Chapter 9
Standards and Communication Systems in Smart Grid

Bhargav Appasani, Jaya Bharata Reddy Maddikara and Dusmanta Kumar Mohanta

Abstract The present-day power system is rapidly progressing in the fields of generation, transmission, and distribution of energy. Factors such as diverse and distributed nature of power consumption, increased use of the renewable energy that enables the consumer to also be an energy provider have exacerbated the complexity of the power grid. A glitch or a failure in one part of this complex network, unless espied and curtailed, can translate into a major power outage. This requirement has led to the inception of the smart grid. A smart grid consists of several intelligent sensors with advanced communication capabilities that collect, communicate, and monitor the real-time information pertaining to the grid dynamics. Apart from fault detection and outage prevention, there are several other applications of the smart grid such as electric substation automation, distributed energy resource management, automatic metering infrastructure (AMI), electrical vehicles (EVs), home automation. These applications require efficient communication technologies for transfer of information. This chapter presents a comprehensive description of the various smart grid communication systems and standards from the perspective of their application in smart grid. The future technologies and the challenges they pose are also discussed for the benefit of the research groups working on smart grid communications.

Keywords Smart grid communication standards · Smart grid communication systems · Distributed energy resource management · Substation automation

B. Appasani
School of Electronics Engineering, Kalinga Institute of Industrial Technology, Bhubaneswar 751024, India
e-mail: bhargav.appasanifet@kiit.ac.in

J. B. R. Maddikara (✉)
Department of Electrical and Electronics Engineering, National Institute of Technology, Tiruchirapalli 620015, Tamil Nadu, India
e-mail: jayabharat_res@yahoo.co.in

D. K. Mohanta
Department of Electrical and Electronics Engineering, Birla Institute of Technology, Mesra 835215, India
e-mail: dkmohanta@bitmesra.ac.in

E. Kabalci and Y. Kabalci (eds.), *Smart Grids and Their Communication Systems*, Energy Systems in Electrical Engineering,
https://doi.org/10.1007/978-981-13-1768-2_9

Synchrophasor measurement system · Powerline communication technology
Cellular communication

9.1 Introduction

A smart grid is an advanced version of the conventional power grid with enhanced communication and monitoring capabilities. It is a combination of several heterogeneous components exchanging information with one another. The US Department of Energy (DoE) has identified 1400 different data flows having varying payload size, payload type, desired reliability, and security, in a smart grid [1]. This diversity makes the grid very complex and the communication technologies should be able to cater to the demands of the various applications. These technologies are developed by several standard developing organizations (SDOs), consortia, forums, etc., and there has been an increasing effort to warrant their reliable operation. The following are the basic features that are desired of a smart grid communication system [2]:

- