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RELIABILITY ANALYSIS OF SMART GRID NETWORKS INCORPORATING HARDWARE FAILURES AND PACKET LOSS

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Key words: Synchrophasor communication networks, Smart grid, Wide area monitoring system, Reliability.

The developments in communication technologies paved way for the materialization of the envisioned smart grid (SG). The SG is the next generation power grid with enhanced capabilities for monitoring and control. Especially, the development of high-speed digital processing devices known as the phasor measurement units (PMUs) has increased the monitoring capabilities of the grid. The measurements acquired by the PMUs which are known as the synchrophasor are communicated to a central monitoring station for processing and control. The communication networks based on synchrophasor applications, referred to as synchrophasor communication networks (SCN) can also be used for providing connectivity between the control station and the PMUs and thus, this paper discusses different communication architectures for the synchrophasor applications from the perspective of their reliability and cost. The unique contribution of the work is that it considers both the hardware failures as well as the packet delivery ratio (PDR) for estimating the reliability indices for these networks. Three scenarios based on dedicated, shared and hybrid SCNs have been proposed for a practical power grid with the PMUs located at the optimal locations. These networks were simulated using the QualNet network simulator and their performance is analyzed in terms of reliability, end-to-end delay (ETD) and cost.

1. INTRODUCTION

The past few decades witnessed the emergence of innovative and disruptive technologies that were a consequence of developments in the design of integrated circuits (ICs), computational capabilities and communication networks [1–2]. These developments have also contributed to evolutions for a traditional power system into smart grids (SG) [3–6]. The SG is the future power grid that not only aims at reliable distribution of power but also provides connectivity between several intelligent devices capable of exchanging information [7]. In the SG, the phasor measurements units (PMUs) act as sensors by providing useful information about the health rank of this grid in the form of synchrophasor data that are transmitted to the phasor data concentrator (PDC) [8-11]. These measurements can be used for various synchrophasor applications such as state estimation, generator synchronization, etc. The required data rate and acceptable latency for these applications were identified in [12-14] and are summarized in Table 1. Thus, these stringent requirements make it a challenging task to develop highly reliable and low latency communication networks for synchrophasor applications [14].

Table 1
Data rates and latency requirements

Synchrophasor Application	Communication Delay (ms)	Data Rates
State Estimation	100	136.8 Kbps
Generator Synchronization	50	91.2 Kbps
Intelligent Scheduling	50	300 Kbps
Islanding	50	10 Kbps
Oscillation control	200	27.4 Kbps

A plethora of research is available on the topic of communication networks for synchrophasor applications. These SG communication networks can either be dedicated, shared, centralized or decentralized [15–18]. Dedicated networks are used only for synchrophasor applications and are not shared with other devices. This increases the cost of the system but provides better security against unauthorized access. Moreover, it also performs far better in terms of reliability and latency [17]. In a centralized architecture, the PMUs communicate with a single PDC, whereas, in a decentralized architecture, the PMUs communicate with different data concentrators that coordinately implement the control action. A centralized communication architecture has been analyzed in [18] for different practical scenarios. Both dedicated as well as shared networks were simulated for obtaining communication delay and packet loss. Nevertheless, the reliability study of the communication networks had not carried out [19]. Similarly, other communication network architectures based on different communication protocols have been proposed without providing the means for analyzing their reliability [20–22]. Even though some of the recent works on the synchrophasor communication networks (SCNs) propose methods for estimating the reliability, it is restricted to the analysis of the hardware reliability [19, 23–24]. Moreover, these works provide analysis only for the dedicated networks with the assumption that the packets are lost only when the equipment's fail that is not valid in real-life applications. This paper presents several SCNs for synchrophasor applications from the perspective of latency as well as reliability.

1.1. SIGNIFICANT CONTRIBUTIONS

The most significant contribution of this work is the reliability analysis of different SCNs for practical smart grid applications. Unlike the existing works, the communication equipment failure *i.e.*, hardware failures as well as the packet loss (data reliability) are included in the analysis. Series-parallel network models are used for

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estimating the hardware failure probability and QualNet network simulator is used for obtaining the packet loss probability. The next significant contribution is that different architectures, namely, dedicated networks, shared networks and hybrid networks are considered for a practical power grid, and are analyzed for their cost, end-to-end delay and reliability. The end-to-end delay (ETD) includes the data transmission time, the propagation delay, processing and queuing time at the intermediate nodes. However, the time associated with transducer signal processing, DFT processing, data collection and multiplexing, etc., at PMU (which is typically around 20 *msec*) is not included in this delay. The PMUs are placed at optimal locations such that the entire grid is observable and the effect of large geographical separations between the end devices is also included in the analysis.

1.2. OUTLINE OF THE PROPOSED WORK

The paper is arranged into five sections. The different types of architectures that are considered in the work are described in the second section. The third section provides the reliability models for estimating the failure rate of the communication equipment. The fourth section presents the simulation results for a practical power grid. Finally, in the last section, the conclusions along with the direction and scope for the further research in the field of SCNs is presented.

