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A review on synchrophasor communication system: communication technologies, standards and applications

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Abstract

The present-day power system is a complex network that caters to the demands of several applications with diverse energy requirements. Such a complex network is susceptible to faults caused due to several reasons such as the failure of the equipment, hostile weather conditions, etc. These faults if not detected in the real-time may lead to cascading failures resulting in a blackout. These blackouts have catastrophic consequences which result in a huge loss of resources. For example, a blackout in 2004 caused an economic loss of 10 billion U.S dollars as per the report of the Electricity Consumers Resource Council. Subsequent investigation of the blackout revealed that the catastrophe could have been prevented if there was an early warning system. Similar other blackouts across the globe forced the power system engineers to devise an effective solution for real-time monitoring and control of the power system. The consequence of these efforts is the wide area measurement system (WAMS). The WAMS consists of several sensors known as the phasor measurement units (PMUs) that collect the real information pertaining to the health of the power grid. This information in the form time synchronized voltage and current phasors is communicated to the central control center or the phasor data concentrator (PDC) where the data is analyzed for detection of power system anomalies. The communication of the synchrophasor data from each PMU to the PDC constitutes the synchrophasor communication system (SPCS). Thus, the SPCS can be considered as the edifice of the WAMS and its reliable operation is essential for the effective monitoring and control of the power system. This paper presents a comprehensive review of the various synchrophasor communication technologies, communication standards and applications. It also identifies the existing knowledge gaps and the scope for future research work.

Keywords: Phasor measurement unit, Wide area measurement system, Synchrophasor communication system, Communication standards, Communication technologies, Optimal placement

1 Introduction

The modern-day power grid aims at providing reliable and quality power, which requires careful monitoring of the power grid against catastrophic faults [1]. The Phasor Measurement Unit (PMU) based Wide Area Measurement System (WAMS) was instituted for providing the time synchronized measurements pertaining to the health of the power system [2]. The timely detection of the faults and the subsequent contingency measures are not only dependent on the PMU but also on the underlying synchrophasor communication system (SPCS) [3]. It is analogous to the nervous system in the body. Just as the nervous system connects the various sensory organs to the brain and enables the interaction between them, the SPCS connects the PMUs to the Phasor Data Concentrator (PDC) or to the control center resulting in the exchange of data and control commands. Hence, the SPCS is considered as the edifice of the WAMS. The researchers have explored several PMU based monitoring and control schemes with the assumption that the underlying communication system is inherently capable of meeting the desired performance requirements. However, the subject matter of the SPCS is relatively less explored as compared with that of the

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PMU and this fact can be corroborated by a year wise comparative publication statistics illustrated in Fig. 1. It is observed that the literature on SPCS is very sparse and less than 10% of the published articles on PMU are related to the SPCS. In this regard, the chapter provides a comprehensive review of the various important pertaining to the SPCS that are available in the literature. These works are classified into the following topics and the topic-wise distribution of major works published in this context is shown in Fig. 2.

1. Synchrophasor communication standards.
2. Communication requirements for various WAMS applications.
3. Communication schemes for various WAMS applications.
4. Wide area control incorporating communication system parameters.
5. Reliability analysis of the SPCS.
6. Optimal placement of PMUs and their communication infrastructure.
7. Software-Defined Networking (SDNs) for PMUs

1.1 Evolution of communication technologies in power system

In the initial stages, the power system was very simple. The size of the system was small and the generating stations were mostly located nearby the load centers. The monitoring and control of the system were achieved based on the observation and judgment of the system operators. The control instructions were exchanged via verbal communication. By the mid of the 20th the size and complexity of the power systems increased enormously. The load centers were no longer located in the proximity of the generating stations and hence the need for communication systems for faster exchange of control information was realized. Supervisory control and data acquisition (SCADA) systems were developed to achieve the monitoring and control. Even at this stage, the number of stations was limited and hence telephone lines were primarily used for the purpose of data exchange [4].

However, with the increase in demand for electricity and the geographically distributed nature of the power system elements exacerbated the need for more sophisticated monitoring and control mechanisms. Huge amounts of data were to be measured at the load centers continuously and processed in real time to obtain meaningful interpretations of the health of the power system, thereby allowing the power system operator to execute appropriate control actions. Minicomputers and microprocessors were used for the purpose of obtaining the status regarding the power system. Powerline communication (PLC) systems were set up to enable the communication between the stations and the control centers. Information pertaining to the voltage, frequency, power flow, circuit breakers, isolators, etc. was measured at the station in cycles of every few seconds and was sent to the control center for continuous monitoring.

The synchronization of regional power grids led to the establishment of a national grid. The establishment of a national grid increased the complexity of the power system. In addition, the increase in the use of renewable sources of energy with their unpredictable nature presents a serious challenge for the monitoring of the system. In the early 80s PMUs were developed for effective real-time monitoring of such a large network. PMUs are capable of providing fine-grained measurements pertaining to the power system dynamics but they also require high speed, reliable and secure communication systems. These factors led to a drastic increase in the communication needs of the power system. The evolution of the communication needs in the power system for the purpose of monitoring and control goes hand in hand with the evolution of the measurement technology. The evolution of communication technologies in the power system is depicted in Fig. 3 [4].

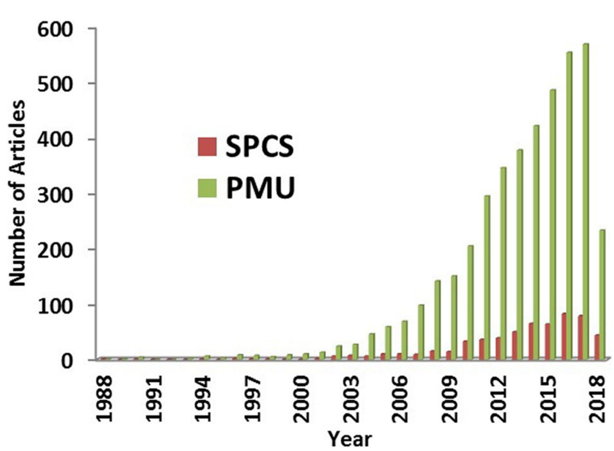

Fig. 1 Year-wise publication comparison

1.2 Functions of a communication network in a power system

The important functions of communication networks in a power system are listed below.

(a) The most important function of the communication system is to facilitate the real-time detection of faults and to facilitate the implementation of the appropriate control actions thereby ensuring the stable operation of the power system.
(b) Optimization of the power flow through real-time economic load dispatch.

