a converged end-to-end FiWi infrastructure and we study the performance from both power system and communications perspectives.

The remainder of this paper is organized as follows. In Section 2, a background discussion about Smart Grid and the multidiciplinary aspects is provided. Section 3 provides an overview of our communications and distribution power network co-simulator. Section 4 presents implementation details. Section 5 investigates a case study about the impact of data rate-based and event-based sensors on reactive control

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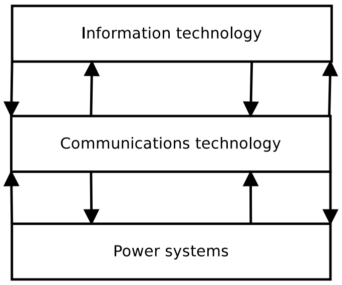

Figure 1: Interactions between the Smart Grid perspectives.

algorithms with a converged FiWi communications infrastructure by using our developed co-simulator. Conclusions are finally drawn in Section 6.

2. BACKGROUND

This section describes the knowledge base related to the developed co-simulator. First, we briefly overview the three Smart Grid perspectives. We then describe the simulated power distribution network. Then, the communications infrastructure is described.

2.1 Smart Grid Perspectives

The Smart Grid can be decomposed into perspectives. Each perspective represents a main part of the entire system as specified in IEEE P2030 [4]. IEEE P2030 presents generic design and implementation guidelines among systems in order to exchange data between Smart Grid entities. Each perspective is decomposed into multiple domains for each main part of the power system. Also, each domain contains several entities to manage the domain. IEEE P2030 defines the following three perspectives:

- *Power systems interoperability architectural perspective (PS-IAP):* The PS-IAP deals with the generation, delivery, and consumption of electrical energy.
- *Communications technology interoperability architectural perspective(CT-IAP):* The CT-IAP integrates networking components and communications protocols.
- *Information technology interoperability architectural perspective (IT-IAP):* The IT-IAP processes and controls the data flow related to applications managing the power system.

As depicted in Fig. 1, the power system perspective interacts with the communications technology which itself receives and sends messages to the information technology perspective. Thus, these perspectives have to be studied as a whole, especially for the communications technology and power systems. In this paper, we focus on the multidiciplinary study of the communications technology and power systems by means of co-simulation to address impacts on both perspectives.

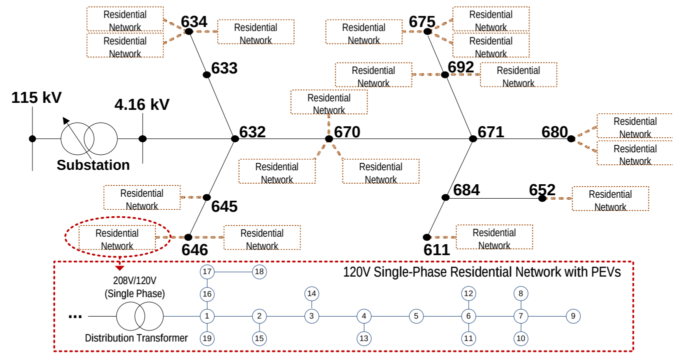

Figure 2: Power Distribution Network: IEEE 13-Node network.

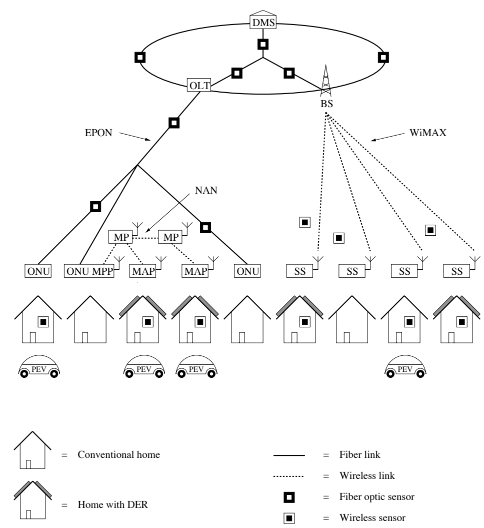

Figure 3: Converged FiWi infrastruction (DER: Distributed energy resources).

