Bandwidth and Latency Requirements for Smart Transmission Grid Applications

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***Abstract*—The rapid increase of phasor measurements on the high voltage power system has opened opportunities for new applications to enhance the operation of the grid. To take advantage of the high sampling rates of these measurement data, these applications will require a high-bandwidth, networked communication system. The specifications for this next generation communication system that will overlay the continental power grids are under intense discussion at this time by organizations like the North-American Synchro-Phasor Initiative (NASPI). In this paper we present a method to simulate, design and test the adequacy of a communication system for a particular transmission grid. The main difference from typical communication system studies is that we formulate the communication requirements from the power grid application requirements, that is, the communication design, simulation and testing is from the viewpoint of the anticipated power applications. The method is demonstrated on a WECC 225 bus and a Polish 2383 bus transmission system models.**

***Index Terms*—Bandwidth, C37.118, communication protocols, latency, NS2, PMU, smart grid.**

I. INTRODUCTION

THE IDEA OF collecting fast measurements that can give us an insight into grid dynamics is fundamental to understanding the grid behavior that is operating near margins and to make it more reliable [1]. With availability of Phasor Measurement Units (PMU), the synchronized measurements can be taken at rates of about 30 to 120 samples per seconds. The smart grid applications [2]–[13] are designed to exploit these real-time measurements. Most of these applications have a strict latency requirement in the range of 100 milliseconds to 5 seconds [11], [12]. To feed these applications we also need a fast communication infrastructure that can handle a huge amount of data movement and can provide near real-time data delivery. These issues become more and more critical when we imagine having phasor measurement units everywhere in the power grid. The latency and bandwidth requirements for smart grid are two very critical issues among these that are addressed in this paper.

Rest of the paper is organized as follows. Section II discusses smart grid applications, as the design of these will determine the communication requirements. Section III discusses various aspects of communication infrastructure needed for the smart grid. Section IV presents the simulation results of possible communication scenarios for two different power systems. We conclude with Section V.

II. SMART GRID APPLICATIONS

A. Measurements

The data which we need in real time for successful analysis, operation and control of the grid is its topology and state. The topology defines the interconnection of the grid and is almost constant over time [13]. On the other hand, the state (voltage and angle at all buses) of the power system changes dynamically over time due to changes in loads, generation and switching operations. Without PMUs, state of the grid is derived from voltage magnitude (V), real power (P) and reactive power (Q) measurements using a computer program called State Estimator (SE). Most of the power grid applications based on this set-up are bottlenecked by the latency and accuracy of the estimated state of the system as calculated by state estimator. As these measurements are collected by Supervisory Control and Data Acquisition (SCADA) system by polling over 2–4 seconds, the measurements do not represent a snapshot of the actual system state at one particular time. This set-up seems to work fine for an unstressed grid working in almost steady state conditions. The present operation of the grid is often very close to its security margins and the system ventures into the emergency state more frequently than before. State-estimator cannot capture the changing state of the system and sometimes fails to converge. With PMUs all over the system, the state of the grid (voltage phasors) can be directly measured and moreover can be measured many times per second with time-stamps giving insight into the dynamics of the system.

B. Current Status

A number of smart grid applications have already been developed and some are in the process of development [11]. To understand their communication needs, a brief survey of some of the most important applications in terms of their data requirement and latency is presented in Section II-C and Table I. A communication network designed to handle these basic applications would be able to handle other applications as well.

C. Classification

1) State Estimation: Even though voltage phasors across the grid can be directly measured with PMUs everywhere, state estimation is an essential tool to eliminate effect of bad measurements on the final calculation of the state. Most of the Energy Management System (EMS) applications are fed from state

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TABLE I
Survey of Smart Grid Applications Based on Latency and Data Requirements

Main Application	**Applications based on it**	**Origin of Data/Place where we need the data**	**Data**	**Latency requirement**	**Number of PMUs we may need to optimally run the application**	**Data time window**
State Estimation	Contingency analysis, Power flow, AGC, AVC, Energy markets, Dynamic/ Voltage security assessment	All substations/ Control center	P,Q, V, theta, I	1 second	Number of buses in the system	Instant
Transient Stability	Load trip, Generation trip, Islanding	Generating substations/ Application servers	Generator internal angle, df/dt, f	100 milliseconds	Number of generation buses (1/20 buses)	10-50 cycles
Small Signal Stability	Modes, Modes shape, Damping, Online update of PSS, Decreasing tie-line flows	Some key locations/ Application server	V phasor	1 second	1/10 buses	Minutes
Voltage Stability	Capacitor switching, Load shedding, Islanding	Some key location/ Application server	V phasor	1-5 seconds	1/10 buses	Minutes
Postmortem analysis	Model validation, Engineering settings for future	All PMU and DFR data/ Historian. This data base can be distributed to avoid network congestion	All measurements	NA	Number of buses in the system	Instant and Event files from DFRs

estimated data and are benefited by faster, accurate and synchronized measurements. Also with PMUs, two level state estimators [14] can be designed to run locally within the substation to feed applications like transient stability.

