Influence of Communication Irregularities and Co-simulation on Hybrid Power System State Estimation

Vanja G. Švenda, Alex M. Stanković
Tufts University
Dept. of Electrical and Computer Eng.
Medford, MA, USA
vanja.svenda@tufts.edu; astankov@ece.tufts.edu

Andrija T. Sarić
Faculty of Technical Sciences
Dept. of Power, Electr. and Comm. Eng.
Novi Sad, Serbia
asaric@uns.ac.rs

Mark K. Transtrum
Brigham Young University
Dept. of Physics and Astronomy
Provo, UT, USA
mktranstrum@byu.edu

***Abstract*—The paper explores the effects of sensor behavior and communication system (CS) irregularities on power system state estimation (SE). CS are modeled in Network Simulator 2 (NS-2), allowing the quantification of irregularities, including delays and dropped packets. The overall information is obtained combining SCADA measurements with phasor measurement unit (PMU) derived data, where time stamping (based on GPS or an equivalent local clock) for all measurements is assumed. To fully analyze the effects of irregularities, a detailed analysis of sensitivities to different communication system parameters is provided as well. Using the co-simulation environment PiccSIM, a SE with these irregularities is quantified for CS parameter variation, with detailed models of power and communication flows.**

***Index Terms*—State estimation, Communication delay, Packet drop, Co-simulation.**

I. Introduction

With increasing demands from their customers and regulators, electric utilities have started to focus on the Smart Grid concept, with potent communication systems (CS) being one of its main features. The Smart Grid is often envisioned as an entity that serves millions of customers, and has an intelligent communication infrastructure enabling timely, secure and adaptable information flow, needed to provide power to an evolving digital economy [1]. The main goal of such a power system is to distribute electricity between generators (both traditional bulk power generation and distributed generation sources) and end users (industrial, commercial and residential consumers). This is done by using bi-directional information flow, as well as pervasive computing capabilities, which as a result provide improved control, efficiency, reliability and safety [2]. The collected information is used for performing different tasks, such as [3]:

- making real-time operational decisions that ensure dispatching power efficiently,
- identifying certain aspects related to system operation planning, and
- identifying where the consumers' power comes from and how much it costs at a given time.

The utilities will thus come to rely on dedicated (private, internal) CS, whose performance exceeds typical commercial communication providers. For example [4], the latency must be much lower than on commercial networks (under 20 milliseconds for some utility applications). Communication availability must be much greater than on commercial networks (requiring 99.999 % or even 99.9999 % reliability for some applications), and utilities must be able to communicate during emergency conditions and after power is switched-off.

One of the main functions in a Smart Grid is state estimation (SE). It refers to the procedure that takes as input the measurements with the goal of estimating voltage phasors at all system buses, at a given time point [5]. It is a logical starting point for almost all operational functions in a power system. The measurements come from different sources, such as: 1) phasor measurement units (PMUs), 2) remote terminal units (RTUs), and 3) smart meters. Most of them have different sampling rates and operate asynchronously. Additionally, communication channels are not ideal – they are prone to irregularities, such as transfer delays and packet drops.

Examining the CS irregularities under different circumstances, and their effects on SE is the main objective of this paper. Section II formulates the SE problem. The communication infrastructure and the irregularities it may have are explored in Sections III and IV, respectively. Test cases on a 14-bus benchmark system, including the analysis of the sensitivity to irregularities, as well as the effects on the SE are described in Section V. The conclusion in Section VI is followed by a list of references.

II. State Estimation (SE) Problem Formulation

The SE model for the *k*-th time instant is:

$$\boldsymbol{z}(t_k,\tau_k)=\boldsymbol{h}(\boldsymbol{x}(t_k))+\boldsymbol{e}(t_k)\,, \tag{1}$$

with telecommunication delays:

$$z(t_k,\tau_k)=z_k(t_{k-1}\le t^{\mathrm{meas}}+\tau_k\le t_k)\,, \tag{2}$$

where:

$\boldsymbol{z}(t_k,\tau_k)$ – measurement vector;
$\boldsymbol{x}(t_k)$ – state vector;
$\boldsymbol{h}(\boldsymbol{x}(t_k))$ – vector of the system state vector functions;
$\boldsymbol{e}(t_k)$ – measurement error vector;
t^{meas} – time of measurement;
$\tau_k=\sum_i \tau_k^i$ – sum of time delays from measurement point to SE hub (typically on Energy or Distribution Management System (EMS or DMS) levels).

III. Communication Infrastructure and Communication Types

To meet the fundamental requirements of a Smart Grid, the communication architecture is envisioned as a multilayer structure that extends across the whole network [3]. Fig. 1 illustrates a general concept for power and communication infrastructures, which includes [2]:

1) home area networks (HANs);
2) business area networks (BANs);
3) neighborhood area networks (NANs);
4) wide area networks (WANs);
5) data centers (Supervisory Control and Data Acquisition (SCADA), Phasor Data Concentrator (PDC)) and
6) substation automation and/or integration control systems (EMS and DMS hubs).