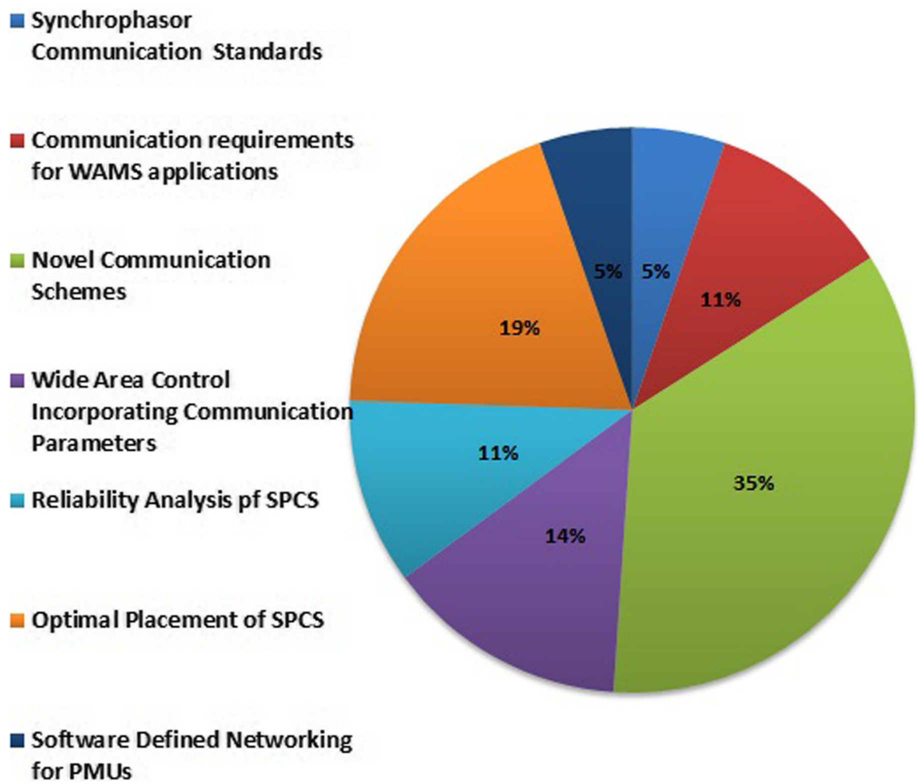

Fig. 2 Topic-wise distribution of literature on SPCS

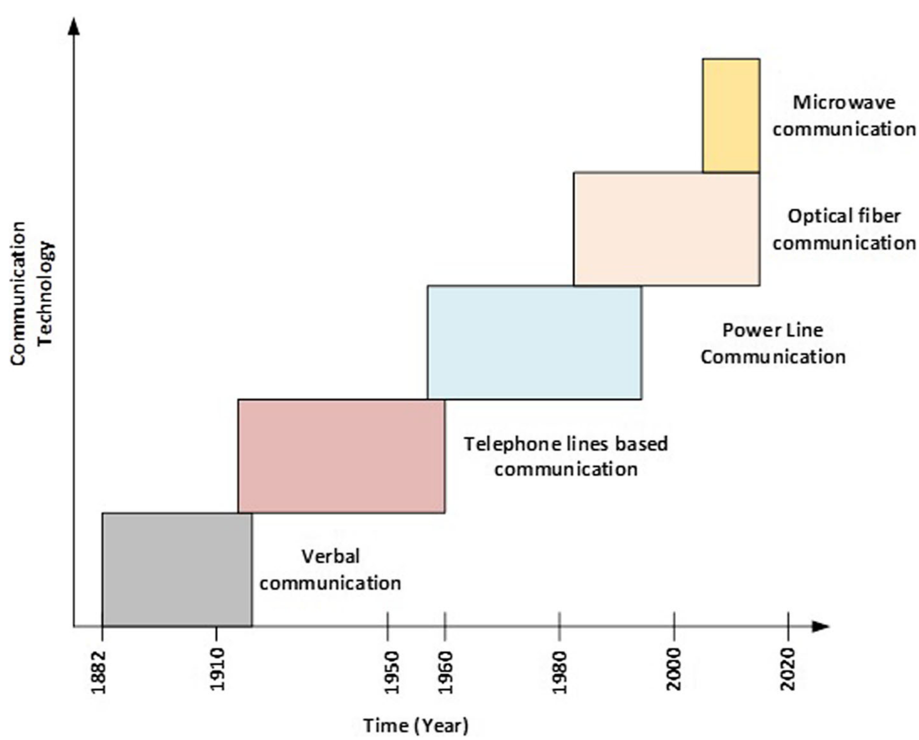

Fig. 3 Evolution of communication technologies in power system

(c) Wide area protection schemes for the various generating sources and transmission infrastructure.

Security and reliability are the most important requirements of a communication system. The data flowing through the communication system should be inaccessible to unauthorized agents and the failure rate of the communication infrastructure should be as low as possible in order to facilitate the implementation of real-time monitoring and control actions.

1.3 Organization of the paper

This paper presents a comprehensive review of the communication system for synchrophasor applications and is organized into five sections. To better appreciate the importance of the SPCS a brief description of the WAMS is given in the second section. This section also describes the various synchrophasor communication technologies. The synchrophasor communication standards are described in the third section. All the PMUs and the PDCs manufactured by various vendors have to comply with these standards for the exchange of data.

The communication network architecture, the location of the infrastructure and the quality of service has to be assessed for effectual operation of the WAMS. Researchers have proposed network architectures and have created simulation models for evaluating the performance of the practical SPCS. These various contributions are reviewed in the fourth section. The other aspects of SPCS that have received the attention of the researchers are the optimal placement of the PMU communication infrastructure and software-defined networking for PMUs. These works are separately discussed in the fifth and sixth sections respectively. The last section identifies the knowledge gaps and the potential challenges that can act as an inspiration for future research.

2 A brief description of the WAMS

In the past few decades, the PMU has carved its niche as an important sensor for estimating the state of the power system [5]. The PMUs are installed at the electrical nodes, which are usually separated by large geographical distances. The measurements from several such PMUs are reported to the local PDC. Data from several such local PDCs may be passed on to a regional PDC which is on a higher level in the hierarchy. The PMUs, the PDCs and the SPCS together constitute the WAMS and a typical WAMS is illustrated in Fig. 4.

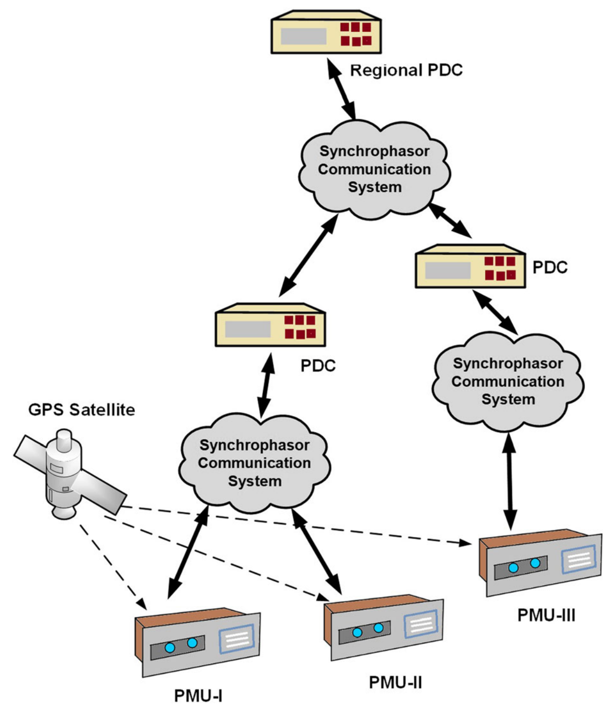

Fig. 4 A typical WAMS systems with communication hierarchy

The IEEE defines the PMU as “a device that produces synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal”. Thus, the PMU is a digital signal processing unit that can calculate the voltage phasor and current phasor, time synchronizes these phasors and communicates them to the PDC. Time synchronization is achieved with the aid of the timing signals received from the Global Positioning System (GPS) satellites. The various constituent components of the PMU are depicted in the block diagram illustrated in Fig. 5 [6].