2) Transient Stability: Transient stability is a concept related to the speed and internal angles of the generators. A typical system can get transiently instable in approximately 10 cycles. The way to prevent this is to island the system in coherent groups or shed load/generation using Special Protection Schemes (SPS). The wide-area control to do so is still not in place because of latency requirements and it would to be a big challenge to design such a control system even in the future.

3) Small Signal Stability: To solve small signal stability problem, we need signals only at selected key locations where modes are more visible. For any of these modes, if damping happens to change then it changes slowly over time. Moreover, if the damping is negative, even in that case, oscillations take time to build. So small signal instability occurs over a period of time and by observing the mode damping near real time, this can be prevented by resetting the power flows across the lines or by setting Power System Stabilizer (PSS) online.

4) Voltage Stability: Voltage instability spreads over time starting from reactive power (VAR) deficient area and can ultimately cascade and lead to a blackout. The problem can be solved if the voltage in an area can be measured and corrected by balancing VAR in the particular area or by islanding the area.

5) Post-Mortem Analysis: This will be a key application to correct power system models and to update engineering settings for the system. The engineering settings are bound to change as the system changes. This application does not need to run real time and has no latency requirements. This application will require PMU data as well as data from other IEDs (Intelligent Electronic Devices) like DFRs (Digital Fault Recorders).

III. SMART GRID COMMUNICATIONS

A. Infrastructure

We assume smart grid of the future will have PMU data available across the grid. To meet the latency requirements and to handle the huge amounts of data, a real time information infrastructure was proposed [13]. Because of the huge amount of data generated at each substation, not all the data can be sent to one central location. Therefore, there is a need for the application servers to be distributed as shown in Fig. 1. Separating out application servers will also help to tag packets for latency purpose. The middleware system to handle this distributed data base and to provide the latency and other Quality of Service (QoS) is one of the major goals of the NASPI [11], [12] and some research initiatives like Gridstat [15], [16].

B. PMU Data Format (C37.118)

The standard mostly used in practice for PMU data format is C37.118 [17]. Among the four frames that are defined in C37. 118, Data Frame is the one that is sent out from substation during normal system operation. Hence, it is important to know the data formats to exactly evaluate how much data is being generated in bytes at each substation. Also, one data frame can carry data from multiple PMUs.

C. Latency

We define data latency as the time between when the state occurred and when it was acted upon by an application. Each application has its own latency requirements depending upon the kind of system response it is dealing with. Among the other delays [18], communication delay also adds to the latency and needs to be minimized. The communication delays on the network are comprised of transmission delays, propagation delays, processing delays, and queuing delays [1]. Each of these delays must be looked into to understand the complete behavior of the communication network for a given network.

D. Communication Within one Control Area

The data from various PMUs from a substation is sent out in C37.118 format Data frame. This data is then received at the location of the application in its respective Phasor Data Concentrator (PDC) usually using proprietary software; the only open source software called Open-PDC is used in this paper.