2. SCN OF THE SMART GRID

In the SG, the PMUs are geographically located at distinct electrical buses. The communication between a PMU and the PDC, is achieved by sending or receiving synchrophasor data (hereafter referred to as 'data'). In IEEE Standard C37.1118.2 [25], the detailed frame format for synchrophasor communication between the devices has been presented, which suggests that the frame size typically varies from 40 to 70 bytes for frames originating from single PMU. In fact, the PMU reporting rate depends on the synchrophasor application and may vary from 10 Kbps to several hundred Kbps.

Optical fiber communication is widely adopted for establishing long-distance communication networks due to its high bandwidth, low latency, high reliability and low attenuation. Depending on the number of synchrophasor measurements acquired by the PMU and the number of frames transmitted per second, the output data rate for each PMU may vary [26]. This data generated by the PMU is to be converted into optical signals prior to its transmission over the optical cable. This conversion from electrical to an optical signal and vice-versa is achieved by using an optical transceiver. Another optical transceiver is placed at the PDC end to perform the similar operation. At intermediate locations between the two transceivers, optical repeaters are placed in order to maintain the adequate signal strength (typically, after every 100 km). Another important component of this network is the switches and routers. These are mainly required when the communication resources are shared with other applications or for connecting a local area network to the internet. Thus, the basic components of a synchrophasor communication network are the optical transceivers, optical fiber, optical repeaters, switches and the routers. The manner in which these resources are utilized results in different architectures, which are described to elucidate the work.

2.1. DEDICATED SCNS

In a dedicated synchrophasor communication network scenario, each PMU is connected to PDC through a dedicated optical fiber cable. At both the ends, optical transceivers are placed for conversion of signals from optical to electrical and vice-versa. The diagrammatic representation of a dedicated synchrophasor communication network is shown in Fig 1 (a). The number of optical repeaters required by these networks depends on the geographical distance between the end devices and it is typical placed at every 100 km. The dedicated scenario uses wired communication. The protocols used at various layers for this scenario are shown in Table 2.

2.2. SHARED SCNS

In a shared scenario, the communication resources are shared with several other applications. A local area network (LAN) is considered at the PMU end, which comprises of several other devices such as intelligent electronic devices (IEDs), remote terminal units (RTUs), etc., along with the PMU. Further, the network will consist of many other connecting devices such as switches and router that are used to connect several IED and RTUs. Every LAN has a router, also referred to as a network router, which is used to connect it to the other LANs and in general to the internet. This is important to note that the network router is an intelligent device running Network Address Translator (NAT) on it which will segregate the PMU and other local devices IP addresses (global to private or vice-versa). Moreover, a LAN can be composed of various basic network topologies such as bus, mesh, star, ring, tree or even hybrid, etc., using different networking devices like a switch/bridges, hub, repeaters, routers, and gateways, etc. The PMU is connected to the LAN via Ethernet cable and the network router is connected to the IP network via optical fiber. A typical shared synchrophasor communication network for smart grid application is illustrated in Fig 1 (b). This scenario involves wired communication, and the protocols used at the various layers for the shared scenario is presented in Table 3.

2.3. HYBRID SCNS

Although, wired technology comes with several advantages such as low latency, maximum throughput, higher data rate, high PDR, high security, better data integrity, etc., but these are achieved at the disadvantage of higher implementation and operating cost, less scalable and not suitable to connect remotely located devices. On theother hand, a wireless network promises greater scalability and provide remote access. In this scenario, the PMUs are connected to their respective access points(APs) in a wireless local area network (WLAN) through a Wi-Fi module along with other wireless devices. The network router (having Ethernet and Wi-Fi connections) is used to connect the WLAN to the rest of the network and to facilitate internet connectivity for the data transmission. Further, WLAN is connected to the backbone wired network using a bus topology to achieve the many advantages associated with it. This scenario utilizes both wired as well as wireless technologies as depicted in Fig. 1 (c). The protocols used in this scenario are shown in Table 2. The protocols selected at different layers are: application layer- file transfer protocol (FTP), transport layer- transmission control protocols (TCP); internet layer-internet protocol (IP); data link layer- point-to-point protocol over Ethernet (PPPoE) and IEEE 820.11 for logical link control sublayer, carrier sense multiple access (CSMA) collision detection CSMA/CD and carrier sense multiple access collision avoidance CSMA/CA for media access control (MAC) sublayer of data link layer; and physical layer- IEEE 802.3 and IEEE 802.11.