The current and potential transformers located in the power system network provide the current and voltage measurements to the PMU in the form of analog inputs required for digital processing. To prevent the aliasing of the sampled signals, the inputs are fed through an anti-aliasing filter that limits the bandwidth of the input analog signal as per the requirements. The output of the anti-aliasing filter is further fed to an analog to digital (A/D) converter for converting it into the desired digital output which is fed into a central processing unit (CPU). The CPU computes the magnitude and the phase of the input signal using the DFT technique and time synchronizes the data using a sampling clock that is phase locked to the one-pulse-per-second provided by the GPS receiver. As the signal is time stamped, it is transmitted from the PMU to the PDC through the synchrophasor communication network.

The key communication technologies, for synchrophasor data transfer, can be broadly classified into two categories: wired and wireless [7]. The wired communication technology offers high reliability, huge bandwidth and protection against interference [8, 9]. On the other hand,

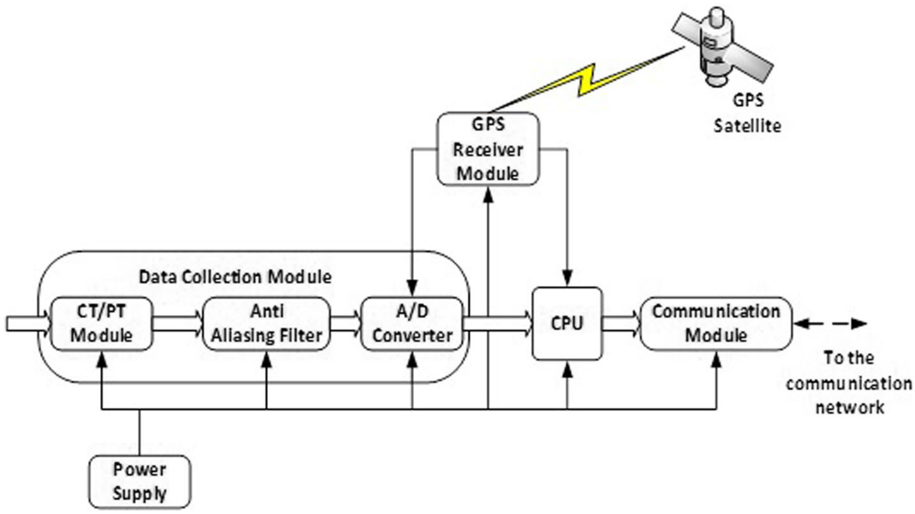

Fig. 5 The various functional blocks in the PMU

wireless technology enjoys superiority in terms of rapid deployment, low installation and maintenance costs, access to remote geographic locations, etc. The various synchrophasor communication technologies are depicted in Fig. 6.

2.1 Power line communication for Synchrophasor data transfer

This power line communication (PLC) uses the existing power line cables for the transfer of synchrophasor data [10]. As there is no need for additional communication infrastructure, this technology provides the fastest and economical means for the deployment of communication networks. There are two types of PLC technologies: Narrow Band PLC (NB-PLC), which is for low bandwidth applications and Broad Band PLC (BB-PLC), which is for applications requiring higher bandwidth. As the synchrophasor application is mission critical, BB-PLC would be the preferred choice. Typical data rates ranging from 2 to 3 Mbps can be achieved using this technology. The use of this communication technology for synchrophasor applications can be understood from Fig. 7.

In spite of having several advantages, the technology suffers from many disadvantages such as the difficulty in modeling the communication channel due to the noisy background in the power cables. Moreover, the PLC is not meant for high bandwidth applications due to fading and interference. The signal to noise ratio (SNR) is low and this technology is usually combined with other communication technologies, such as cellular communication, to provide a hybrid solution for power grid communications.

2.2 Optical Fiber-based Synchrophasor communication system

The benefits of optical fibers for long-distance communication has been known to the communication engineers since the early 1990s. The practical use of these fibers for communication gained momentum in the early 2000s due to a substantial reduction in the cost of the cables and improvement in their quality. The high data rates, low attenuation, high reliability and negligible interference

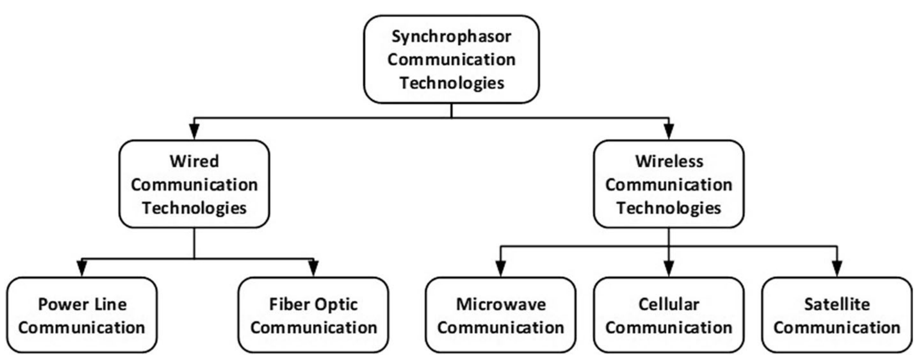

Fig. 6 The various synchrophasor communication technologies

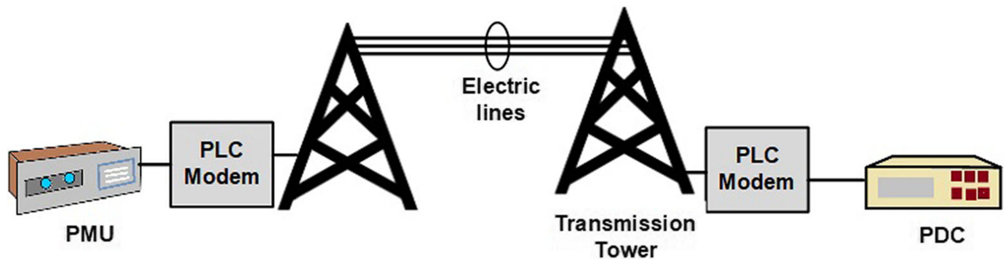

Fig. 7 PLC for Synchrophasor Data Transfer

made them a widely used synchrophasor communication technology [11]. They also have applications in substation automation, tele-protection, tele-control, vehicle to grid communications, etc. A typical fiber optic SPCS is shown in Fig. 8.