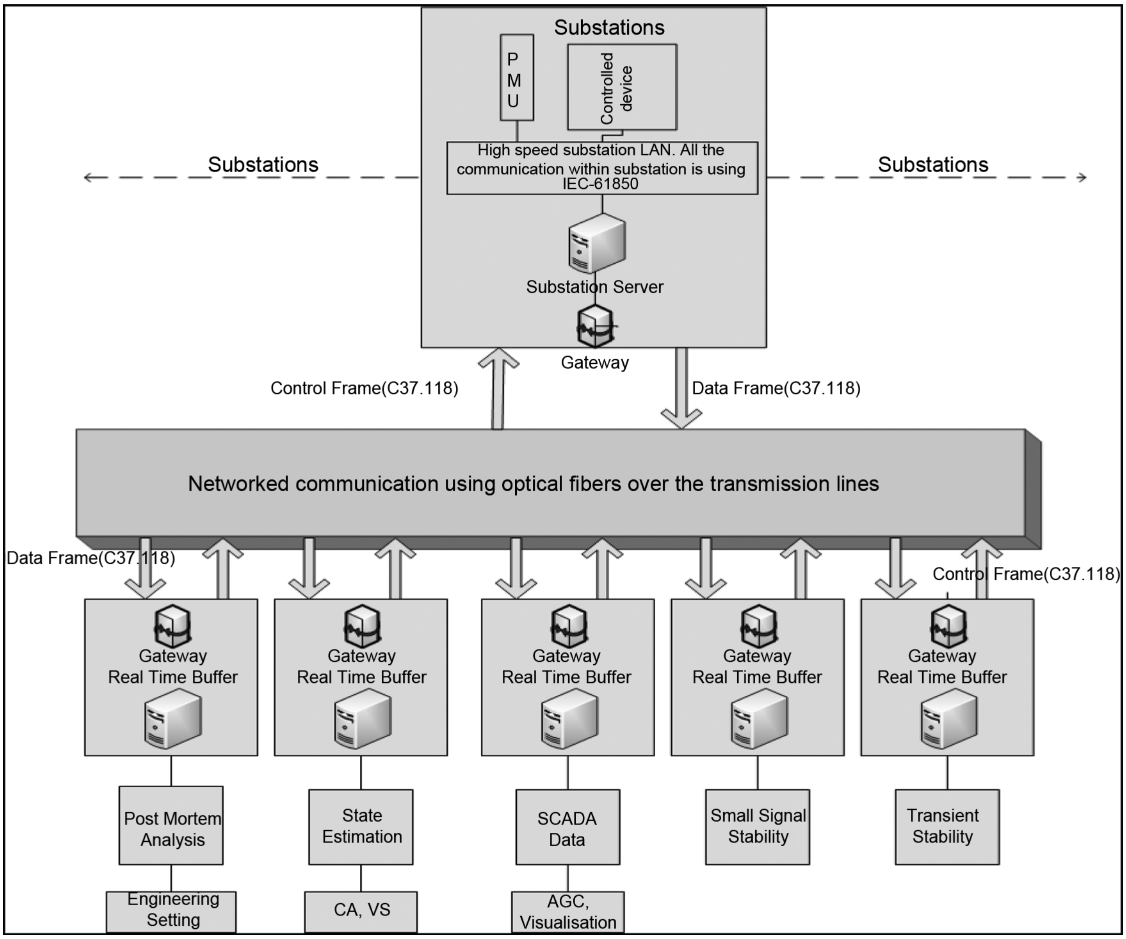

Fig. 1. Communication Architecture.

TABLE II
PROTOCOL LAYERS FOR COMMUNICATION IN ONE CONTROL AREA

Layer	Protocol
Application	CBR
Transportation	UDP
Network	IP
Data	Ethernet
Link	Ethernet (Optical fiber)

We know that PMUs are constantly sending out the data frame on the network. For many of the smart grid applications latency is an important consideration in designing a communication infrastructure. Keeping this in mind, User Datagram Protocol (UDP) becomes a preferred protocol at the transportation level over Transportation Control Protocol (TCP). At the application layer, Constant Bit Rate (CBR) is a good choice to carry the continuously generated data frames of PMU. Maximum Transmission Unit (MTU) size of the link layer will play an important role as OpenPDC is designed to receive a complete C37.118 packet and not a broken one. As shown in the simulations, packet size can be around 1500 bytes, i.e., Ethernet communication having MTU size as 1500 bytes is the obvious choice. Given the latency and bandwidth requirements, optical fibers and Broadband over Power Line (BPL) are the promising solutions. For uniformity we assume that optical fiber is present throughout the network. Hence the protocol stack will look like as shown in Table II.

IV. SIMULATION RESULTS

A. *Simulation Setup*

Here we present the simulation results for Western Electricity Coordinating Council (WECC) 225 bus system and Poland 2383 bus system [19]. We simulated one of the possible communication scenarios using an event based, open source communication network simulator called NS2 version 2.34 [20], [21]. We further wrote Matlab, Python, Tcl and Awk scripts to do the analysis. We identified the following 7 basic traffics in the network as shown in the simulation snapshot for IEEE 14 bus system in Fig. 2.

1) All the Substation (S/S) to Control Center (CC).
2) Control Center to Control Substation (Generating stations and substation having control units like transformers and reactors).
3) Special Protection Scheme (SPS) substation to SPS.
4) SPS to SPS substation.
5) Generating substation to Generating substation.
6) SPSs to Control Center.
7) Control Center to Control Center.

Here, SPS is used generically to represent any wide-area closed-loop control and/or protection. An SPS may not be located at the control center or at any substation and it needs data only from a few locations and issues commands back to