Table 2

Protocols used at various layers of an SCN

TCP/IP Layers		For Wired Networks	For Wireless Networks
Application Layer		FTP	FTP
Transport Layer		TCP	TCP
Internet Layer		IP	IP
Data Link Layer	LLC	PPPoE	802.11
	MAC	CSMA/CD	CSMA/CA
Physical Layer		Ethernet (IEEE 802.3)	WiFi (IEEE 802.11a)

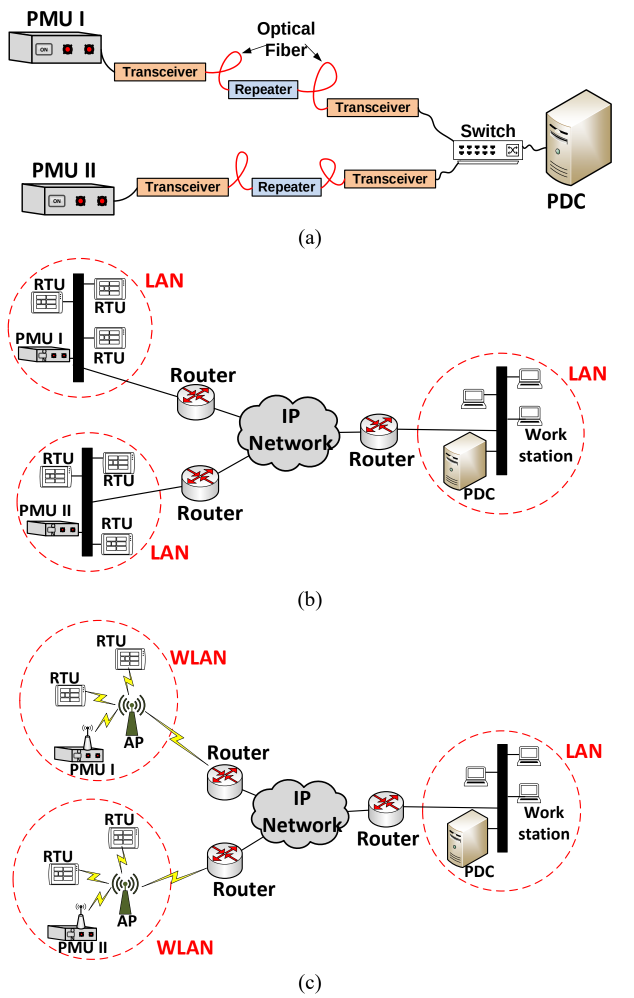


Fig. 1 – SCNs: a) dedicated: b) shared; c) hybrid.

3. RELIABILITY MODELS FOR SCNS

Synchrophasor applications require highly reliable communication networks for successful performance and in-time response. Depending on their architecture, SCNs have varying hardware reliabilities and varying packet loss probabilities. These issues are taken up in the next sections.

3.1. HARDWARE RELIABILITY MODELS

A multi-component system can be modeled as series and parallel networks that can be used for calculating its reliability [27]. The reliability for these series parallel networks can then be calculated in terms of the failure probability. A multi-component system can be modeled as a series network, if the system fails as a consequence of failure of any one of its components. It can be modeled as a parallel network, if the system fails only when all of its components fail. A multi-component system packet loss probability may not have any resemblance with the equipment reliability. The block diagram of a multi-component system having '*m*' components in series is shown in Fig. 2 (a) and for that of an '*m*' component parallel system is shown in Fig. 2 (b). The failure probabilities of an '*m*' component series system and an '*m*' component parallel system are given by the eq. (1) and eq. (2), respectively [19].

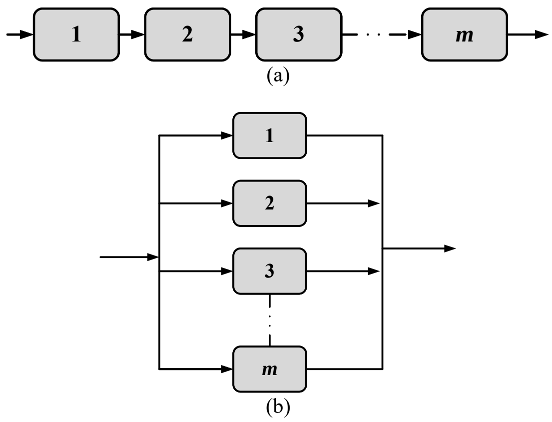


Fig. 2 – Block diagrams for: a) series networks; b) parallel networks.

$$P_{series} = 1 - \sum_{i=1}^{m} F_i \,, \tag{1}$$

$$P_{parallel} = 1 - \prod_{i=1}^{m} F_i \,, \tag{2}$$

where 'F_i' is the failure probability of the i^{th} component in the system.

The models for calculating the hardware reliability of the SCNs can be easily estimated by constructing the series-parallel networks. Further, it is assumed that every equipment has a redundant component operating in hot standby mode. When the original component fails, the redundant component comes into operation. It is assumed that the switching time to bring the redundant component into the operation is negligible. This redundancy reduces the probability of communication failure. The failure probabilities and cost of the various communication equipment are shown in Table 3. The failure probability of the router and the switch also includes the failure probability of the software running on them.