The data received from the PMU is converted into an optical signal by the optical transmitter, which is basically a light emitting diode or a laser. These optical signals are then carried via the optical fibers to the PDC. At the PDC, the optical signal is converted back into electrical signals using a photodiode. Between the PMU and the PDC, optical repeaters are placed at regular intervals to boost the signal strength and to maintain the signal quality.

This technology even though widely adopted for synchrophasor data transfer is still plagued by several problems that are common to the other wired communication technologies. The installation cost is very high and substantial time is required to lay and erect the communication infrastructure. Moreover, it is also difficult to install the cables in hilly or rocky terrain.

2.3 Cellular communication for Synchrophasor data transfer

Due to the high proliferation of the wireless communication infrastructure, cellular communication technology provides another viable alternative for synchrophasor data transfer [11, 12]. It is one of the fastest growing technologies in the world and the research is already in progress to achieve data rates of 100 Gbps per user. The different cellular technologies that can cater to the demands of the synchrophasor application are shown in Table 1. Even though this technology can cater to the demands of the synchrophasor application in terms of the data rate requirements, the shared nature of this technology makes it unacceptable for mission-critical applications that require uninterrupted communication services. The cellular technology based SPCS is illustrated in Fig. 9.

2.4 Satellite communication for Synchrophasor data transfer

Satellite communication technology has undergone tremendous growth over the past few decades. The uniqueness of this technology is that the communication equipment is located in space. Thus, this technology is unaffected by natural disasters such as floods, earthquakes, etc. It consists of two different segments: the earth segment and the space segment. The space segment consists of the satellites and the ground facilities that are responsible for Tracking Telemetry and Control (TT&C). The earth segment consists of transmitting and receiving earth stations. This technology can be used for the transfer of synchrophasor data when the end equipment is separated by several hundred kilometers. However, the major disadvantage for synchrophasor application is that communication delay is higher compared to any other technology and is seldom used [12]. The satellite-based SPCS is shown in Fig. 10.

2.5 Microwave-based Synchrophasor communication system

Microwave communication is another wireless communication technology that can cater to the demands of the synchrophasor applications [12]. With the growth of wireless technology, data rates in the order of several Gbps are being achieved. Thus, this technology provides a viable alternative to the optical fiber SPCS, as it has

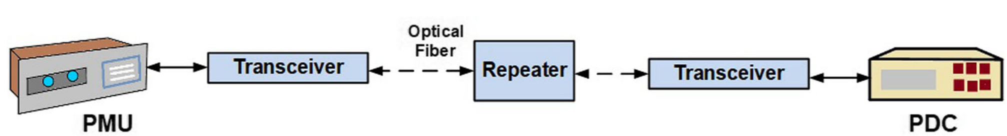

Fig. 8 Optical Fiber Synchrophasor Communication System

Table 1 Cellular Technologies for Synchrophasor Applications

Technology	Data Rates
General Packet Radio Service (GPRS)	Up to 114 Kbps
Enhanced Data rates for GSM Evolution (EDGE)	Up to 384 Kbps
Universal Mobile Telecommunications System (UMTS)	Upto 2 Mbps
High-Speed Packet Access (HSPA)	600 Kbps – 10 Mbps
Long Term Evolution-Advanced (LTE-A)	Up to 100 Mbps

several conspicuous advantages which have been presented in section 1.3 of the first chapter. A typical microwave based SPCS is shown in Fig. 11.

In the microwave communication, the synchrophasor data generated by the PMU is fed to a PMU radio terminal that converts the electrical signal into radio frequency (RF) signal. The RF signal is then fed to a microwave antenna that converts the RF signal into an electromagnetic signal. This electromagnetic signal propagates in free space and is received by the microwave antenna at the PDC. The PDC radio terminal converts the RF signal back into the electrical signal, which is sent to the PDC for analysis. Intermediate repeaters are required to maintain the signal strength and to ensure communication feasibility in the case of non-line of sight propagation. The main disadvantage of this technology is that the signal propagates in free space and hence is susceptible to cyber-physical attacks.

The PDC can exchange the data and commands with PMUs and also with other PDCs. It receives data from multiple PMUs, performs a check on the received data, time aligns the data and creates an output stream. It may also provide the power system operator with appropriate visualizations that are needed for monitoring and control.

3 Review of the Synchrophasor communication standards

To standardize the communication of synchrophasors between the devices manufactured by different vendors, IEEE has developed a synchrophasor data transfer standard. This standard defines the method for exchange of synchrophasor data between the PMUs, the PDC and other applications. The initial standard for the synchrophasor measurement was the IEEE Std 1344-1995 [13]. This standard was reaffirmed in the year 2001 and replaced by the IEEE Std C37.118–2005 in the year 2005 [14]. The IEEE Std C37.118–2005 introduced the concepts of compliance testing and Total Vector Error (TVE). It also provided clarification regarding the definitions of the phasor and synchrophasor. The message formats were revised to enhance the exchange of information with other systems. Additional fields were added to the message frames and the existing format was replaced to improve the information exchange. This standard specified both the communication requirements and the measurement requirements. To increase the widespread adoption of this standard, IEEE further split this into two standards: IEEE Std C37.118.1 [15, 16] which defines the synchrophasor measurement requirements and the IEEE Std C37.118.2–2011 [17, 18] which defines the synchrophasor communication requirements. The IEEE Std C.37.118.2–2011 contains all the communication requirements specified in its predecessor standard and an additional configuration frame has been incorporated. The IEEE Std C37.118.2-2011 specifies the message formats for enabling the transfer of synchrophasor data. The