2.2 Power Distribution Network: IEEE Benchmark Test Feeder

For the power system perspective, we focus on the power distribution network with a modified IEEE 13-Node radial distribution test feeder, as IEEE standard test feeders have been widely studied by academia and industry [10], as depicted in Fig. 2. The feeder has a substation, which steps down the 115kV transmission network to the 4.16kV distribution grid. Each node in the feeder is connected with one or more low voltage (LV) residential networks according to [8]. The LV residential network is supplied from the distribution grid via one 2.4kV/120V 200kVA single-phase distribution transformer. Each residential network consists of 19 nodes corresponding to 19 customer households with some assigned PEVs. The whole system has a total number of 18 LV residential networks, representing a densely populated residential area of 342 customer households.

2.3 Communications Infrastructure: Converged FiWi Network

For the communications technology perspective, we focus on a fiber-wireless (FiWi) infrastructure already proposed in our recent works [6]. Optical fiber has several advantageous properties such as longevity, low maintenance cost, and immunity against electromagnetic interference. Optical fiber and wireless networks are complementary technologies and are expected to converge in order to realize future-proof FiWi broadband access networks [2]. The converged FiWi network is decomposed into two main subnetworks: (*i*) a Smart Grid wireless neibourhood area network (NAN) and (*ii*) a broadband access network, which can be either an EPON, where optical network units (ONUs) and fiber are available, or WiMAX subscriber stations (SSs), as depicted in Fig. 3. The NAN is based on IEEE 802.11b/g/n with mesh support and contains three node types: (*i*) the Mesh access point (MAP) interconnects the home area network (HAN) and the NAN, (*ii*) Mesh portal point (MPP) which acts as wireless access point to an ONU or SS, and (*iii*) Mesh point (MP) acts as a relay between MPPs and MAPs, when MAPs cannot reach MPPs. For densely populated areas, EPON is a viable alternative. Where EPON is not available, e.g., rural areas, WiMAX can be used. WiMAX provides broadband coverage in remote areas and its deployment costs are less than those of wired solutions.

The power systems can interact with the FiWi infrastructure in order to operate multiple applications, such as reactive control of PEVs during critical voltage fluctuations as we show in the co-simulation results section by using our developed co-simulator, which we first overview in the next section.

3. CO-SIMULATOR OVERVIEW

To evaluate Smart Grid applications in a multidiciplinary manner with both the power distribution network and our recently proposed converged FiWi infrastructure, we developed a co-simulator based on OMNeT++ and OpenDSS, as depicted in Fig. 4. OMNeT++ [1] is an extensible component-based open source simulation framework. OpenDSS [2] is a power distribution system simulator (DSS) to support distributed resource integration. Fig. 5 depicts the co-simulator designer useful to configure a co-simulation. The configuration toolbar ((1) in Fig. 5) enables to configure the base loads in the power distribution network, traffic matrix in the FiWi infrastructure, mappings between the communications node and nodes in OpenDSS in order to build the power system layer, and PEV arrivals during each simulation. The editor ((2) in Fig. 5) enables to build the communications topology by using the right toolbar ((3) in Fig. 5).

In order to build a co-simulator, we needed to add some components in order to merge both simulators. The co-simulator contains the following two main components (Fig. 4):

- *Communications and Power Distribution Network Co-Simulator:* It runs in OMNeT++ and maintains a power system layer by remotely calling the power system calculator when the load in the power system layer changes. The remote calls are done by sending hypertext transfer protocol (HTTP) requests to the power system calculator with the parameters of the power system layer ((1) in Fig. 4) and then, followed by copying the result from the HTTP response to the power system layer ((2) in Fig. 4). The co-simulator runs on a Linux machine while OpenDSS runs on a Windows machine. Thus, HTTP is used to enable communication between the two systems. In order to speed up the simulation duration and not to request two times the same calculation to the power system calculator, results are copied in a local cache in the co-simulator ((3) in Fig. 4).

- *Power system simulator:* It receives HTTP requests from the co-simulator with POST parameters. Then, a hypertext preprocessor (PHP) script writes the OpenDSS configuration file and executes OpenDSS to perform time-driven load flow analysis. The results are then parsed and sent back to the co-simulator.