Table 3

Failure probability of various equipment

Equipment	Failure probability	Cost (in USD)
Transceiver [19]	$F_T = 4{\times}10^{-6}$	$C_T = 500$
Repeater [19]	$F_R = 8{\times}10^{-6}$	$C_R = 1000$
Switch [27]	$F_S = 2{\times}10^{-4}$	$C_S = 120$
Router [27]	$F_{RO} = 1.5{\times}10^{-4}$	$C_{RO} = 300$
Wi-Fi module [28]	$F_W = 7.6{\times}10^{-6}$	$C_W = 10$
Access point [29]	$F_A = 3.03{\times}10^{-5}$	$C_A = 200$

The communication network between a PMU and the PDC in this architecture consists of two transceivers, a switch and intermediate hubs (repeaters). For maintaining the signal quality adequate, the repeaters are placed after every 100 km and thus, their number is dependent on the distance between the end devices. Optical fibers and other passive devices such as couplers have very low probability of failure and are assumed to have zero failure probability. Also, it is believed that the power required for these devices is always available. The series-parallel model for a dedicated synchrophasor communication network with a single intermediate repeater is shown in Fig. 3 (a). Also, the shown components in the figure are the redundant components acting in parallel (indicated by dashed lines). The equipment reliability 'P_{Ded}' for this network consisting of 'n' intermediate hubs can be calculated using the eq. (3) and its cost 'C_{Ded}' can be estimated using the eq. (4).

$$P_{Ded} = 1 - 2F_T^2 - nF_R^2 - F_S^2 , \tag{3}$$

$$C_{Ded} = 4C_T + 2nC_R + 2C_S + D \times C_O , \tag{4}$$

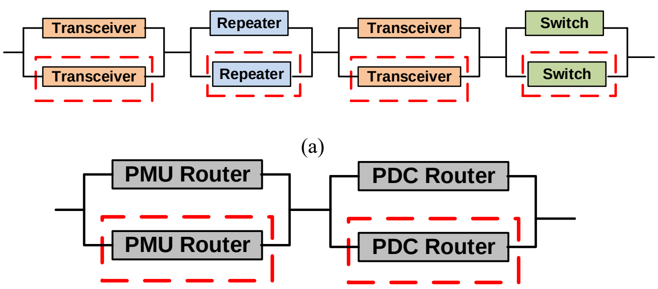
where, FT, FR, FS are failure probability of transceiver, repeater and switch respectively; and CT, CR, CS are the cost of the transceiver, repeater and switch respectively. The cost of the optical fiber in USD per meter per meter is CO which is taken as 12 USD/meter [19]. So, if PMU and PDC are at the distance of D meter, then the cost of optical fiber would be D_{CO}.

In the shared network scenario, the data generated by the PMU fails to reach the PDC when the routers fail. Without loss of generality, it is assumed that even in heavy traffic conditions, the IP network remains operational and can exchange data packets between the PMU router and the PDC router. The series-parallel model for the shared synchrophasor communication network is as shown in Fig. 3 (b). If F_{RO} indicates the failure probability of router, then the hardware reliability 'P_{sha}' for the shared synchrophasor network can be calculated using the eq. (5). Moreover, no additional equipment is needed to establish the communication link.

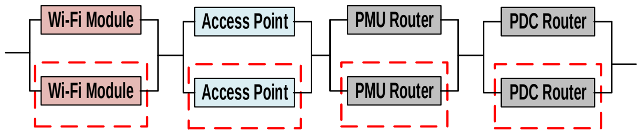
$$P_{Sha} = 1 - 2F_{RO}^2 . \tag{5}$$

The hybrid SCNs require a Wi-Fi to connect the PMU to the access point. The communication link depends on the probability with which the Wi-Fi, access point, PMU router and PDC router remains available. As with the case of the shared networks, it is assumed that the IP network can provide a data path between the PMU and the PDC routers under all traffic conditions. The series-parallel model for the corresponding network is shown in Fig. 3 (c). If F_W, and F_A indicates the failure probability of Wi-Fi module and access point respectively, then the hardware reliability 'P_{hyb}' is given by the equation (6). Moreover, the only additional cost needed to establish a hybrid network is the cost of the Wi-Fi module.

$$P_{Hyb} = 1 - F_W^2 - F_A^2 - 2F_{RO}^2 , \tag{6}$$



(a) (b)



(c)

Fig. 3 – Reliability Models for SCNs: a) dedicated; b) shred; c) hybrid.

3.2 DATA RELIABILITY

The reliability of data received by the PDC is another important aspect that has to be taken into account. When the communication networks are shared by many applications, all the packets transmitted by the PMU may not be received by the PDC and the data reliability can be measured in terms of its packet delivery ratio (PDR), which is given by:

$$\text{PDR} = \frac{\text{Packets received by the PDC}}{\text{Packets transmitted by the PMU}} . \tag{7}$$

4. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In a power system, it is not essential to place PMUs on every bus to observe the entire power grid. By placing the PMUs at optimal locations, it is possible to obtain the phasor measurements of all the buses. This is known as the optimal PMU placement problem, which is comprehensively studied in the literature [30-33]. Several methods have been proposed for solving this problem and simplest of all is the integer linear programming (ILP) method [33].