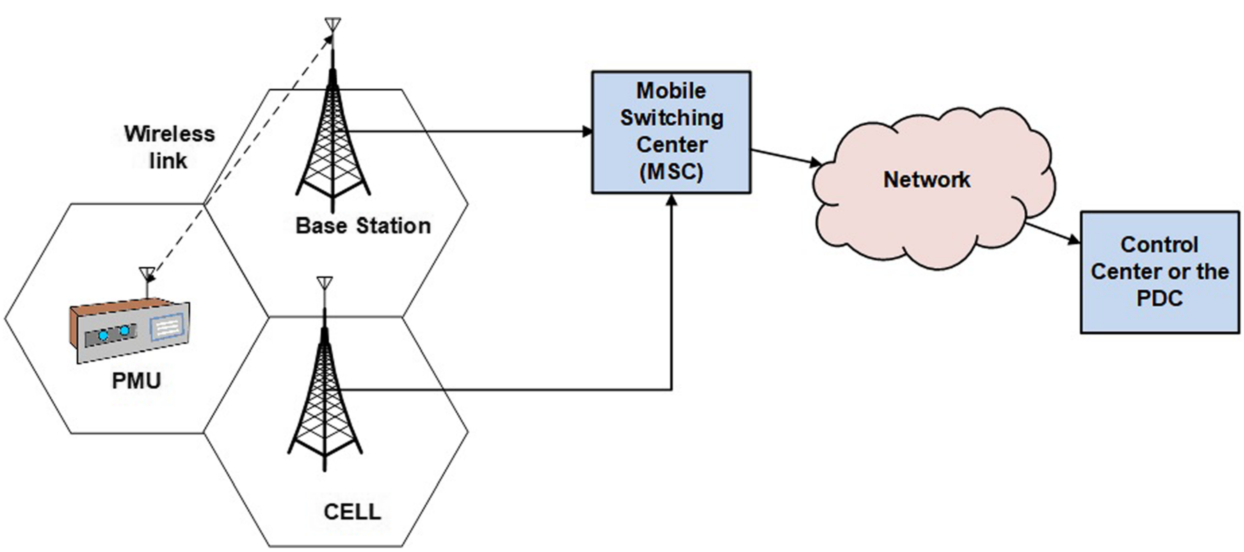

Fig. 9 Cellular Technology Based Synchrophasor Communication System

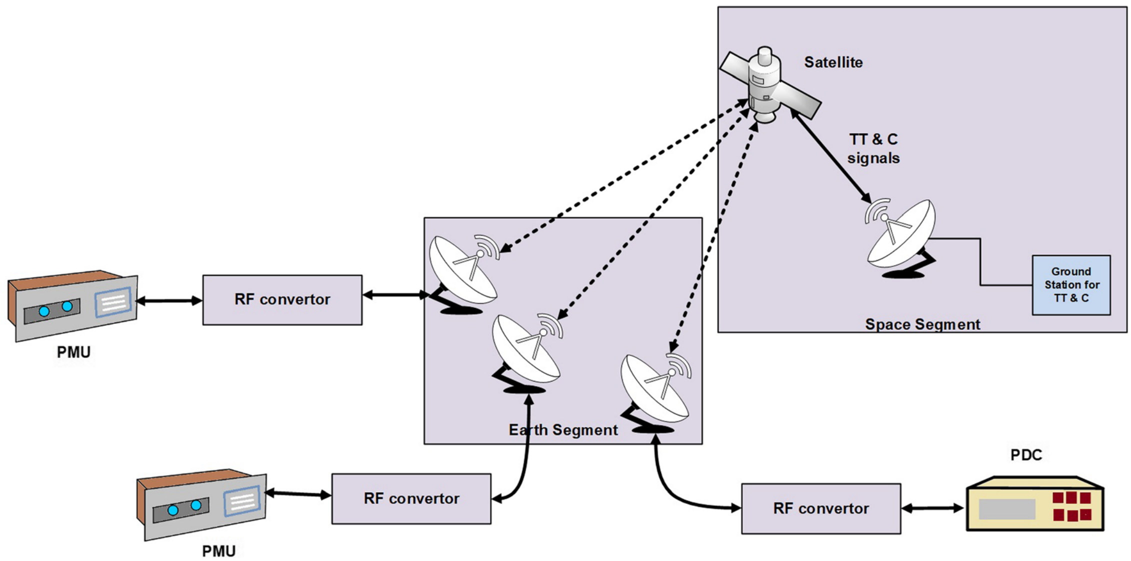

Fig. 10 Satellite-Based Synchrophasor Communication System

document is conceived in six separate clauses, which are summarized below:

Clause 1: Scope and need for the standard
Clause 2: References to the other standards related to the current standard
Clause 3: Defines the terminology found in the standard
Clause 4: Presents the background for synchronized phasor measurements
Clause 5: Describes the synchrophasor measurement system
Clause 6: Describes the communication protocol and message formats

The IEEE C37.118.2-2011 standard defines the message format for the transfer of data between the PMU and the PDC. The various fields of the message frame are shown in Fig. 12 and are briefly described in Table 2.

There are four types of message frames that are exchanged between the PMU and the PDC. These are data, configuration, header and command frames. The first three frames, namely, the data frame, the configuration frame and the configuration frame are sent from the PMU to the PDC. The last frame is the command frame that sent from the PDC to the PMU. A summary of each of these frames is presented in Table 3.

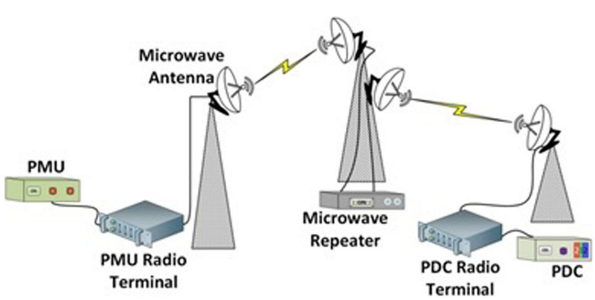

Fig. 11 Microwave Based Synchrophasor Communication System

4 Review of the Synchrophasor communication requirements, communication schemes and their applications

The SPCS consists of equipment that is spread over a large geographical sprawl. Modeling of the SPCS and their subsequent analysis through simulations can provide crucial insights into their performance prior to their physical deployment. A considerable amount of research has gone into areas such as identifying the communication requirements, modeling of the communication networks, analyzing their performance through simulations and developing schemes for enhancing the real-time control of the power system.

4.1 Communication requirements for various WAMS applications

Synchrophasor technology has several applications with varied communication requirements. State Estimation (SE), intelligent load shedding, islanding, wide area System Integration Protection Schemes (SIPS), oscillation

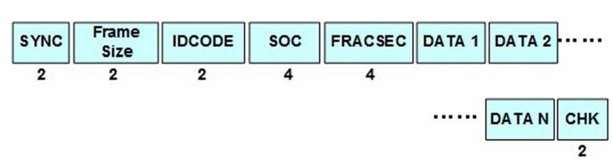

Fig. 12 The Various Fields of the Synchrophasor Message Frame

Table 2 Description of the Various Fields of the Message Frame

Field	Size (Bytes)	Description
SYNC	2	This field marks the beginning of the frame. The first byte is AA (Hex) and the next byte describes the type of the message.
Frame Size	2	This field presents the length of the entire message including the CHK field.
IDCODE	2	This field is used for identifying the data stream.
SOC	4	This field carries the information about the time stamp and is used for time synchronization of measurements.
FRACSEC	4	This field indicates the time at which the measurements are made for data messages and the time at which the frame is transmitted for other messages.
CHK	2	This field marks the end of the message frame and is used to perform the cyclic redundancy check.

control, synchronization, etc. are some of the applications based on synchrophasor technology. The communication requirements for these applications have been theoretically analyzed and are summarized in Table 4 [19]. Further theoretical studies were carried out by Lin et al. to identify the interdependency between the power system applications and the communication infrastructure [20] and, a probabilistic model-based approach was proposed in [21] to obtain the communication delay characteristics in a WAMS. However, these theoretical studies have not been verified through suitable simulation models [22]. Simulation results can provide a realistic perception of the operation of practical communication networks.