[1] http://www.omnetpp.org/
[2] http://sourceforge.net/projects/electricdss/

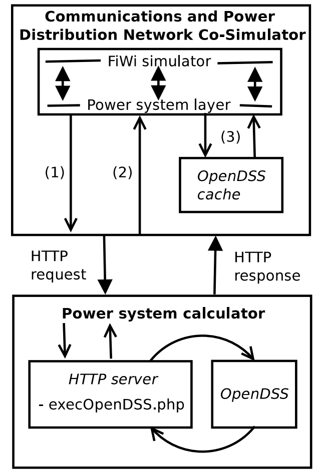

Figure 4: The communications and power distribution network co-simulator.

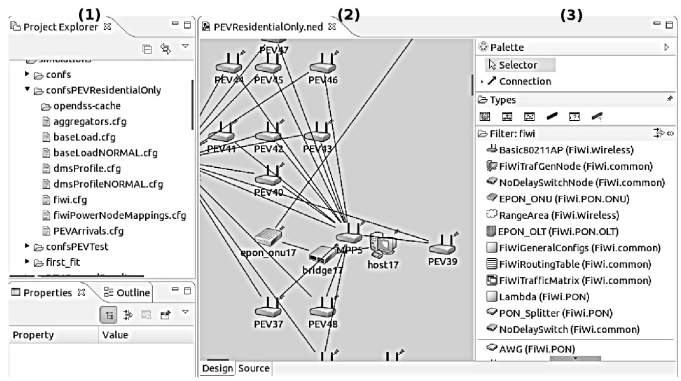

Figure 5: The co-simulator designer in OMNeT++.

During each simulation cycle, the following packets are exchanged in order to run PEV applications:

- *Authentication:* When a PEV arrives, it first sends an authentication message to the DMS, containing the

```
POST /pev/charging_deadline/{node_id} HTTP/1.1
Host: {IPv6 address}
Content-Type: application/xml
Cookie : session_id= {session_hash}
Content-Length: {length}

<?xml version="1.0" encoding="UTF-8"?>
<ChargingDeadline xmlns="http://zigbee.org/sep">
<Vehicule>
        <VehicleID>{Value : positive integer}</VehicleID>
        <CustomerID>{Value : positive integer}</CustomerID>
        <NodeID>{Value : positive integer}</NodeID>
</Vehicule>
<Scheduling>
        <DeadlineTimestamp>{Format : YYYYMMDDThhmm}</DeadlineTimestamp>
</Scheduling>
<Battery>
        <Capacity>{Value : a decimal number}</Capacity>
        <DepthOfDischarge>{Value : a decimal number}</DepthOfDischarge>
        <StateOfCharge>{Value : a decimal number}</StateOfCharge>
</Battery>
```

Figure 6: Charging deadline request message example.

distribution node ID, customer ID, and vehicle ID. When the DMS receives the packet, it sends back an authentication ACK packet to the PEV.

- *Charging deadline request:* When the PEV has been authenticated, a packet is sent containing the node ID, customer ID, vehicle ID, scheduling deadline, battery capacity, depth of discharge, and the number of kWs per hour.

- *Charging deadline response:* When the DMS receives a charging deadline request, it finds, if possible, the best scheduling slot by executing the scheduling algorithm. Then, it sends the start time and the status of the scheduling to the PEV.

- *State of charging notification:* When the PEV is charging, it periodically sends notification packets to the DMS to notify the current state-of-charge of the battery.

- *Node notification:* Periodically, each distribution node sends a message containing the node ID, voltage, and load.

- *Substation notification:* The substation sends its node ID, total power load, and total power losses to the DMS.

- *PEV control message:* The DMS sends control messages to the PEVs to reactively control the distribution network.

Each message shown above uses an XML format to structure the information following the message format used in ZigBee Smart Energy. The XML message is encapsulated in an HTTP message. Fig. 6 shows an example of charging deadline request message.

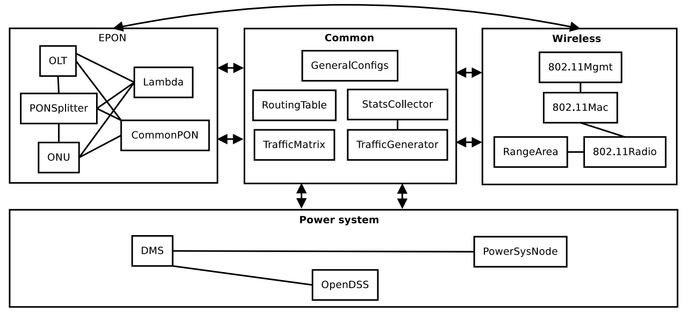

Figure 7: Intercommunications between the co-simulator modules.