A power system consisting of 'k' buses can be indicated using a connectivity matrix 'N' whose elements are given by the eq. (8). Another matrix 'P' is used to indicate the location of the PMUs in the network. The elements of this matrix are given by the eq. (9).

$$n_{ij} = \begin{Bmatrix} 1 & \text{if bus } i \text{ has a PMU} \\ 0 & \text{if bus } i \text{ has no PMU} \end{Bmatrix} , \tag{8}$$

$$p_i = \begin{Bmatrix} 1 & \text{if bus } i \text{ has a PMU} \\ 0 & \text{if bus } i \text{ has no PMU} \end{Bmatrix} . \tag{9}$$

The minimum number PMUs with which the entire power system can be observed is now formulated as an ILP problem as given by:

$$N_{\min} = \min\left(\sum_{i=1}^{k} p_i\right) , \tag{10}$$

subject to the observability constraint $NP \geq [1 \quad 1 \quad \dots \quad 1]^T_{(k\times 1)}$

So, the SCNs are required for communication between the PMUs placed at these optimal locations and the PDC. To analyze the various SCNs, an Indian power grid for the West Bengal state comprising of 24 buses has been considered. Its single line diagram (SLD) is shown in Fig. 4 and the information pertaining to these buses is given in [23]. The ILP based method is implemented in MATLAB and is used for finding the locations of the PMUs for the case study of West Bengal's power grid and these locations are indicated by red colored buses in Fig. 4. The optimal locations of the PMUs and their geographical coordinates are shown in Table 4.

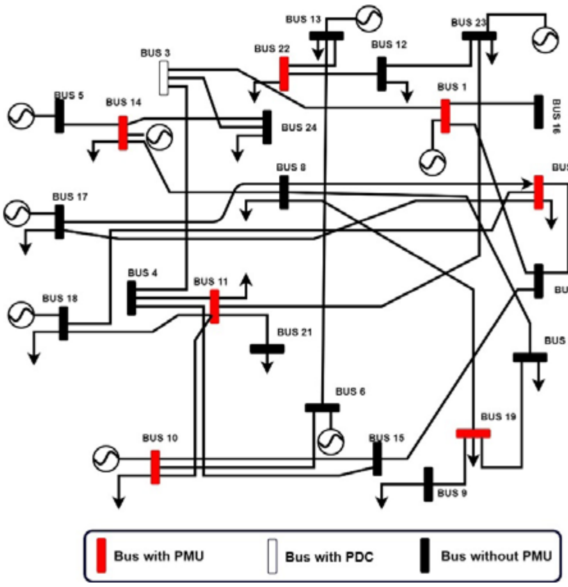


Fig. 4 – The power grid of West Bengal.

Table 4

Location of PMUs and the PDC

Location	Device	Latitude (ºN)	Longitude (ºE)	Distance from PDC [km]
Bus 1	PMU I	24.7828	87.9041	154.11
Bus 7	PMU II	22.7494	88.5417	141.03
Bus 10	PMU III	22.4442	87.8672	124.07
Bus 11	PMU IV	22.8361	87.9594	90.78
Bus 14	PMU V	22.3997	88.2177	145.61
Bus 19	PMU VI	22.1188	88.3319	177.71
Bus 22	PMU VII	25.8502	87.8500	265.57
Bus 3	PDC	23.4814	87.4464	0

These devices are placed at their respective geographical coordinates and their SCNs were constructed for different scenarios and for varying data rates using the commercially available QualNet 5.2 network simulator software.

4.1. ANALYSIS OF DEDICATED SCNS

Dedicated networks were constructed in the QualNet referring to the latitudes and longitudes of the PMUs and the PDC shown in Table 4. Each PMU is connected to PDC via a full-duplex dedicated link of bandwidth 10 Mbps as shown in Fig. 5 and the simulation runtime has been taken as 600s which is equivalent to approximately 90 minutes of real-time. The number of repeaters needed by these networks, their hardware reliabilities and approximate cost are shown in Table 5. The ETDs and PDRs for various data rates were obtained from the simulation results and are reported in Table 6.

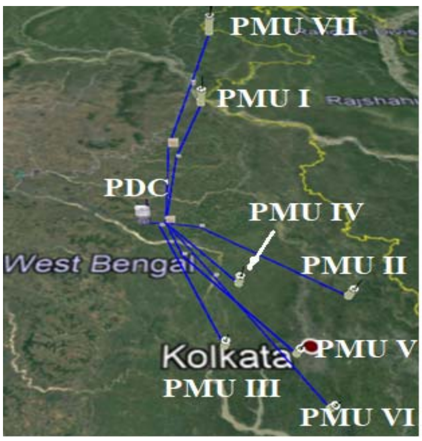


Fig. 5 – Dedicated SCNs for power grid of West-Bengal.

Table 5

Hardware reliabilities of dedicated synchrophasor networks

Dedicated IoT network between PDC and	Repeaters required	Hardware reliability	The cost in million USD
PDC and PMU I	1	0.999999959904	1.854
PDC and PMU II	1	0.999999959904	1.697
PDC and PMU III	1	0.999999959904	1.493
PDC and PMU IV	0	0.999999959968	1.092
PDC and PMU V	1	0.999999959904	1.752
PDC and PMU VI	1	0.999999959904	2.137
PDC and PMU VII	2	0.99999995984	3.193

Table 6

ETD and PDR for dedicated synchrophasor networks

PMU	PMU Data Rate					
	64 Kbps		150 Kbps		300 Kbps	
	PDR	ETD (msec)	PDR	ETD (msec)	PDR	ETD (msec)
PMU-I	1	0.130	1	0.130	1	0.130
PMU-II	1	0.149	1	0.149	1	0.149
PMU-III	1	0.139	1	0.139	1	0.139
PMU-IV	1	0.101	1	0.101	1	0.101
PMU-V	1	0.111	1	0.111	1	0.111
PMU-VI	1	0.120	1	0.120	1	0.120
PMU-VII	1	1.199	1	1.199	1	1.200

From the above tables, it can be observed that dedicated synchrophasor networks have high hardware reliability. As the networks are dedicated, none of the data packets are lost and thus, the PDR is unity i.e., 100%. Also, the ETDs are very low and the main cause of the delay is the propagation time. However, the cost of these networks are very high and the communication bandwidth is wasted as the data rate of PMUs for even all synchrophasor applications cumulatively can reach up to 456.4 Kbps (from Table 1), which is only 4.56% of the allotted channel bandwidth.

4.2. ANALYSIS OF SHARED SCNS

In the shared scenario, each PMU is connected to a particular LAN which is connected to the PDC via shared IP networks. The PMU is connected to the LAN using Ethernet cable and two LANs are connected using the duplex link of bandwidth 10 Mbps which is estimated to handle the traffic effectively as discussed earlier. This link carries background traffic corresponding to the other applications that share the IP network. This scenario is shown in Fig 6. The LAN on which the PMU is located is also shared by other local devices that generate variable traffic which is also depicted in Fig 6. The hardware reliability of these shared synchrophasor networks obtained using the eq. (5) is 0.999999955, which is similar to the hardware reliability of the dedicated synchrophasor networks.

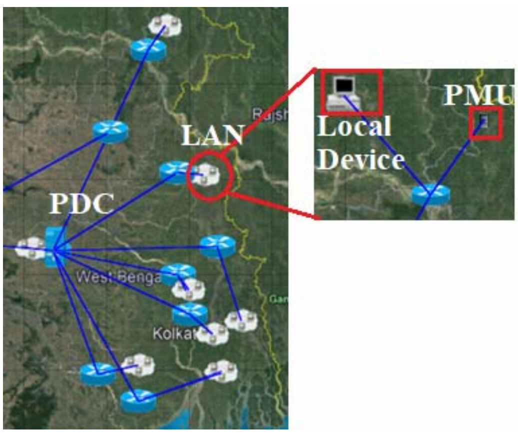


Fig. 6 – Shared SCNs for power grid of West-Bengal.

The quality of service (QoS) is measured in terms of ETD and PDR. The ETDs and PDRs are obtained for PMU data rates of 64 Kbps, 150 Kbps and 300 Kbps with the local devices generating a traffic of 2 Mbps and 0% background traffic in the IP networks. These results are shown in Table 7.

Table 7

Shared synchrophasor networks with 2 Mbps local device traffic

	PMU Data Rate with local device traffic of 2 Mbps					
	64 Kbps		150 Kbps		300 Kbps	
PMU	PDR	ETD (msec)	PDR	ETD (msec)	PDR	ETD (msec)
PMU-I	1	0.388	1	0.593	1	0.596
PMU-II	1	1.489	1	1.764	1	1.765
PMU-III	1	0.305	1	0.594	1	0.596
PMU-IV	1	1.090	1	1.089	1	1.089
PMU-V	1	0.495	1	0.822	1	0.825
PMU-VI	1	0.598	1	0.850	1	0.852
PMU-VII	1	1.867	1	1.898	1	2.012

From the results shown in Table 7, it can be seen that the performance of the shared IoT networks with 0% background traffic (excluding the traffic generated by the local devices) is almost similar to that of the dedicated networks. The increase in the ETD is due to the increase in the queuing time due to the traffic generated by the local devices. Most importantly, the processing time and queuing delay is completely random and thus, may vary for each router. Thus, when the traffic in the networks is less, then the shared synchrophasor networks perform similar to the dedicated networks w.r.t PDR and ETD metrics with the advantage that no additional cost is required for constructing these networks. Moreover, since the PMU and local devices together generate traffic lower than the bandwidth of the communication link, no significant reduction in the QoS is observed.However, in practical cases, the IP network has some background traffic and in order to analyze its effects, the shared synchrophasor networks are simulated for varying background traffic. The results with varying background traffic are reported in Table 8. The PMU data rate is taken as 64 Kbps and the local devices are generating traffic at 1 Mbps.

Table 8

ETD and PDR for 64 Kbps PMU data with background traffic

PMU	95% Background Traffic		80% Background Traffic		70% Background Traffic	
	PDR	ETD (msec)	PDR	ETD (msec)	PDR	ETD (msec)
PMU-I	0.717	1864.67	1.0	3.102	1.0	2.926
PMU-II	0.717	1864.33	1.0	2.667	1.0	2.492
PMU-III	0.710	1850.84	1.0	2.766	1.0	2.588
PMU-IV	0.717	1864.55	1.0	2.928	1.0	2.753
PMU-V	0.714	1859.87	1.0	3.674	1.0	3.495
PMU-VI	0.717	1864.51	1.0	2.840	1.0	2.665
PMU-VII	0.710	1851.02	1.0	3.025	1.0	2.847

From the results shown in Table 8, it can be observed that even with 80% background traffic the shared IoT networks provide reliable performance. However, increasing the background traffic beyond 95% significantly increases the queuing time as well as processing delay at the intermediate nodes, and also reduces the PDR. Thus, during peak traffic conditions, the shared synchrophasor networks have low data reliability. To further understand the effect of background traffic on high data rate synchrophasor applications, the shared synchrophasor networks are simulated for varying background traffic with the PMU data rate as 300 Kbps and the local device traffic rate of 2 Mbps. These results are shown in Table 9.