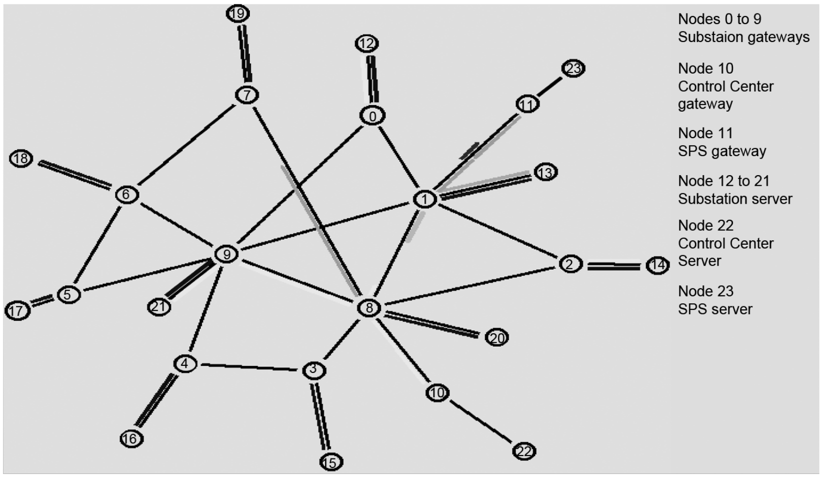

Fig. 2. Snapshot of 14 bus NS2 simulation with 6 traffic types.

few substations only. SPS can be especially useful for transient stability applications where latency is of significant importance.

The key assumptions that we have to make in the simulation are discussed in Section IV-B and Section IV-C. Similar network simulations [22] have been carried out before and some of the assumptions in this paper are similar to [18], [22]–[24]. The main difference in this work is that the assumptions are developed by starting from the power network, substation configurations and anticipated on-line applications (Section IV-B) to determine the data transfer needs. Different scenarios can be studied using different protocols, routing algorithms, data formats, sampling rates, and communication infrastructure. Also, accuracy of the results would depend on the modeling details and some of it may require changing the NS2 source code. This paper focuses on presenting a methodology to simulate a possible communication scenario using power system topology information with design parameters based on smart grid application requirements.

B. Assumptions for Power Systems Data

The information that is required to calculate the amount of data for an actual power system is substation configuration and connected equipment (generators, reactors, and transformers). Location of the application servers (control center and SPS) and location of controls along with their individual data needs then define the amount of data that need to be communicated. For a real power system this information is easily available.

The connection between substations is from the given power system network data and the communication network overlays that. In case of multiple transmission lines between two substations, only one communication link is considered to connect them. Control center (CC) node is connected to the substation node having maximum number of communication links. This will allow distribution of traffic to the CC node through multiple paths. Similarly SPSs are connected to the available substation nodes having maximum connectivity. This completes a communication network graph of network gateways (Gw) for a given power system.

Each gateway is connected to a server. Power system applications and PDCs are running in these servers. As an integrity check and to run communication simulation, we wrote a computer program to verify the connectivity of the network graph obtained after this step.

The second step is to estimate packet sizes in each of these substations, control centers and SPSs. We calculate packet size for data traffic between substation and control center (type-1 traffic) as follows.

1) The configuration for each substation is usually known (in our examples in Sections IV-D and IV-E we assume a breaker and half scheme for all substations). The 3 phase quantities for each section and CB status are measured and communicated.
2) Channels for each PMU are known (assumed to have 9 analog channels and 9 digital channels in examples below).
3) Given the number of PMUs and number of phasors in a substation, the size of C37.118 data frame is calculated.

Type-2 to type-6 traffic have packet sizes smaller than the type-1 traffic because only selected data for control purposes constitute these types.

For the two example power networks used in Sections IV-D and IV-E, we had the power network data but not the substation details. The identification of substation configurations, control substations, control centers and SPSs is first step to determine the data traffic for our simulation studies. We wrote a computer program to do this step. We combine buses that are connected through transformers into one communication node per substation. We then calculated the number of feeders in each of these substations. On top of the substation, we added one control center per zone where we treated each zone as one control area. We then added SPSs assuming that a group of approximately 10 substations will be connected to one SPS.

C. Assumptions for Communication Simulation

After obtaining the network graph and data requirements based on the Sections IV-A and IV-B discussions, the following assumptions are made for communications.

1) As discussed in Section III-D, we used CBR over UDP to simulate the traffic with MTU size as 1500 bytes.
2) As a base case, we assumed duplex links of sufficiently high bandwidth between substations as OC-3 i.e.,

TABLE III
WECC STATISTICS AFTER NODE REDUCTION

S.No.	Parameter	Value
1	*Buses*	225
2	*Substations*	161
3	*Control Center*	1
4	*SPS*	16
5	*Generating S/S*	31
6	*Control S/S*	58
7	*SPS S/S*	160

155 Mbps and the receiving link for the CC/SPS as OC-12 i.e., 622 Mbps.

3) To observe larger queuing delays and to avoid packet drops, based on few simulation runs, we assumed the queue size as 5000 packets.
4) To simulate large network such that every packet reaches its destination node without being dropped, based on few simulations run, we set the Time-To-Live (TTL) value to 64 hops.
5) Number of CC and SPSs are chosen based on the size of the network.
6) Data set out from the substation/SPS/Control center server is in C37.118 format (fixed 16-bit).
7) The routing used by NS2 is the shortest route (number of hops) and is kept default as static.
8) We assumed that the system is under normal operation and only Data frames are being communicated.
9) The sampling rate is assumed to be 60 samples/second for all the traffic sources
10) The processing delays in gateways (10–100 microseconds [25]) are assumed to be zero. Here gateways are considered as forwarding nodes only to simulate communications. Data aggregation/ processing occur at end nodes/PDC only and we consider this delay as computation delay and not communication delay. The computation delays can be added at each end node for specific application without making it a part of the communication simulation.
11) We assumed that the communication is uniform i.e., no spikes in data.
12) To calculate propagation delay, we converted the network reactance into miles [26].
13) Propagation delay between server and gateway is assumed to be 1 microsecond.

NS2 simulation is run after following the steps/assumptions discussed in Sections IV-A to IV-C above. NS2 generates a trace file with all the events (packet drop, packet receive, etc.) for each packet generated in the system. These files are analyzed using various computer programs [27] for results on latency and bandwidth presented in Sections IV-D and IV-E.

D. WECC Results

1) WECC 225 Bus Power System: The WECC 225 bus is a reduced model of the WECC transmission network though representing almost same geographical area. Power system statistics after following the methodology discussed in Section IV-B are presented in Table III. Note that we have only one control center and hence six traffic types for WECC.

TABLE IV
PACKET SIZE OF TRAFFIC TYPE-1

Maximum (Bytes)	Minimum (Bytes)	Average (Bytes)	Median (Bytes)
1540	148	401	280

TABLE V
LINK BANDWIDTH USAGE

Topology	Max. of used links (Mbps)	Min. of used links (Mbps)	Average of used links (Mbps)	Median of used links (Mbps)	% of unused Gw2Gw links
Min S.T.	58.75	0.10	5.46	0.39	28.6%
1CC links	45.60	0.08	3.34	0.62	11.4%
3CC links	46.80	0.10	2.97	0.51	11.7%
5CC links	44.09	0.08	2.03	0.38	10.8%

2) Packet Size: As shown in Table IV the maximum packet size for type-1 traffic in a substation can be as much as 1540 bytes. Also, packet sizes for a given power system would be same for all communication topologies. We assumed type-1 to type-6 traffic packet size to be 250 bytes for the simulation purposes which is lower than the median of type-1 packet size.

3) Average Link Usage for Different Communication Topologies: As shown in Table V, we did simulation for four different cases. In the first simulation we used Kruskal's algorithm [28] to get minimum spanning tree (S.T.) for the communication network. This gives us the minimum number of links required for networked communication of a given power system. In next three simulations we used the complete graph as obtained after node reduction program with variation in number of control center links, for example, 3 CC link means connecting CC gateway to the three substation gateways (with maximum connectivity) in the network. Clearly, connecting control center with some substations geographically distant is really important as it makes the routing really efficient by avoiding bottlenecks and providing alternate shortest path to the traffic. Also, we must not use spanning tree configuration from reliability perspective. For full topology case, by adding just 4 more CC links we can save 40% on link usage and delays reduces to ¼ for 5CC link configuration compared to 1CC link configuration. Hence, this helps in decreasing delays by adding just few links. Also, notice that average bandwidth usage decreases because now packet takes shorter route and traverses lesser link to reach its destination.

4) Maximum Delays in Traffic for Different Communication Topologies: As shown in Table VI, we have figured out the maximum delays for the six identified traffic types. With the large bandwidth of fiber optics and meshed communication, it can be noted that maximum delays for all the traffic types are well within the latency requirements for most applications.

5) Queuing Delays: As shown in Table VII, we have calculated the queuing delays for each system. Notice that with the huge bandwidth available queuing delays are almost negligible. Queuing delay can increase really fast if the network get congested or if the bandwidths on incoming link and outgoing link are disproportionate.

6) Number of Hops: As shown in Table VIII, we have calculated the number of hops that a packet has to traverse assuming

TABLE VI
MAXIMUM DELAYS FOR DIFFERENT TRAFFIC TYPES

Network Topology	**Type1 (ms)**	**Type2 (ms)**	**Type3 (ms)**	**Type4 (ms)**	**Type5 (ms)**	**Type6 (ms)**
Min S.T.	49.9	40.3	45.1	46.3	44.0	40.3
1CC links	26.2	27.6	26.6	27.1	29.4	23.9
3CC links	19.2	19.1	25.2	25.5	29.3	16.4
5CC links	11.7	5.2	13.8	12.9	15.6	4.5

TABLE VII
QUEUING DELAYS

Topology	**Maximum (µs)**	**Minimum (µs)**	**Average (µs)**	**Links with queue delay as zero (%)**
Min S.T.	586	0	17.7	53.1%
1CC links	441	0	13.7	60.1%
3CC links	259	0	12.0	60.2%
5CC links	354	0	12.6	60.8%