4. IMPLEMENTATION DETAILS

The co-simulator is based on the event-driven simulator OMNeT++ and OpenDSS. This section describes implementation details about the event-driven co-simulator written in OMNeT++.

The intercommunications between the co-simulator modules are depicted in Fig. 7. *Common* is the central module used by the EPON, Wireless, and power system modules. During the initialization process, the co-simulator executes the following operations:

- The *GeneralConfigs* class initializes the DMS load profile which is used for unknown future power loads at each node in the IEEE 13-Node network. Then, the distribution network nodes are mapped to the FiWi nodes. Finally, this class constructs aggregator mappings. An aggregator is a communications node which collects information from a group of nodes. In this paper, the only defined aggregator is the DMS such that all communications nodes send their messages to the DMS.

- The *TrafficGenerator*, which is the main class generating events, first reads the base load file which contains all pre-generated events of modifications of load at each node. The base load corresponds to the daily power consumption (in kW). Thus, all modification of load events are created during initilization. Then, the PEV arrivals configuration file is read, also precomputed with an external script. This configuration file contains a set of rows, where each row contains the minimum time, maximum time and number of PEVs arriving during this interval. Based on these configurations, PEV arrival events are created by randomly selecting PEVs in the IEEE 13-Node network. The number of state-of-charge (λ_{SOC}) messages per second per PEV is initilized.

- The *TrafficMatrix* class initializes the number of notification messages $\lambda_{src,dest}$ per second, representing the sensor traffic, for each possible node permutation <source, destination> in the FiWi communications infrastructure. In this paper, we set the traffic matrix to be from PEVs to DMS only.

- The *RoutingTable* class initilizes an empty routing table and topology. This class enables to return the

MAC address of the next hop of the shortest path based on the current node and destination node. Note that any node in the wireless mesh network and EPON can be used without limitation. Thus, the forwarding table is built on demand by assuming that all information about the network topology is available since routing algorithms are not the focus of this work.

After the initialization process, the main events of the PEV application and their respective operations are described in the following. An illustrative case study using this application is presented in the next section. The main events at PEV nodes are first presented:

- Base load modification at node n: It locally updates the base load at node n. Then, the OpenDSS caching system is checked. The caching system works as follows. It generates a list of parameters ($params$) such as node_id1=<load>&node_id2=<load>...node_idN=<load>. A unique hash string h is then generated as follows:

$$h = hash(params), \tag{1}$$

  where $hash$ is a function taking a string as input and generates a unique compressed string. Then, if the file h is locally available, the result read directly, otherwise OpenDSS needs to be called. When OpenDSS is called, the result is locally written into h.

- PEV arrival: It sends an authentication message.

- Authentication response message received at PEV p: It calculates the following deadline:

$$\mathcal{D}_p = MD_{p,t} + uniform(\mathcal{D}_{p,min}, \mathcal{D}_{p,max}), \tag{2}$$

  where $MD_{p,t}$ is the minimum deadline of PEV p if it starts charging at time t, $\mathcal{D}_{p,min/max}$ the minimum or maximum additionnal constant deadline durations.

- PEV control message received: It finds the node in the power system layer according to its own address. Then, the load according to this PEV is removed.

The main events at the DMS are described as follows:

- Notification message received: It updates the voltage and load of a given node in the power system layer at the DMS. A reactive control algorithm (described thereafter) is then executed, returning a list of nodes to deactivate to fix critical voltage fluctuations. For each node to deactivate, a control message is sent to temporarily stop these PEVs to charge.

- Substation notification message received: Periodically the substation node sends notification messages containing the total load and total losses of the power distribution network. When these messages are received, it updates the power system layer at the DMS.

- Charging deadline request message received: Based on the state-of-charge of the battery and required deadline of this request, the PEV is scheduled by applying a scheduling algorithm. Then, the scheduling algorithm result is sent back to the PEV by transmitting the response to the OLT node in the FiWi infrastructure. Due to limitations of space, we do not use a scheduling algorithm in the case study shown in next section.