The role of HANs is to communicate with various smart devices, which provide energy efficiency management and demand response. NANs connect multiple HANs to local access points. However, BANs provide the communication links between the NANs and the commercial/industrial customers. The superset of all small networks (HANs, BANs and NANs) represents a WAN. Data from different units is collected at data centers and then forwarded to control systems (EMS or DMS), which use them to run different operations.

Forming the Smart Grid communication infrastructure, like the one shown in Fig. 1, it is possible to support monitoring and control applications, such as SCADA, EMS, and DMS.

Throughout networks there is a hybrid mix of technologies, including the ones shown in Fig. 1 [2, 6]:

1) fiber optics – Synchronous Optical Networking (SONET), Synchronous Digital Hierarchy (SDH), Asynchronous Transfer Mode (ATM), Transmission System 1 (T-1), Multiprotocol Label Switching (MPLS);
2) power line carrier (PLC) systems;
3) copper-wire line T-1, and
4) a variety of (un)licensed wireless technologies – General Packet Radio Service (GPRS), Worldwide Interoperability for Microwave Access (WiMAx), Wireless Local Area Network (Wlan), ZigBee and other.

In this paper, communication types MPLS and T-1, which are explained in Sections III.A and III.B, respectively, are used.

A. *Multiprotocol Label Switching (MPLS)*

To overcome the flaws in the traditional Internet Protocol (IP) networks, Internet Engineering Task Force (IETF) has developed the MPLS, which uses a labeling technique for forwarding packets [7]. The communication is multiprotocol as it allows different protocols, while the label switching provides for data-packets forwarding [8].

MPLS directs data from one network bus to the next, based on short path labels, rather than long network addresses, avoiding complex lookups in a routing table. Before a packet is forwarded to its next hop, it is "labeled", that is the label is sent along with it. That label is used as an index into a table, which specifies the next hop and a new label. The old label is replaced with the new label, and the packet is forwarded to its next hop. As the packet is transmitted, no further header analysis is done by subsequent routers – all forwarding is driven by the labels [8]. It can be used to carry many different kinds of traffic, including IP packets, as well as ATM and SONET.

B. *Transmission System 1 (T-1)*

T-1 was introduced in the 1960s by Bell System [9]. It is a digital communications link that uses Digital Signal 1 (DS-1), as a signaling scheme and enables the transmission of voice, data and video signals at the rate of 1.544 million bits per second (Mb/s) [10]. By enabling diverse signal type transmission on a single digital communications link it simplifies communication network managing.

Since T-1 can transmit both digital and analog signals, having the analog voice signals first digitalized into compressed data by a 64 kb/s standard rate by using Pulse Code Modulation (PCM) [9]. Once digitalized, voice and/or data signals from many sources can be combined and transmitted over a single T-1 link, by using Time Division Multiplexing (TDM). TDM divides the T-1 link to 24 discrete 64 kb/s timeslots.

IV. Communication System (CS) Irregularities

For a real-world CS, it is not surprising that it is prone to irregularities, such as packet delay, drop, bad data and cyber-attacks. While packet delay and drop are mostly a result of an imperfect CS, bad data and cyber-attacks are to a great extent affected by outside factors (noise and human interference). This paper focuses on CS problems and as such examines:

1) *Packet delay* – a packet cannot be transferred instantaneously, certain time has to pass between the packet being sent and received at the final destination.
2) *Packet drop* – there is a risk that a packet will be lost (dropped) and never received at the final destination.

Both of these irregularities can occur while the sent packets are going through the transmission and the queue, which is explained in Sections IV.A and IV.B, respectively.

A. *Transmission irregularities*

These irregularities are due to non-ideal channels. Packets cannot instantaneously travel from one bus to another, which causes delay. Also, there always is a risk that the transmission might fail resulting in a packet being dropped. While the drop chance depends vastly on the channel and cannot be uniquely defined, the delay can approximately be calculated as [11]:

$$\tau = s / (b + d) \tag{3}$$

where: s – packet size (as recorded in its IP header);
b – speed of the link, in [bits/sec], and
d – default link delay, in [sec].

B. *Queueing irregularities*

Queues represent locations where packets may be held (or dropped). Delay is due to the waiting time for the transmission line to be free for use, while packet drop is due to the queue being full. If there is currently a packet being transmitted the next packet might be queued which will cause additional delay. If the queue is currently full, the next packet will be dropped. This depends on many communication parameters, such as: bandwidth, transmission delay, queue limit, packet size and send interval. In this paper, drop-tail queueing is implemented, which uses the "First In First Out" (FIFO) mechanism.