Performance considerations for various synchrophasor applications have been identified by Chenine et al. through suitable simulations [23]. They also developed simulation models for the Nordic region and identified the communication requirements in terms of bandwidth and delay [24]. These models consider the communication networks to be dedicated to carrying only the synchrophasor data. However, in practical networks, the communication resources are shared and background traffic exists, which affects the performance of these applications [25, 26]. The dedicated and shared communication networks for synchrophasor applications are shown in Fig. 13.

In dedicated networks, the communication resources are entirely utilized for synchrophasor communication and no other application can utilize these resources. Thus, the source of delay would be the processing delay at the PMU and the propagation delay. Thus, dedicated networks can be used to realize all of the synchrophasor application. Shared networks are economical and can be rapidly deployed. The communication resources are shared by several applications which increases the end-to-end delay and reduces the reliability of the communication network. As the synchrophasor applications are mission-critical, it is desirable to use dedicated communication resources, even though it increases the overall cost of the system.

The performance of the communication networks also depends on the transport layer protocol. The effect of these protocols on the delay characteristics has been carried out by Babazadeh et al. [27] and, in particular, an in-depth study of the communication delay in TCP/IP networks was carried out in [28–30]. TCP/IP is connection-oriented protocol that involves handshaking between the communicating devices. The presence of handshaking reduces the packet loss ratio but increases the end-to-end devices. Synchrophasor applications that require low communication latency should use connectionless protocols like UDP. Using connectionless protocols reduces the communication delay as there is no concept of handshaking. However, this increases the packet loss thereby reducing the reliability. Thus, the choice between reliability and latency must be carefully balanced and the selection of the transport layer protocol should be based on the application requirement.

Table 3 Summary of the IEEE C37.118.2-2011 message frames

Frame Type	Function
Data frame	This contains the real-time synchrophasor data measured by the PMU. It includes an identification header, the length of the message, message source ID, a time stamp, detailed status information regarding the data and its source and quality, frequency, ROCOF and analog and digital quantities.
Header frame	The header frame is sent from the PMU to the PDC to help the PDC identify the sender.
Configuration frame	There are three configuration frames. The first configuration frame *config*1 indicates the data reporting capability of the PMU. The *config*2 and *config*3 indicate the current measurements that are being reported in the data frame.
Command frame	These frames are sent by the data receiving device to the data transmitting device requesting it to start or stop the transmission, to transmit the configuration frame or the header frame.

Table 4 Communication Requirements for WAMS Applications

Application	Communication Delay (msec)	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

4.2 Review of the various Synchrophasor communication schemes and communication architectures

Synchrophasor communication networks for various applications have been proposed in the literature. Communication schemes based on TCP/IP [28, 29, 31], Controller Area Network (CAN) bus [32, 33], 3G [34, 35], LTE [36], optical fiber [37–39], Internet of Things (IoT) [40], Wireless Local Area Networks (WLAN) [41] etc. have been proposed. Apart from these simple communication schemes several other novel methods have been reported in the literature which are summarized in Table 5.

The communication architecture also affects the performance of the WAMS. To analyze this effect Deng and his colleagues have modeled various wide area measurement scenarios and obtained the simulation results. They have observed that most WAMS applications can perform satisfactorily by properly choosing the network architecture and communication protocol [41]. There are two types of network architectures: centralized networks and decentralized or distributed networks. These two architectures differ in terms of network latency, reliability and cost and are shown in Fig. 14.

In the centralized architecture the PMUs report to a single control center. This architecture requires simple communication strategies but it is less reliable than the decentralized architecture especially for large power systems. The failure of communication networks would seriously affect the monitoring capability of the WAMS.

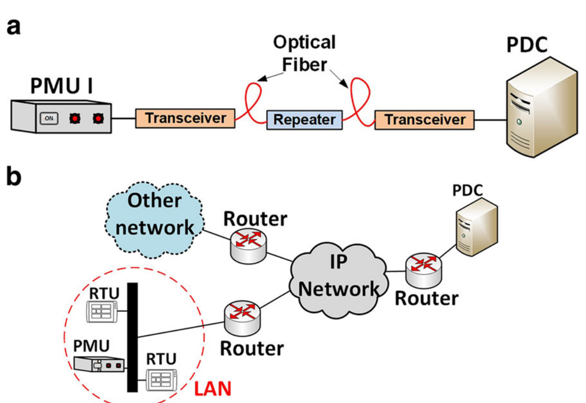

Fig. 13 a Dedicated Communication Network. **b** Shared Communication Network

On the other hand, in the distributed architecture there are several control centers that can coordinate among themselves in implementing the control action. Such networks are more robust to component failures but are more expensive and the communication requirements are complicated. Depending on the WAMS application, the size of the system and the communication requirements, both the network architectures have been incorporated and analyzed by the researchers.

A study on the communication in decentralized networks has been carried out in [42]. This work discusses communication grouping and routing problems in large networks. A decentralized control approach was proposed in [43], where the communication amongst the control centers was implemented using the message-passing interface (MPI) protocol for obtaining the state of the wide area power system. Another novel distributed phasor measurement system and its communication networks were analyzed in [44] for obtaining the dynamic state of the power system. In [45], three different communication architectures were proposed for a decentralized control application where the local control centers can share their estimates obtained from the local PMUs with other control centers to compute the global estimate of the system. These architectures were analyzed for their relative merit with the aid of simulations carried on IEEE 68 bus and IEEE 145 bus systems.

Chenine and Nordström have modeled the centralized communication architecture and obtained the simulation results for various wide area measurement scenarios [46]. Centralized communication architecture has been considered in [47] for obtaining the communication delays in WAMS with the PMUs spread over large geographical separations. A co-simulator has been developed in [48] for simultaneously simulating the power system along with the communication infrastructure. Several communication network architectures have been modeled and simulated using this hybrid approach. Three different communication architectures have been proposed and verified for their relative merits and de-merits through suitable simulations. Another co-simulation platform was proposed in [49] for emulating the power system as well as the communication networks. Using this platform, the impact of communication delays, packet losses and noise in the data on the monitoring and control capabilities of the WAMS was investigated.

4.3 Review of the various methods for wide area control incorporating communication parameters

Another domain that has attracted the attention of the power system engineers is the use of PMU measurements for damping of oscillations. These wide area damping controllers are susceptible to communication delays and packet losses. Several works have been

Table 5 Synchrophasor Communication Schemes

Reference	Contribution
[72]	A multi-protocol label switching aided IP with better performance than the TCP/IP and other transport layer protocols.
[73]	An evolutionary traffic routing algorithm for routing the traffic such that the communication delay is minimized.
[74]	An advanced TCP/IP protocol that minimizes the communication delay by reducing redundant transmissions in the event of packet loss
[75–77]	An internet for synchrophasor applications called as NASPInet developed by the collaborated effort of U.S. Department of Energy (DoE), North American Electric Reliability Corporation (NERC), North American electric utilities and other individuals from industry and academia.
[78]	A co-operative congestion control protocol through coordinated scheduling and bandwidth reassignment for minimizing communication delay and to ensure real-time data transfer. Congestion causes unnecessary packet losses and also increases the wait time. Therefore, minimizing congestion effectively reduces the communication delay.
[79]	A low power communication scheme for secure PMU communications.
[80]	Synchrophasor communication network for hydropower plants.
[81, 82]	Communication networks for generation, substation and control center have been modeled and the performance is evaluated in terms of delay for various bandwidth criteria.