Next, we describe a reactive control algorithm implemented at the DMS in order to quickly react when critical voltage fluctuations happen.

Algorithm 1 Reactive control algorithm based on voltage fluctuations. Return a set of nodes to deactivate.

Require: $nodes : a\ set\ of\ nodes.$
Require: $voltageLimit_{min} : minimum\ voltage\ value.$
  $result \leftarrow \{\}$
  for $n \in nodes$ **do**
    while $n.voltage < voltageLimit_{min}$ **do**
      $voltage_{min} \leftarrow \infty$
      $nFound_{min} \leftarrow \varnothing$
      for $n_{min} \in nodes$ **do**
        if $n_{min}.voltage < voltage_{min} \wedge n_{min}.isCharging()$ **then**
          $voltage_{min} \leftarrow n_{min}.voltage$
          $nFound_{min} \leftarrow n_{min}$
        end if
      end for
      if $nFound_{min} \neq \varnothing$ **then**
        $removePEVScheduling(nFound_{min})$
        $result \leftarrow result \cup \{nFound_{min}\}$
        $recalculateLocalInformationWithOpenDSS()$
      end if
    end while
  end for
  return result

Algorithm 1 returns a list of power distribution nodes which must be deactivated in order to solve critical voltage fluctuations. For each IEEE 13-Node, if its voltage is critical (for example for $voltage < 0.95$ p.u.), it successively removes PEVs to the nodes with the lowest voltage profile as long as the voltage remains critical. When a PEV is removed, OpenDSS is called and the result is updated in the power system layer at the DMS. This algorithm is extensively experimented in the following section.

5. CO-SIMULATION RESULTS

In this section, we investigate an illustrative case study on a small-scale profile as depicted in Fig. 8. The DMS profile is based on history data, typically used for a future unknown load at a given node. The load at each node is randomly generated with ±15% of the DMS profile following a uniform distribution. Fig. 8 shows the load variation of nodes 611_1 and 611_2 in the power distribution network. 70 PEV arrivals are randomly distributed during 30 seconds. The communications infrastructure is composed of a 1:32 EPON having a line rate of 1 Gbps with ONUs distributed in the IEEE 13-Node network. Each household cluster (the network contains 18 clusters of 19 households) communicate using a wireless mesh network based on IEEE 802.11g (54 Mbps). In this scenario, we investigate the random charging strategy with the reactive control algorithm detailed in

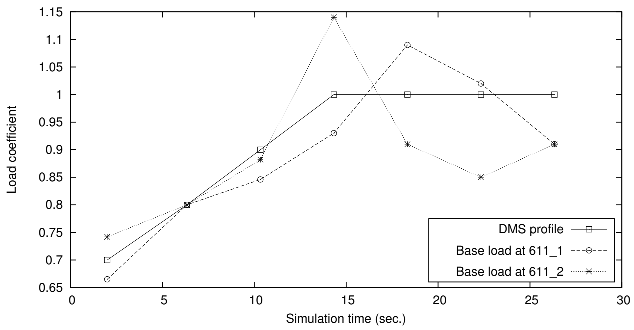

Figure 8: DMS profile and base load of nodes 611_1 and 611_2.

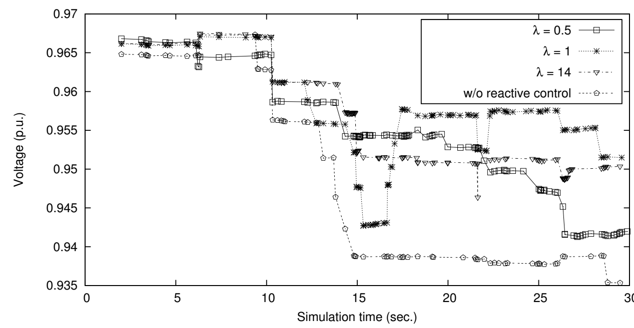

Figure 9: Voltage comparison without reactive control and with data rate-based sensors.

Algorithm 1. Thus, when a PEV arrives, it starts charging automatically. The reactive control algorithm is used to stop PEVs to charge when critical voltage fluctuations happen. This reactive control algorithm uses information sent by sensors (notification messages) in order to detect a critical voltage problem on a local scale. In the following, we investigate two types of sensor: data rate-based and event-based [1].