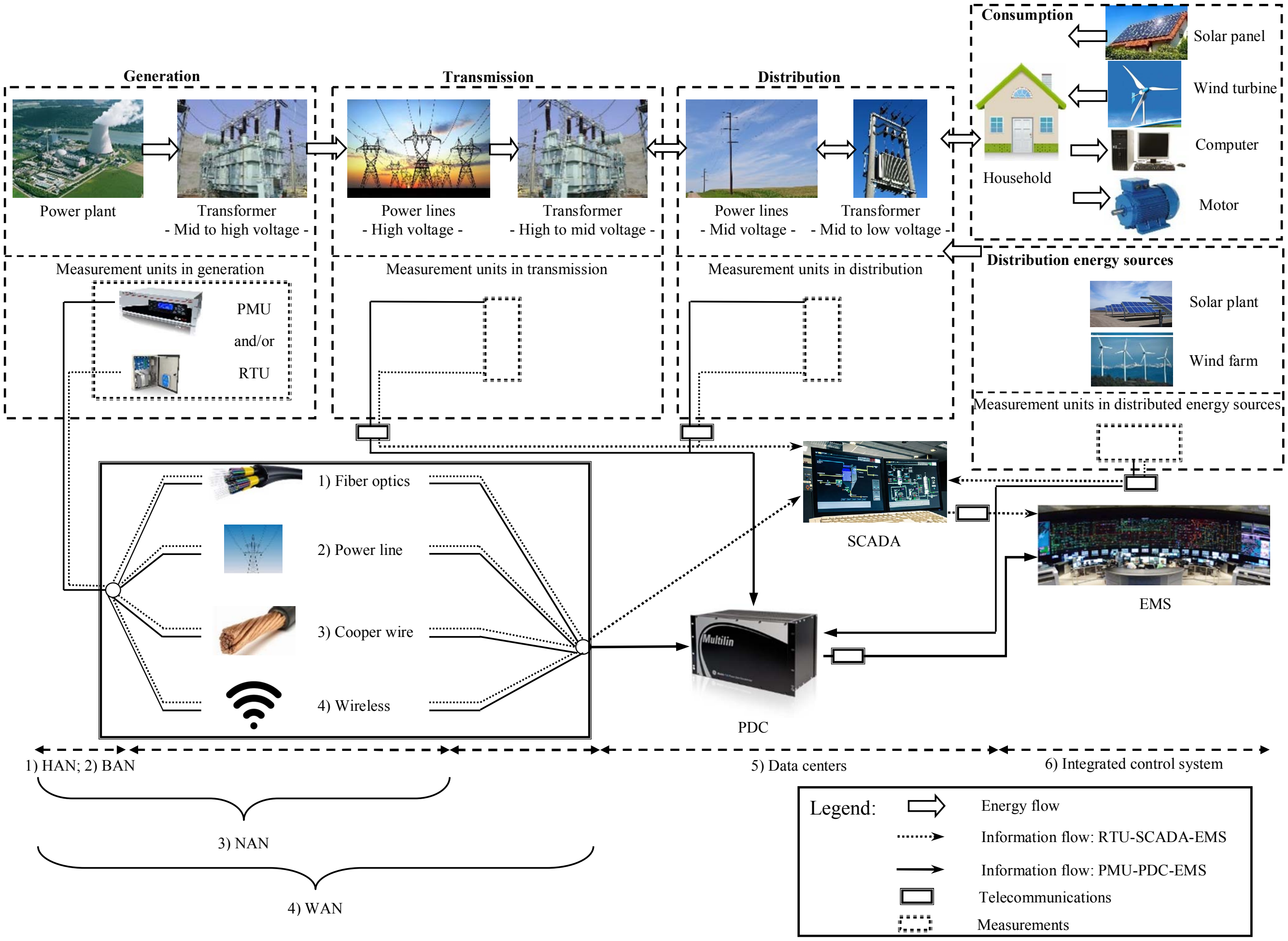

Fig. 1. Smart Grid power and communication infrastructure

Packet drops are implemented in such a way that queues contain a "drop destination"; that is an object that receives all packets dropped by a queue.

The irregularities are taken into account by modeling the CS in Network Simulator 2 (NS-2) [11], described in Section V.B.

V. Application

In this section, the effects of CS irregularities (delay and packet drop) on SE results are examined. Tests are performed on a 14-bus power and communication system, which is described in Sections V.A and V.B, respectively. The power system is modeled in MATLAB (version R2012b), while the CS is modeled in NS-2 (version 2.33). These two systems were co-simulated using PiccSIM (version 1.15) [12]. Next, the CS's behavior for the base parameters and its sensitivity analysis are given in Sections V.C and V.D, respectively. Finally, in Section V.E results of SE when communication irregularities are present are given.