Table 9

ETD and PDR for 300 Kbps PMU data with background traffic

PMU	90% Background Traffic		80% Background Traffic		70% Background Traffic	
	PDR	ETD (msec)	PDR	ETD (msec)	PDR	ETD (msec)
I	0.6371	1443	0.9998484	3.050	0.9998484	2.854
II	0.6371	1442	0.9998484	2.669	0.9998484	2.473
III	0.3770	1325	0.9998484	2.874	0.9998484	2.649
IV	0.6367	1442	0.9998484	2.903	0.9998484	2.708
V	0.5258	1407	0.9997726	21.12	0.9998484	19.68
VI	0.6371	1442	0.9998484	2.816	0.9998484	2.621
VII	0.3773	1326	0.9998484	3.079	0.9998484	2.854

From Table 9, it can be observed that even with 70% background traffic there is a significant reduction in the data reliability. Thus, shared SCNs are not reliable for high data rate synchrophasor applications particularly during peak traffic conditions. In certain cases, the ETD appears to decrease when compared with the previous simulation scenario, which is due to the increase in the number of dropped packets which can be corroborated from the reduced PDR. For high data rate applications or during peak traffic conditions a simple methodology of increasing the data reliability while using shared SCNs is to reduce the local data generated by the devices located on the same LAN as the PMU. A complex alternative to improve the QoS during the peak traffic is to enable the prioritize the PMU data over the local device data. This ensures better QoS during peak traffic hours.

4.3. ANALYSIS OF HYBRID SCNS

In the hybrid network, the PMU is located on a WLAN. A WLAN consisting of PMU is connected to the backbone network using a shared bus topology to facilitate data transmission from PMU to the PDC through its edge router. The WLAN consists of an AP through which the devices in the LAN communicate with the edge router. The WLAN consists of other local devices which are wirelessly connected to the AP. The hybrid synchrophasor network for the proposed case study is shown in Fig. 7. The WLAN also consists of other local devices that are connected to the AP along with the PMU, and the scenario is also depicted in Fig 7.

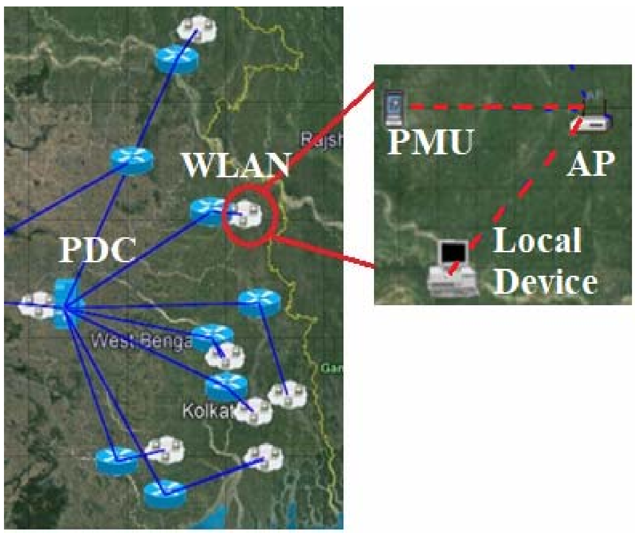


Fig. 7 – Hybrid SCNs for power grid of West-Bengal.

The hardware reliability of the hybrid synchrophasor networks obtained using the eq. (6) is 0.999999954024, which is comparable to the hardware reliability of the dedicated synchrophasor networks and shared synchrophasor networks.

For evaluation of hybrid SCNs, PMU data rates of 64 Kbps and 300 Kbps are considered. The data rates of the local devices are taken to be 64 Kbps, 150 Kbps and 300 Kbps, in order to provide a comparative analysis. The ETD and PDR corresponding to three different cases with constant PMU data rate of 64 Kbps and 300 Kbps are reported in Table 10 and Table 11 respectively.