We first compare data rate-based sensors with the reactive control algorithm and without reactive control. As expected, not using any communications infrastructure (w/o reactive control) can quickly lead to critical voltage fluctuations ($voltage < 0.95$ p.u.) by using random charging, as shown in Fig. 9. To overcome this issue, data rate-based sensors can quickly solve critical voltage fluctuations, for example with 1 notification message per second per sensor ($\lambda = 1$), where the voltage issue is solved within 2 seconds. To solve critical voltage fluctuations faster, the data rate λ can be increased, for example with $\lambda = 14$ which fixes the problem in less than one second. Fig. 10 depicts the variation of the critical voltage duration as a function of the data rate λ.

As shown, the data rate-based approach enables to quickly solve critical voltage fluctuations. However, such approach can overuse the communications infrastructure with redundant information from sensors, as noted in [1]. Thus, we then investigate event-based sensors. Fig. 11 depicts a voltage comparison between data rate-based and event-based approaches. A threshold th is used for the event-based approach. This threshold is used as follows. Let $l_{i,t-1}$ and $l_{i,t}$ be the load of node i at times $t-1$ and t, respectively. Thus, if $|l_{i,t} - l_{i,t-1}| \geq th$, $l_{i,t}$ is sent to the DMS. As shown in Fig. 11, event-based sensors with $th = 0$ can solve critical voltage fluctuations as quick as the data rate approach with $\lambda = 14$. However a higher threshold can increases the probability of critical voltage fluctuations, for example with $th = 0.10$ as depicted in Fig. 11.

Next, we compare the DMS throughput of data rate-based and event-based approaches in our converged FiWi infrastructure. The throughput of data rate-based sensors with $\lambda = 14$ corresponds to approximately 14 Mbps and 100-700 Kbps with event-based sensors (Fig. 12). Note that a higher threshold may decrease the throughput, as depicted in Fig. 13. At simulation time 7, the throughput with threshold $th = 0.10$ is 250 Kbps lower compared to the throughput while using threshold $th = 0$.

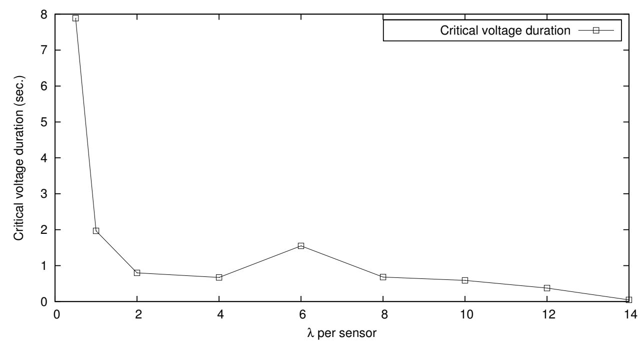

Figure 10: Critical voltage duration depending on the data rate of sensors.

Thus, our novel co-simulator enables to study, in a multidiciplinary manner, Smart Grid experimentations such as the impact on the power distribution network of using data rate-based or event-based sensors in a converged FiWi infrastructure.

6. CONCLUSIONS

The vision of Smart Grid is all about controlling and sensing the electric power network by using a communications infrastructure. Multiple simulation tools have been built and studied independently in the communications and power system perspectives. However, very few works have been done on co-simulation by combining both perspectives in a multidiciplinary manner. We have shown implementation

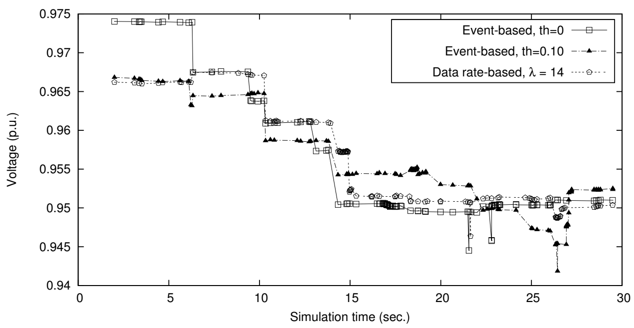

Figure 11: Voltage comparison between data rate-based and event-based sensors.