A. Test System

A single line diagram of the 14-bus system is shown in Fig. 2, with both its power and communication parts. Details of the power part of the system are given in [13]. All measurement sources (RTU, PMU), data centers (SCADA, PDC), control systems (EMS) and channel types are noted. To exhaust all possibilities, PDC and EMS are physically in the same place, while this is not the case with SCADA and EMS. In this way, two cases are examined: 1) when measurements travel directly to their final destination, and 2) when there exists a hop.

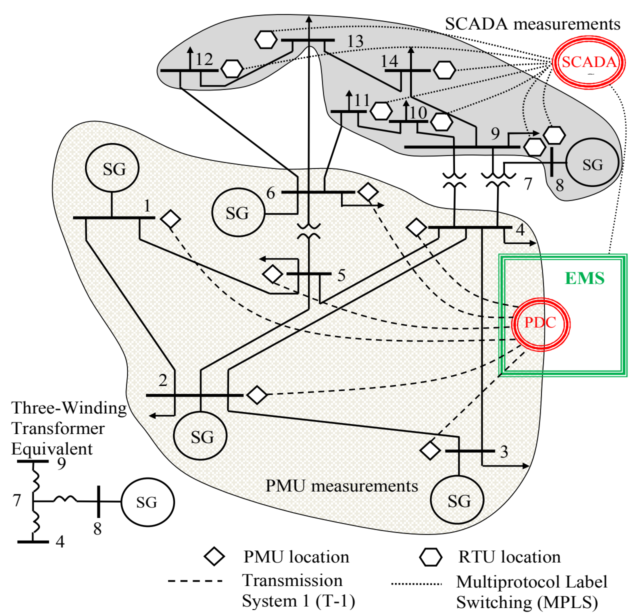

Fig. 2. 14-bus test system with both power and communication lines

B. Network Simulator 2 (NS-2)

To get a fair sense of packet drops and delays, both analyzed CS (MPLS and T-1) were modeled in NS-2 (a discrete-event computer network simulator). NS-2 takes these irregularities into account both while the packets are queued and transmitted. Queueing irregularities are calculated as given in Section IV, while transmission irregularities are calculated using LinkDelay Class and ErrorModel Class from NS-2 (both are explained in details in [11]). The Error Model simulates link-level errors (drops) by either marking the packet's error flag, or dumping the packet to a drop target. In simulations, errors can be generated from a simple model, such as the packet error rate, or from more complicated statistical and empirical models. In this paper statistical model 'Uniform' has been used. T-1 communications can be modeled by using regular wired nodes, while MPLS communications use special (mpls) nodes, whose modeling is given in [14].

All the CS parameter values that need to be adjusted in NS-2 are given in the following Section V.C.

C. Base Parameter Example

To model the CS with the base parameters, the following values has to be adjusted in NS-2:

- Type of link – duplex link for each channel is assumed. This is a two-way communication link which is standard in a Smart Grid environment [1].
- Bandwidth [parameter *b* in (3)] – values given in Table I.
- Default delay [parameter *d* in (3)] – values given in Table I.
- Packet size [parameter *s* in (3)] – 1000 bits for each channel.
- Send interval – PMU measurements are sent 50 times per second, while RTU measurements are sent every 2 seconds.
- Queue type – drop-tail for each channel (Section IV).
- Traffic type – Constant Bitrate (CBR) for each channel is assumed. This means that traffic moves at a constant rate.
- Queue Limit (Section IV) – values given in Table I.
- Drop model distribution – uniform distribution for each channel (Section IV).
- Drop model rate (Section IV) – values given in Table I.

Communications over the given network are simulated for a time interval of one hour. Communication irregularities (delays and drops), which were started at time instance t = 100 s, are given in Table II. The total number of sent, delivered and dropped packets, average drop rate and delay over each communication channel is given in Table III.

D. Sensitivity Analysis

In this part the effect of different CS parameters on communication behavior is given. The parameters for which the sensitivity analysis is performed are:

Case 1:Bandwidth; Case 2:Default delay; Case 3:Send interval

For each parameter it should be noted that:

- Its values are taken as different percentage of the base parameter example (shown in Section V.C).
- Simulations are run for one hour (3600 seconds).
- The results are given as the percent of dropped packets and the average delay for both RTU-SCADA-EMS and PMU-PDC-EMS communications.
- For a better comparison of the two communication types, the relative value of the average delay is given.