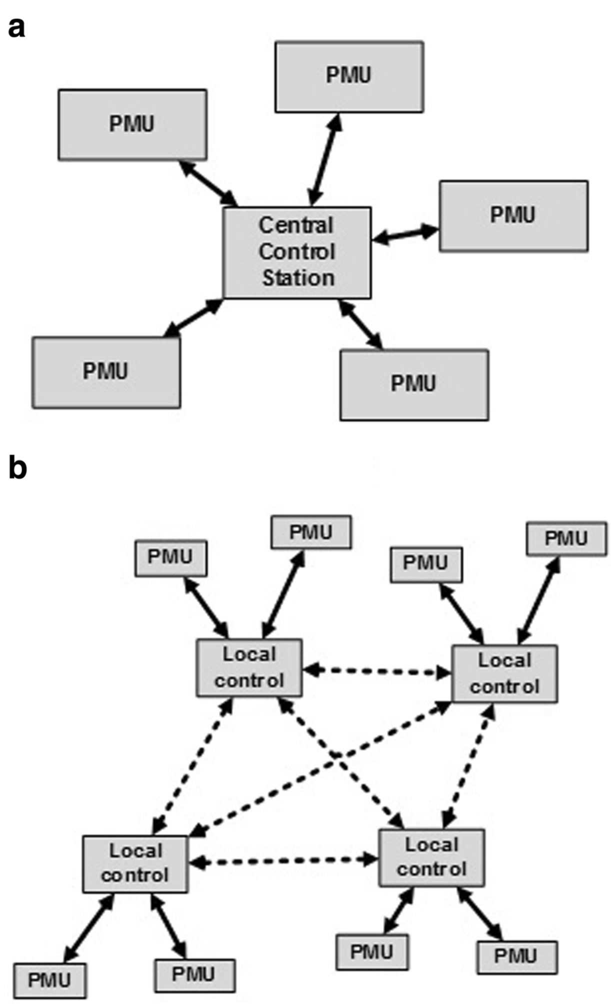

Fig. 14 **a** Centralized architecture. **b** Decentralized architecture

proposed in this regard to achieve improved wide area control. The communication delay essentially causes a time-varying phase lag to the wide area damping system whereas packet losses results are scarce data being available for achieving wide area control. Moreover, the uncertainties in the system parameters pose a severe challenge for estimating the communication delay and the packet loss ratios. Thus, several works have been reported for modeling these losses and delays for realizing effective damping control of the power system. The important works in this regard are described in Table 6.

5 Optimal placement of SPCS and their reliability analysis

The reliable operation of the PMUs and their communication infrastructure is paramount for the safe operation of the grid. A state-of-the-art review of the various methods for reliability analysis of the PMUs is presented in [5]. However, the literature available on the reliability analysis of the SPCS is very sparse. Another research problem that has grabbed the attention of the researchers is the optimal placement of the PMUs and their communication infrastructure. As is the case with the reliability analysis, the problem of optimal placement of PMU (OPP) has been extensively explored by the researchers but the problem of optimal placement of the PMU communication networks has not been sufficiently explored.

5.1 Reliability analysis of the SPCS

The earliest work on the reliability analysis of the SPCS has been carried out by W. Liu and his colleagues [50]. They model the SPCS as an auxiliary evaluation system. Series-parallel networks are used for obtaining the reliability parameters. The proposed approach is used to obtain the reliability parameters of an IEEE 14 bus system. In [51], the WAMS was modeled as a combination of both the PMUs and the communication networks. The communication network reliability is measured in

Table 6 Wide Area Damping Controllers

Reference	Significance
[83–85]	Requirements for wide area control in terms of communication delay and data losses have been identified.
[45]	A distributed multi-agent control concept for achieving wide area control. The local PMU measurements and local optimization algorithms are shared to achieve global control.
[86]	Uncertainties in delays were included in the analysis and a centralized non-linear controller was used.
[87–90]	Communication delays were compensated to achieve the damping control.
[91]	A novel Flexible AC Transmission System (FACTS) controller architecture has been proposed to achieve improved control even when sufficient measurement data is available (due to bandwidth constraints or packet losses).
[92]	Effect of communication network topology was included into the control mechanism.
[93]	Adaptive PDC that configures itself based on communication delays for effective delay compensation of the wide area controller.
[94]	Damping of power system oscillations using a co-simulation platform for simulating the power and communication infrastructures.
[95]	Time delay estimate and packet loss probability were obtained using Markov models to achieve improved oscillation control.

terms of the intermediate node failures. A minimum path is considered between the source and destination pair and the reliability is measured in terms of the probability of connectivity existing between the nodes. The reliability parameters were obtained for the Henan power grid, China to substantiate the merit of the proposed approach. In [52], assessment of the effect of communication infrastructure failure on the various WAMS applications has been investigated. Even though the paper does not directly deal with reliability estimation, it identifies the potential causes of service disruption and presents the possible recommendations for the reliable operation of the communication networks. Another work has been reported in the literature that investigates the effect of communication node failures on the accuracy of the SE [53]. Using the system of systems concept, the dependency of the power system monitoring process on the communication failures has been observed. In [54], the SPCS was modeled using a queueing theoretic approach to obtain the reliability indices. Reliability was measured in terms of the probability of packet loss and communication delay. The communication link between the PMU and the PDC was modeled as a cyclic polling system and reliability parameters were obtained using Markov chains. A simultaneous optimal placement of PMUs and the PDC has been explored in [55] to enhance the reliability of data transmission. A multi-stage elimination method is used to obtain the optimum configuration with the highest reliability of data transmission with minimum losses. Reliability parameters were computed in [56] for the communication networks of a hierarchical WAMS using the Fault Tree Analysis (FTA). Case studies indicate that the reliability of the WAMS not only depends on the reliability of the SPCS but also on the transmission mechanism and the PDC. Assessment of Situational Awareness (SA) which is another parameter that is dependent on the reliability has been explored in [57]. Several assessment metrics are proposed and the effect of the communication system's availability on the SA has been investigated through numerous case studies. In [58], two parallel communication links have been proposed to enhance the reliability of the SPCS. One of the links is a wired link and other is a wireless link. These parallel networks can compensate for the temporary unavailability of any one of the communication link, thereby increasing the reliability of the system. In [59], Markov model (MM) based graph theory was used for assessment of the impact of communication network failures on the overall reliability of the WAMS.