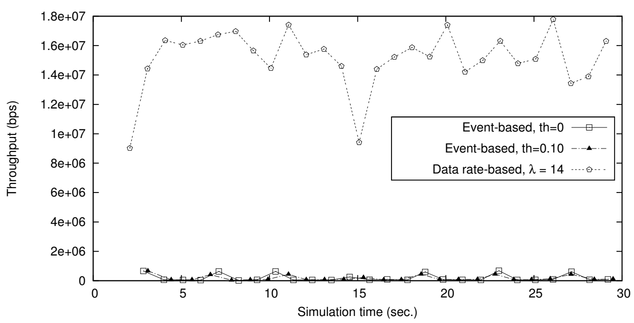

Figure 12: Throughput comparison between data rate-based and event-based sensors.

details of our novel co-simulation platform to examine reactive control of PEVs in a IEEE-Node 13 power distribution network of 342 households with a converged end-to-end FiWi communications infrastructure. We investigated two types of sensor, namely, data rate-based and event-based sensors. With data rate-based sensors, our novel co-simulator enabled to show that, with a data rate of 14 notification messages per second per sensor, critical voltage fluctuations can be fixed in less than 1 second resulting to 10-18 Mbps of throughput. We then shown that event-based sensors can solve critical voltage fluctuations as quick as the data rate-based approach by having a significantly lower throughput of 500 Kbps. Thus, co-simulation enables to study in a multidiciplinary manner Smart Grid experimentations in order to design an integrated system of systems composed of the three perspectives of IEEE P2030, namely, information technology, communications technology, and power systems.

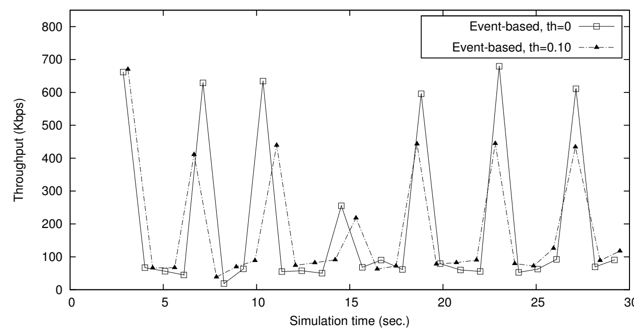

Figure 13: Impact of the threshold value on the throughput with event-based sensors.

7. REFERENCES

[1] G. Balasubramanian and S. Chakrabarti. Modelling Information Generation in Event-Driven Sensor Networks. In *Proc., IEEE IEEE/ACS International Conference on Computer Systems and Applications*, pages 820–823, Doha, Qatar, Mar. 2008.

[2] N. Ghazisaidi and M. Maier. Fiber-Wireless (FiWi) Access Networks: Challenges and Opportunities. *IEEE Network*, 25(1):36–42, Jan./Feb. 2011.

[3] S. S. J. T. H. Lin, S. Sambamoorthy and L. Mili. Power System and Communication Network Co-Simulation for Smart Grid Applications. In *Proc., IEEE PES Innovative Smart Grid Technologies (ISGT)*, Anaheim, USA, Jan. 2011.

[4] IEEE P2030. Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads. *IEEE Standards Association*, Sept. 2011.

[5] V. Liberatore and A. Al-Hammouri. Smart Grid Communication and Co-Simulation. In *Proc., IEEE Energytech*, Cleveland, USA, May 2011.

[6] M. Maier. Fiber-Wireless Sensor Networks (Fi-WSNs) for Smart Grids (Invited Paper). In *Proc., International Conference on Transparent Optical Networks (ICTON)*, Stockholm, Sweden, June 2011.

[7] P. P. Varaiya, F. F. Wu, and J. W. Bialek. Smart Operation of Smart Grid: Risk Limiting Dispatch. *Proceedings of the IEEE*, 99(1):40–56, 2011.

[8] S. Deilami *et al.* Real-Time Coordination of Plug-In Electric Vehicle Charging in Smart Grids to Minimize Power Losses and Improve Voltage Profile. *IEEE Transactions on Smart Grid*, 2, no. 3(3):456–467, Sept. 2011.

[9] T. Godfrey *et al.* Modeling Smart Grid Applications with Co-simulation. In *Proc., IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pages 291–296, Gaithersburg, USA, Oct. 2010.

[10] W. H. Kersting. Radial Distribution Test Feeders. *IEEE Power Engineering Society Winter Meeting*, 2:908–912, 2001.