TABLE I. PARAMETERS FOR BASE CASE EXAMPLE

Connection		**Links**		**Traffic**	
From	To	Bandwidth [Mb/s]	Delay [ms]	Queue Limit	Drop Rate [%]
PMU/PDC/EMS					
PMU–Bus 1	PDC/EMS	0.02	100.00	5	0.5
PMU–Bus 2	PDC/EMS	0.02	200.00	5	0.5
PMU–Bus 3	PDC/EMS	0.02	160.00	5	1
PMU–Bus 4	PDC/EMS	0.02	120.00	5	1
PMU–Bus 5	PDC/EMS	0.02	180.00	5	2
PMU–Bus 6	PDC/EMS	0.02	140.00	5	2
RTU/SCADA/EMS					
RTU–Bus 7	SCADA	0.02	500.00	2	1
RTU–Bus 8	SCADA	0.02	900.00	2	1
RTU–Bus 9	SCADA	0.02	1500.00	2	2
RTU–Bus 10	SCADA	0.02	700.00	2	2
RTU–Bus 11	SCADA	0.02	1700.00	2	3
RTU–Bus 12	SCADA	0.02	1100.00	2	3
RTU–Bus 13	SCADA	0.02	1300.00	2	4
RTU–Bus 14	SCADA	0.02	700.00	2	4
SCADA	EMS	0.1	500.00	20	1

TABLE II. COMMUNICATION IRREGULARITIES FOR T = 100 S

Connection		**Status**	
From	To	Dropped	Delay [ms]
PMU/PDC/EMS			
PMU at Bus 1	PDC/EMS	No	118.40
PMU at Bus 2	PDC/EMS	No	218.40
PMU at Bus 3	PDC/EMS	Yes	/
PMU at Bus 4	PDC/EMS	No	138.40
PMU at Bus 5	PDC/EMS	No	198.40
PMU at Bus 6	PDC/EMS	No	158.40
RTU/SCADA/EMS			
RTU at Bus 7	SCADA	No	518.40
RTU at Bus 8	SCADA	No	1192.38
RTU at Bus 9	SCADA	No	1594.74
RTU at Bus 10	SCADA	No	718.40
RTU at Bus 11	SCADA	No	1933.14
RTU at Bus 12	SCADA	No	1503.16
RTU–Bus 13	SCADA	No	1318.40
RTU–Bus 14	SCADA	No	718.40
SCADA	EMS	No	544.44

TABLE III. COMMUNICATION IRREGULARITIES OVER ONE HOUR

Connection		**Average values over one hour**				
From	To	Sent packets	Delivered packets	Dropped packets	Drop rate [%]	Average delay [ms]
PMU/PDC/EMS						
PMU at Bus 1	PDC/EMS	179978	172824	7154	3.97	131.55
PMU at Bus 2	PDC/EMS	179973	172811	7162	3.98	232.06
PMU at Bus 3	PDC/EMS	179975	171942	8033	4.46	191.38
PMU at Bus 4	PDC/EMS	179977	171985	7992	4.44	151.51
PMU at Bus 5	PDC/EMS	179974	173712	6262	3.48	210.76
PMU at Bus 6	PDC/EMS	179976	173170	6266	3.48	171.97
Total		1079853	1036444	43409	4.02	181.54
RTU/SCADA/EMS						
RTU at Bus 7	SCADA	1799	1784	15	0.83	607.12
RTU at Bus 8	SCADA	1799	1775	24	1.33	1005.35
RTU at Bus 9	SCADA	1798	1765	33	1.84	1608.81
RTU at Bus 10	SCADA	1799	1762	32	2.06	806.76
RTU at Bus 11	SCADA	1798	1739	59	3.28	1794.79
RTU at Bus 12	SCADA	1798	1748	50	2.78	1213.99
RTU at Bus 13	SCADA	1798	1726	72	4.00	1394.32
RTU at Bus 14	SCADA	1799	1726	73	4.06	805.84
Total		14388	14025	358	2.49	1154.62
SCADA	EMS	1799	1786	13	0.72	558.19

Case 1: Bandwidth

Average delay and dropped packets' dependency of bandwidth for both types of communications are given in Fig. 3(a) and (b), respectively. Higher bandwidth results in reduced:

- Average Delay (Fig. 3a) – packets require less time to be transferred, which also infers they spend less time in queues.
- Risk of package drop (Fig. 3b) – packets spend less time in queues, which reduces the risk of it being overrun.

After the bandwidth reaches a certain value, the drop rate and average delay can no longer be decreased (packet transfer is fast enough that packets avoid waiting in queues, resulting in the queue limit never being overrun). The remaining average delay and packet drops are due to default delays and the channel, respectively.

Case 2: Default Delay

Average delay and dropped packets' dependency of default delay for both types of communications are given in Fig. 4(a) and (b), respectively. Higher default delay results in increased:

- Average delay (Fig. 4a) – packets require more time to be transferred, which also infers they spend more time in queues.
- Risk of package drop (Fig. 4b) – packets spend more time in queues, which increases the risk of it being overrun.