Table 10

ETD and PDR for Hybrid SCNs with 64 Kbps PMU Data

PMU	Local Device at 64 Kbps		Local Device at 150 Kbps		Local Device at 300 Kbps	
	PDR	ETD (msec)	PDR	ETD (msec)	PDR	ETD (msec)
I	0.998934	16.507	0.776909	26.387	0.773357	29.345
II	0.997158	15.645	0.784725	17.589	0.780817	19.761
III	0.998934	14.175	0.803197	17.578	0.799645	18.995
IV	0.999290	14.122	0.808526	17.021	0.796092	17.897
V	0.999290	14.818	0.777620	19.378	0.750622	22.001
VI	0.999645	16.391	0.799290	27.468	0.796448	29.886
VII	0.999645	17.103	0.886679	28.132	0.888455	30.397

Table 11

ETD and PDR for Hybrid SCNs with 300 Kbps PMU Data

PMU	Local Device at 64 Kbps		Local Device at 150 Kbps		Local Device at 300 Kbps	
	PDR	ETD (msec)	PDR	ETD (msec)	PDR	ETD (msec)
I	0.998934	17.201	0.76891	26.156	0.75125	39.598
II	0.997158	16.231	0.77373	17.894	0.76537	32.698
III	0.998934	15.871	0.80221	17.756	0.79568	33.876
IV	0.999290	15.981	0.80122	17.897	0.79991	31.367
V	0.999290	16.332	0.77218	19.985	0.76502	35.672
VI	0.999645	17.001	0.79929	28.371	0.79645	40.986
VII	0.999645	19.297	0.87348	29.012	0.87351	43.256

From Table 10 and Table 11, it can be observed that the data reliability of hybrid SCNs is lower than the other two. Even with the local devices generating only 64 Kbps of data, there is a considerable reduction in the data reliability and increase in the ETD. This is because of the wireless environment and increased packet collision to access the channel. Thus, the hybrid networks are employed only when the PMUs are located in remote locations and wired communication is not feasible. Moreover, one should use these networks for low data rate synchrophasor applications with the local devices generating traffic at lower data rates.

The ETD for the three different SCNs with the PMU data rate of 64 Kbps (low data rate applications) is shown in Fig8. The shared synchrophasor networks have local device generating data at 2 Mbps and background traffic of 70% while the hybrid networks have local devices generating traffic at 64 Kbps. Similarly, the ETDs for the high data rate applications are shown in Fig 9. For the comparison the PMU data rate is taken as 300 Kbps with background traffic at 90% for shared synchrophasor networks and local device data rate of 2 Mbps.

Thus, in terms of reliability and latency the dedicated communications networks offer good performance for all synchrophasor applications. Shared SCNs are cost effective and can provide reliable performance for low data rate applications. During peak traffic conditions for high data rate applications, there is a significant decrease in the data reliability and increase in the latency. Finally, the hybrid SCNs are to be employed when the PMUs are remotely located and for low data rate synchrophasor applications.

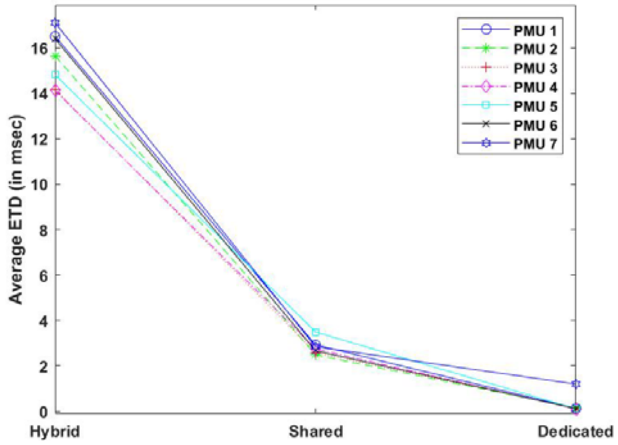


Fig. 8 – Comparison of ETDs for low data rate applications.

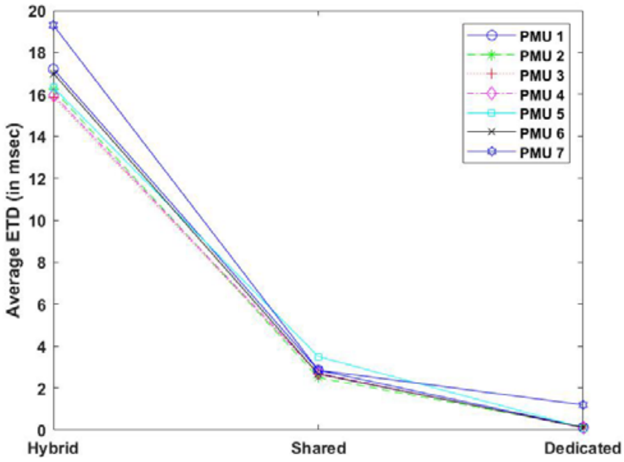


Fig. 9 – Comparison of ETDs for high data rate applications.

5. CONCLUSION AND FUTURE SCOPE

Communication networks play a significant role in realizing the complete forte of the envisioned SG. This paper presents the reliability analysis of low latency SCNs for synchrophasor applications in an SG. Both hardware reliability and data reliability are obtained for the various communication networks. The three communication networks have almost similar hardware reliability but their data reliability differ in terms of the network parameters. The dedicated networks have unity data availability irrespective of the PMU data rates but the infrastructure cost is very high. Shared SCNs perform well when the background traffic is low. However, for peak traffic conditions their performance degrades and their reliability reduces. Finally, the hybrid networks are the least reliable and are to be used only when the PMU data cannot be communicated via the wired channel. The authors intend to investigate novel protocols for shared synchrophasor networks such that they offer reliable performance even during peak traffic conditions.

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