TABLE VIII
NUMBER OF HOPS

Topology	**Max**	**Min**	**Average**	**Median**
Min S.T.	43	2	19	18
1CC links	28	2	12.2	12
3CC links	26	2	10.6	10
5CC links	15	2	7.0	7

TABLE IX
ASSUMED BANDWIDTH FOR SIMULATIONS

Bandwidth	**Base Case (D3-D6) (Mbps)**	**Actual Usage (Mbps)**
Btw CC server and CC Gw	Duplex 622	50Mbps (Gw to Server) / 10Mbps(Server to Gw)
Btw Sps server and Sps Gw	Duplex 622	Simplex 2Mbps
Btw S/S server and S/S Gw	Duplex 155	Simplex 5Mbps
Btw CC Gw and S/S Gw	Duplex 622	Simplex Integer(actual)+1
Btw Sps Gw and S/S Gw	Duplex 622	Simplex Integer(actual)+1
Btw S/S Gw and S/S Gw	Duplex 155	Simplex Integer(actual)+1

shortest hop routing algorithm. This data will help us understand how much an issue can processing delays at gateways can be if they happen to increase due to more intense routing mechanisms or other reasons like security.

7) Simulations With Varying Bandwidth: In Sections IV-D-III–IV-D-VI, we calculated various network parameters using the base bandwidth mentioned in assumptions. In this section we assumed 3CC link configuration and used estimated bandwidth of Section IV-D-III as the actual required bandwidth. Table X shows the result on delays when we varied the bandwidth on the gateway to gateway links (G2G) as the multiple of actual bandwidth. Further for the first three cases of results in Table X, we assumed same bandwidth on gateway to server (G2S) links as pointed in Table IX. Notice that when we scale the bandwidth, we should scale it on the complete network i.e., both on G2G and G2S links or else queuing delay increases. Also as shown in Table X by using twice the actual bandwidth we can get delays similar to base case. Recalculated bandwidth consumption for each case is shown in Table XI.

TABLE X
DELAYS IN WECC SYSTEM WITH VARYING BANDWIDTH

Bandwidth of G2G links	**Max. Delay (ms)**	**Avg. of Max Delay of each traffic type (ms)**	**Max. Queuing Delay(µs)**	**Avg. Queuing Delay(µs)**
Actual BW/2	167.0	91.2	43736	3413
Actual BW	55.3	39.3	8018	694
*Actual BW*2*	40.8	31.3	8018	595
*Actual BW*2*	38.1	28.3	4009	342
*Actual BW*5*	32.1	24.0	1603	131
622Mbps and 155Mbps	29.3	22.4	259	12

TABLE XI
ACTUAL LINK BANDWIDTH REQUIREMENT FOR WECC

Communication infrastructure	**Max. G2G Bandwidth (Mbps)**	**Average G2G Bandwidth (Mbps)**	**Median G2G Bandwidth (Mbps)**
Actual BW/2	24	2.59	1
Actual BW	47	4.48	2
*Actual BW*2*	94	8.28	3
*Actual BW*2*	94	8.28	3
*Actual BW*5*	235	19.88	6
622Mbps and 155Mbps	622	194.56	155

E. Poland 2383 Bus System Results

1) Polish Power System: Polish power system discussed here is a high voltage power system of Poland above 110 kV which is divided into 6 zones. Zone 1–5 is shown in Fig. 3[29]. Zone-6 represents all the tie lines connected to the neighboring countries. For simulation purposes we included each of the Zone-6 bus into the respective Zone 1–5 to which it is actually connected. Each zone will have its own control center and the only interaction between zones is between their respective Control centers. The inter control center communication would have separate direct connection using optical fibers over transmission line. The number of substations being more than 225 in each zone, we used 5CC and 7CC link communication infrastructure to simulate traffic in each zone.

Network statistics following the methodology discussed in Section IV-B are presented here in Tables XII and XIII.

2) Packet Size for Different Zones: After node reduction, we calculate packet size for data traffic for each zone as shown in Table XIV.

3) Average Link Usage for Different Zones Using 5CC/7CC Link Communication Topologies: The bandwidth usage is estimated only on the G2G links and is shown in Table XV.

4) Maximum Delays in Traffic for Different Zones: From our understanding of the WECC system we used twice the actual bandwidth usage as our new bandwidth and estimated the delays for the Polish system as shown in Table XVI. This is well within the latency requirements for most applications.

5) Number of Hops: As shown in Table XVII, we have calculated the number of hops that a packet has to pass during the simulation assuming shortest path routing algorithm.