Case 3: Send Interval

Average delay and dropped packets' dependency of send interval for both types of communications are given in Fig. 5(a) and (b), respectively. Higher send interval means less packets being sent, which for PMU measurements results in reduced:

- Average delay (Fig. 5a) – smaller queue delay.
- Risk of package drop (Fig. 5b) – smaller chance of the queue being overrun.

For the RTU-based measurements, the number of dropped packets and the average delay is almost constant, as the send interval in the base parameter example was pretty high, already avoiding the problem of queue limit overrun and queue delay.

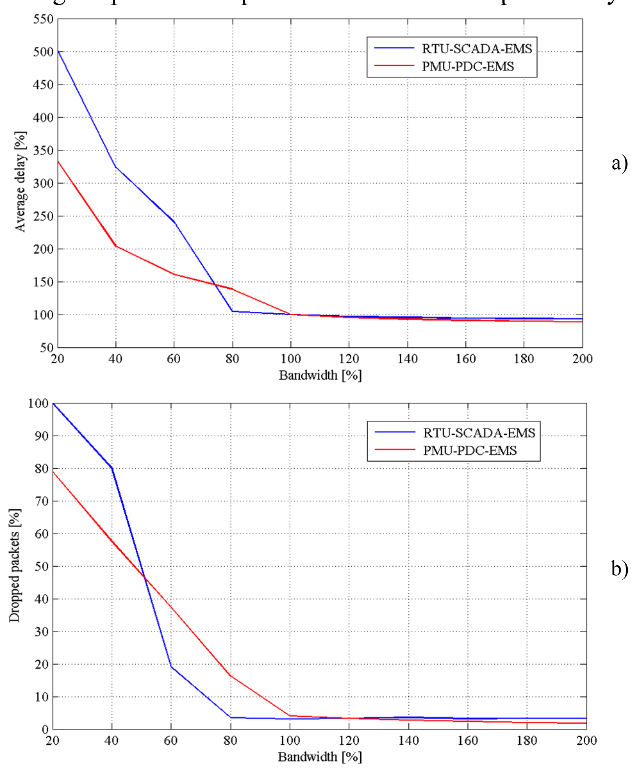

Fig. 3. Average delay (a) and dropped packets (b) for different bandwidths

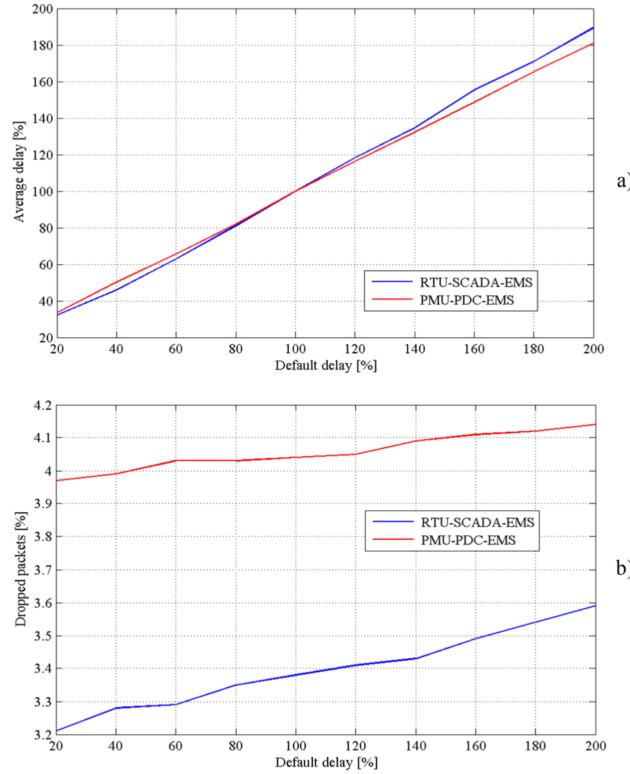

Fig. 4. Average delay (a) and dropped packets (b) for different default delays

E. State Estimation (SE) Results

For the effect of communication irregularities on the SE calculations, the following should be noted:

- Test network from Section V.A is used.
- SE is executed for different values of default delay, all taken as certain percentage of the base case example from Section V.C. The delay values or dropped packets for each channel are shown in Table V.
- Each packet is sent at time $t = 0$ s.
- SE is executed at time $t = 2.3$ s.
- To check the results quality, state estimation (SE) results have been compared with power flow (PF) results (Table IV).
- Packets which have not arrived on time, or which have been dropped are indicated (shadowed cells) in Tables V and IV.