5.2 Optimal placement of Synchrophasor communication networks

The problem of OPP is one of the widely investigated researches in the PMU parlance. As of 2018 there are over 394 research articles that have been published on this topic. Methods based on Integer Linear Programming (ILP) [60], GA [61], Particle Swarm Optimization (PSO) [62], Differential Evolution (DE) [63], simulated annealing [64], etc. have been reported in the literature. Most of these works limit themselves to finding the solution for finding the optimum locations for placement of the PMUs. They undermine the important role played by the SPCS. Consequently, very few researchers have explored the problem of the optimum placement of the SPCS and a summary of the most prominent works in this regard is presented in Table 7.

6 Software defined networking for PMUs

In recent years, several disruptive technologies such as IoT, 5G communications, etc., are being employed for SG applications. One such promising technology is the software-defined networking (SDN) [65]. The need for SDN arises from the limitations of the traditional communication networks. The traditional networks are rigid and are difficult to reconfigure in event of faults or other changes. Their architecture hinders the development of networking devices. The architecture of SDN is shown in Fig. 15.

Table 7 Wide Area Damping Controllers

Constraints	Methods used for optimal placement	Reference
Contingency constraints on communication networks	GA	[96]
Communication constraints on PMU placement	GA	[97]
Data loss constraints on PMU placement	ILP	[98]
Limited communication constraints	ILP	[99]
	Multi-objective discrete Artificial Bee Colony	[100]
	sequential quadratic programming	[101]
	ILP	[102]
	ILP	[103]
Constraint on routing paths between PMUs and PDC	GA	[104]
Constraint on power system observability with maximum communication reliability	ILP	[105]
	Multi-objective GA	[106]
Communication feasibility constraint using a minimum number of nodes.	Randomized greedy algorithm	[107]
Minimization of communication system cost	Simulated Annealing (SA)	[108]
	binary imperialistic competition algorithm	[109]
	GA	[110, 111]
Constraint on communication system reliability incorporating network failures	ILP	[112]
Constraint on power system observability with minimum communication system cost and maximum communication redundancy	Non-domination Sorting GA (NSGA-II)	[113]
Minimization of propagation delay	Multi-objective GA	[114]
Minimization of risk	ILP	[115]

In this architecture, the forwarding devices or the networking devices act according to the instructions given by the controller. The controller dynamically changes the instructions in accordance with the current requirements of the application and so is more flexible than its traditional counterpart. Thus, it simplifies the networking infrastructure management, supports new services and can cater to the demands of the envisioned exponential growth in traffic [66, 67]. The immense popularity of the SDN is its ability to address the challenges presented by the SG. There are around 120 research articles published on the topic of SDN for SGs. In SG SDN is primarily used for substation communication [68, 69] and the concept of SDN for PMUs is relatively less explored (5% of the total articles published on SDN for SGs). In [70], SDN architecture was used for PMUs which makes it easier to manage the PMU traffic as compared to the IP network architecture. The state estimation from PMU data using SDN has been carried out in [67]. Recently, a PMU communication network that is resilient to cyber-attacks has been proposed in [71] that uses SDN architecture for its resiliency.

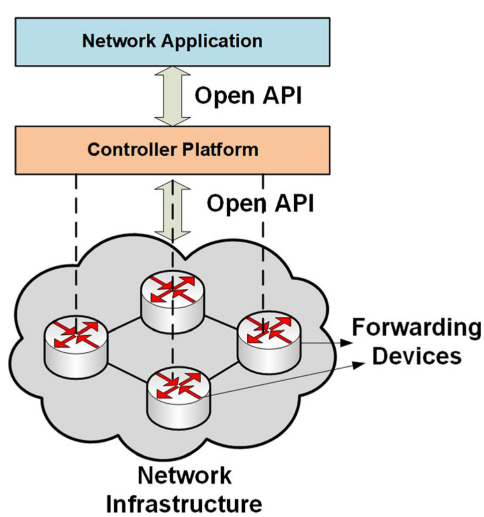

Fig. 15 SDN Architecture

7 Conclusion

SPCS is an important component of the WAMS that has not been extensively explored by the power system engineers. From the review of the state-of-the-art existing knowledge gaps and potential topics for future can be identified. Communication requirements of most of the practical power grids are yet to be investigated. Co-simulation software can be used to carry out the power and communication simulations simultaneously and to obtain the characteristics of the grid. Another interesting topic of research in this context is the characterization of communication requirements of micro-grids.

Several communication schemes have already been proposed for different synchrophasor applications. A potential topic can be the development of novel transport layer protocols for real-time implementation that is directed towards minimizing the propagation delay and packet losses. Such a research can be of immense contribution to the power grid. Another unexplored domain is the development of communication schemes for closely located micro-grids.

The other potential research topics are the development of models for estimating the reliability of the SPCS and the optimal placement of the communication infrastructure. Carrying out the reliability analysis would help in identifying the weakest component in the network, thereby incorporating sufficient component redundancy to minimize the frequency of failures. Development of models for estimating the communication infrastructure particularly using the microwave and optical fiber technology can provide valuable insights regarding the performance of these networks. Co-optimal placement of PMUs along with communication equipment can provide pragmatic results with real-world application. SDN for PMUs is yet to be fully explored by the researchers and PMU applications such as damping controllers, state estimation, etc., developed based on the SDN architecture can be of practical importance for system engineers.

Abbreviations

CAN: Controller Area Network; CPU: Central Processing Unit; DE: Differential Evolution; DFT: Discrete Fourier Transform; DoE: Department of Energy; EDGE: Enhanced Data rates for GSM Evolution; FACTS: Flexible AC Transmission System; GA: Genetic Algorithm; GIS: Geographical Information System; GPC: Generalized Predictive Control; GPRS: General Packet Radio Service; GPS: Global Positioning System; IEEE: Institute of Electrical and Electronic Engineers; ILP: Integer Linear Programming; IoT: Internet of Things; LTE-A: Long Term Evolution-Advanced; MPI: Message Passing Interface; NERC: North American Electric Reliability Corporation; NSGA-II: Non-dominating Sorting GA; OPP: Optimal Placement of PMUs; PDC: Phasor Data Concentrator; PLC: Power Line Communication; PMU: Phasor Measurement Unit; PSO: Particle Swarm Optimization; RF: Radio Frequency; ROCOF: Rate of Change of Frequency; SA: Situational Awareness; SCADA: Supervisory Control and Data Acquisition; SE: State Estimation; SIPS: System Integration Protection Schemes; SNR: Signal to Noise Ratio; SPCS: Synchro-Phasor Communication System; TVE: Total Error Vector; UMTS: Universal Mobile Telecommunications System; WAMS: Wide Area Measurement System; WLAN: Wireless Local Area Networks

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Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Authors' contributions

The author Mr. BA has collected the information pertaining to the state-of-the-art in the synchrophasor communication system. He also prepared a crude draft of the manuscript. The author Dr. DKM provided the idea and other technical guidance required for completion of the study. He also prepared the final draft of the manuscript. Both authors have read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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