6) Control Center to Control Center Simulation: Once the data reaches its zonal control center, state estimation is performed for that particular zone. Each zonal control center then sends its information to all the neighboring control centers. Each

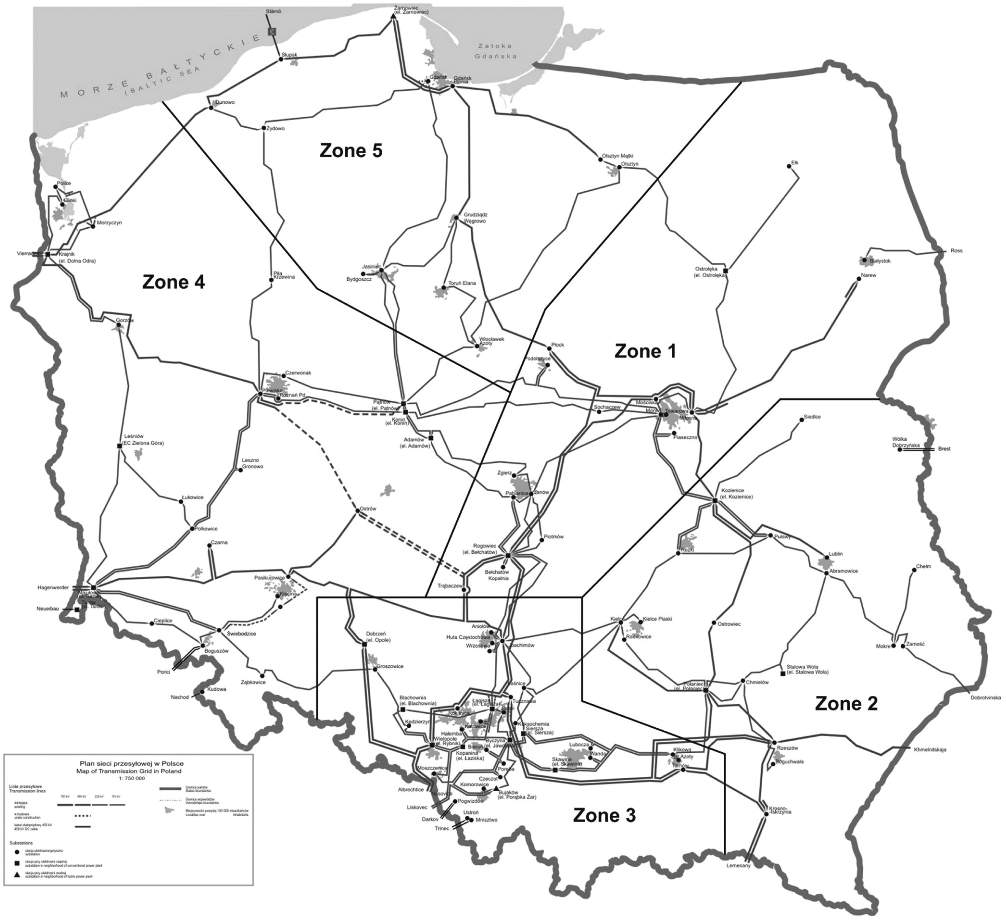

Fig. 3. Polish power system zones.

TABLE XII
OVERALL STATISTICS OF THE POLISH SYSTEM

S.No.	Parameter	Value
1	*Buses*	2383
2	*Substations*	2216
3	*Control Center*	6
4	*SPS*	219
5	*Generating S/S*	305
6	*Control S/S*	386
7	*SPS SS*	2190

TABLE XIII
ZONAL STATISTICS OF THE POLISH SYSTEM

Parameter	Zone1	Zone2	Zone3	Zone4	Zone5
Substations	*343*	259	831	515	268
Control Center	1	1	1	1	1
SPS	34	25	83	51	26
Generating S/S	42	36	88	92	47
Control S/S	56	51	104	112	63
SPS SS	340	250	830	510	260
CC links	*5*	5	7	7	5

TABLE XIV
PACKET SIZE OF TRAFFIC TYPE-1

Zone	Maximum (Bytes)	Minimum (Bytes)	Average (Bytes)	Median (Bytes)
1	1438	148	290.7	262
2	1204	160	303.1	262
3	1540	148	265.6	262
4	1426	148	281.2	262
5	1078	148	293.8	262

TABLE XV
AVERAGE G2G LINK BANDWIDTH USAGE IN MBPS

Max. of used links (Mbps)	Min. of used links (Mbps)	Average of used links (Mbps)	Median of used links (Mbps)	% of unused G2G links
126.77	0.09	4.68	0.94	2.96

TABLE XVI
MAXIMUM DELAYS IN TRAFFIC FOR EACH ZONE

Zone	Type-1 (ms)	Type-2 (ms)	Type-3 (ms)	Type-4 (ms)	Type-5 (ms)	Type-6 (ms)
1	12.4	11.5	22.2	28.7	23.6	11.9
2	12.7	10.8	19.7	24.6	25.3	10.2
3	14.2	13.6	25.4	27.9	25.9	11.2
4	12.5	11.6	18.0	22.9	25.8	10.2
5	15.4	11.1	26.3	26.6	21.0	10.0

control center has the static data of system topology for the complete national grid. Control center sometime performs the state estimation using full system topology, local measurements and usually state estimated data from neighboring grid. The problem in just sending the estimated states to the neighboring control center is that the changes in the substation configurations are not reflected in the state estimated data. To take this into account we assume all the measurements from one system to another along with any changes in substation configurations are sent. Hence