TABLE IV. DETAILED RESULTS FOR DEFAULT DELAY = 160 %

	Voltage magnitude [p.u.]			Voltage angle [rad]		
Bus	PF	SE	Error	PF	SE	Error
1	1.060000	1.059998	0.000002	0.0000	0.0000	0.0000
2	1.035000	1.034991	0.000009	–0.0347	–0.0352	0.0005
3	0.988283	0.988295	0.000012	–0.1369	–0.1403	0.0034
4	1.030454	1.030449	0.000045	–0.0752	–0.0749	0.0003
5	1.040000	1.039991	0.000009	–0.0543	–0.0541	0.0002
6	1.035931	1.035918	0.000013	–0.0644	–0.0642	0.0002
7	1.022747	1.022732	0.000015	–0.0522	–0.0520	0.0002
8	1.080000	1.080003	0.000003	0.0116	0.0128	0.0012
9	1.060992	1.060988	0.000004	–0.0790	–0.0798	0.0008
10	1.057144	1.057153	0.000009	–0.0703	–0.0708	0.0005
11	1.067000	1.066999	0.000001	–0.0385	–0.0389	0.0004
12	1.053604	1.053602	0.000002	–0.0749	–0.0741	0.0008
13	1.050000	1.049982	0.000018	–0.0717	–0.0716	0.0001
14	1.038215	1.038207	0.000008	–0.0933	–0.0952	0.0019

TABLE V. COMMUNICATION IRREGULARITIES FOR DIFFERENT DEFAULT DELAYS

Connection														
Measurement at	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14
Default Delay [%]	**Packet transmission delay [ms]**													
20	38.40	58.40	50.40	43.40	54.40	66.40	222.08	384.19	422.08	262.08	483.98	630.20	382.08	262.08
40	58.40	98.40	82.40	68.40	90.40	114.40	535.30	755.30	935.30	454.20	1036.90	1044.02	545.20	615.30
60	78.40	138.40	114.40	93.40	126.40	162.40	633.20	934.31	1233.20	753.20	1353.20	1262.72	1113.20	753.20
80	113.29	193.30	161.29	133.30	162.40	225.30	890.00	1272.71	1690.00	1050.00	1850.00	1640.32	1530.00	1050.00
100	118.40	218.40	178.40	143.40	198.40	258.40	1151.80	1631.90	2152.00	1351.80	2351.80	2040.92	1951.80	1351.80
120	118.40	229.55	178.40	154.55	198.40	269.55	1154.46	1616.51	2154.46	1354.46	2378.31	2044.93	1954.46	1354.46
140	158.40	298.40	242.40	193.40	270.40	354.40	1472.95	2097.71	2872.95	1752.95	3180.91	2581.42	2590.95	1752.95
160	178.40	338.40	274.40	218.40	306.40	402.40	1622.08	2343.83	3222.08	1943.08	3563.83	2850.65	2882.08	Drop
180	215.10	387.69	323.09	260.10	359.09	459.69	1838.22	2638.92	3638.22	2198.22	4020.72	3188.54	3258.22	Drop
200	218.40	418.40	338.40	268.40	378.40	498.40	2068.04	2952.74	4068.04	2468.04	4489.64	3538.76	3558.04	2468.04

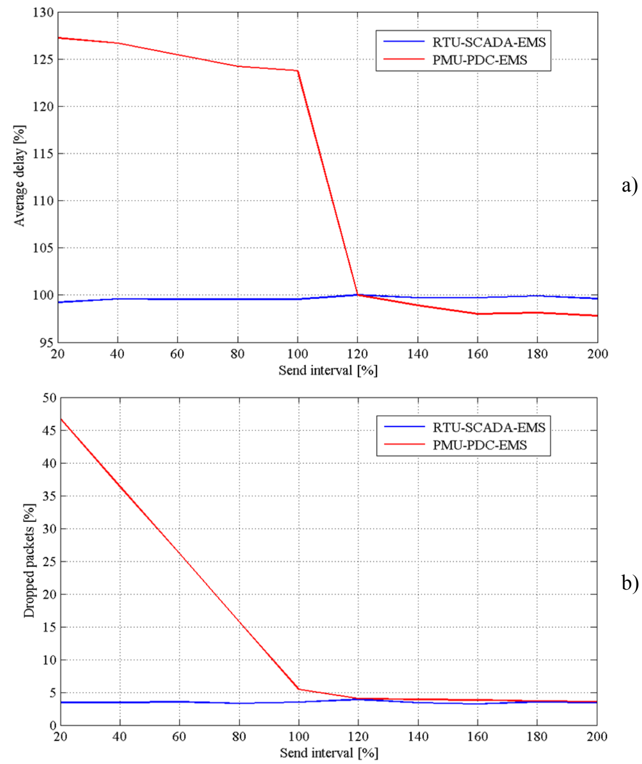

Fig. 5. Average delay (a) and dropped packets (b) for different send intervals

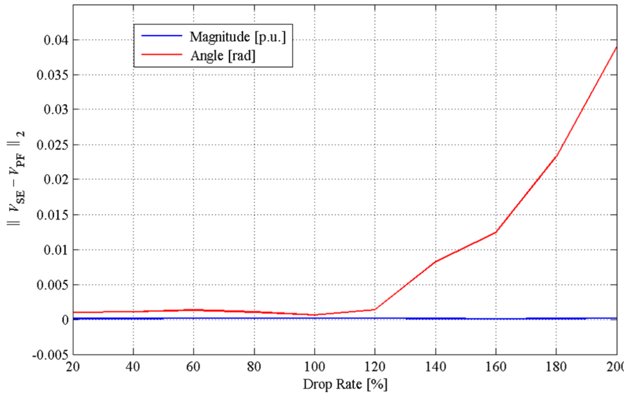

Fig. 6. Mean square errors for different default delays

Mean square error (MSE) between SE and PF for different default delays are shown in Fig. 6. Detailed results for Default Delay = 160 % are shown in Table IV, with indicated buses for which measurements have not arrived (shadowed cells).

The following can be concluded from the results:

- Higher default delays will result in less measurements being available for SE – there is a bigger risk of measurements being delayed or dropped (as shown in Section V.D).
- Less available measurements will cause higher MSE for voltage angle (Fig. 6).
- SE results are not necessarily worse at buses at which measurements have not arrived (Table V) – this is due to a meshed test network with a strong coupling among the buses.

VI. CONCLUSIONS

As the power industry evolves, more precise, timely and trustworthy solutions for various operations are needed. Many utilities have embraced the Smart Grid concept, with internal CS as one of its main features. These communications are not ideal, and irregularities may cause information not arriving on time (packet delay) or even being completely lost (packet drop). Their performance depends on many technical parameters, such as the type of communication, transmission length, packet size, etc., making the predictions hard. SE is perhaps the first affected application, since it requires real-time information and other (pseudo and virtual) measurements. The irregularities can cause further problems for almost all other optimization and control functions requiring SE as an input. Our future work will focus to overcome these irregularities, in hope of achieving appropriate results when using realistically modeled CS.

REFERENCES

[1] M. Daoud, X. Fernando, "On the communication requirements for the smart grid," *Energy and Power Engineering*, vol. 3, no. 1, pp. 53-60, Jan. 2011.

[2] Y. Yan, Y. Qian, H. Sharif, D. Tipper, "A survey on smart grid communication infrastructures: motivations, requirements and challenges," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 5-20, First Quarter 2013.

[3] S.K. Salman, *Introduction to the Smart Grid Concepts Technologies and Evolution,* IET, 2016.

[4] * * *, *Sharing 700 MHz Public Safety Broadband Spectrum with Utilities: A Proposal,* Utilities Telecom Council, 2012. Available: http://utc.org/wp-content/uploads/2016/03/Sharing-700-MHz-Public-Safety-Broadband-Spectrum-With-Utilities.pdf

[5] A. Abur, A.G. Exposito, *Power System State Estimation – Theory and Implementation*, Marcel Dekker, Inc. 2004.

[6] J.G. Cupp, M.E. Beehler, "Implementing smart grid communications," *Burns and McDonnell Tech Briefs*, no. 4, pp. 5-8, 2008.

[7] J. Bhalla, "Multiprotocol label switching," *International Journal of Advanced Research in Management, Architecture, Technology and Engineering (IJARMATE)*, vol. 1, no. 4, pp. 31-35, Nov. 2015.

[8] E. Rosen, A. Viswanathan, R. Callon, "Multiprotocol label switching architecture," RFC 3031, 2001.

[9] K.E. Fultz, D.B. Penick, "The T1 carrier system," *The Bell System Technical Journal*, vol. 44, no. 7, pp. 441-446, Sep. 1965.

[10] * * *, *T1 Basics*. Available: http://materias.fi.uba.ar/6679/apuntes/T1.pdf

[11] K. Fall, K. Varadhan, "The *ns* manual (formerly *ns* Notes and Documentation)," Nov. 2011. Available: https://www.isi.edu/nsnam/ns/doc/ns_doc.pdf

[12] M. Bjorkbom, S. Nethi, T. Kohtamaki, "PiccSIM Manual," Aalto University, Dec. 2013. Available: http://wsn.aalto.fi/en/tools/piccsim/piccsim_manual_1.1.pdf

[13] R. Christie, *14 Bus Power Flow Test Case*, University of Washington, 1993. Available: https://www2.ee.washington.edu/research/pstca/pf14/pg_tca14bus.htm

[14] G. Ahn, W. Chun, "Design and implementation of MPLS network simulator supporting LDP and CR-LDP," *Proc. of the IEEE Int. Conf. on Networks (ICON 2000)*, pp. 1405-1451, Sep. 2000.