TABLE XVII
NUMBER OF HOPS

Zone	Max	Min	Average	Median
1	18	2	7.23	7
2	15	2	7.23	7
3	20	2	8.12	8
4	20	2	7.71	8
5	15	2	6.85	7

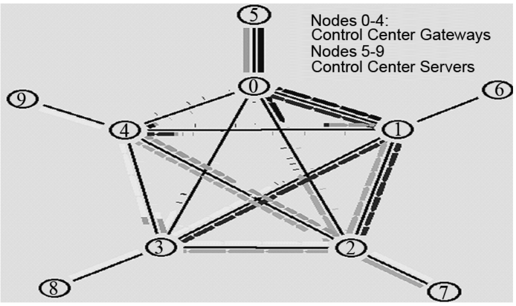

Fig. 4. Communication topology to connect control centers for Polish system.

TABLE XVIII
FILE SIZE OF RAW MEASUREMENTS AND BREAKER STATUS

Zone	File size (bytes)
1	99712
2	78514
3	220758
4	144842
5	78748

TABLE XIX
DELAY FOR INTER CONTROL CENTER COMMUNICATIONS

Bandwidth for CC to CC links (Mbps)	Delay in CC to CC communication	
	Maximum (ms)	Average (ms)
25	118.4	69.1
50	84.3	46.3
75	71.1	39.2
100	65.5	35.5

TABLE XX
DELAY IN EXCHANGING COMPLETE INFORMATION ACROSS POLISH SYSTEM

Zone	Max delay for type-1 traffic (ms)	Max CC to CC delay (ms)	Total delay (ms)
1	12.4	66.5	78.9
2	12.7	65.0	77.7
3	14.2	50.8	65.0
4	12.5	61.3	73.8
5	15.4	84.3	99.7

state estimation at control center can then be performed using local measurements and corrected using system wide measurements. The computation delays in the control center can be of significant importance here.

Currently, the data sharing between control centers is done using Inter Control Center Protocol (ICCP) which is a relatively slow protocol. The data shared between control centers being huge and latency being not the prime concern for EMS application we assumed FTP/TCP kind of traffic. Also it is not suggested to use TCP with UDP as TCP needs to allocate resources on the network before transmission and does get kicked out by UDP. Using TCP helps us in taking care of packet drops, as dropping packets is a concern for data which is collected approximately in a second. In communication infrastructure shown in Fig. 4, control center shares its information with the all control centers using point to point links. We obtained this network from the location of the zones and by finding shortest path to connect these zonal control centers assuming the optical fiber would run over transmission line. Because there would be only few changes in the system topology over time, mainly raw measurements results would constitute to the size of the file. The estimated size of the data file time tagged at one particular time is shown in Table XVIII.

In Table XIX we have shown that delays to send a complete chunk of file from one control center to another varies as we vary link bandwidth.

Based on our understanding for delays in inter control center communication we assumed 50 Mbps bandwidth and then calculated total delays shown in Table XX. These delays represent maximum total delay for packets tagged at time $\mathrm{t} = 0$ to get distributed to all the control centers. Notice that at the control center separate files of raw measurements with different time tags are created. For state estimation purpose one file can be picked up and transmitted every one second.

V. CONCLUSION

The work presented here provides a basis for simulating the performance of communication network for Power Systems. In this paper a method is developed to determine the parameters to simulate a communications system for a power grid starting from the power network configuration and the knowledge of the measurement data and the on-line applications. In designing the smart grid infrastructure for a particular power system, the assumptions should reflect the actual design parameters of the communication infrastructure. Such a simulation tool can be used to develop, design and test the performance of the communication system.

We believe that given the actual applications and their precise data requirements further improvements in the results can be obtained on a case to case basis. For example further reduction in bandwidth and latency is possible by using multicast routing and packet tagging. In another scenario we may not send all the traffic to the control center and SPS's can be used as the distributed data bases. Slower EMS applications running in control center can then source the required data from SPSs using middleware architecture like Gridstat. These improvements have to be made based on individual network needs. However, the results in the paper provide us key insight that the average link bandwidth needed for smart grid applications should be in the range of 5–10 Mbps within one control area and 25–75 Mbps for inter control center communications. Using meshed topology, delays can be contained within the 100 ms latency requirement satisfying all applications. Also with packets traversing just 8–10 hops processing delays at routers should not be a problem.

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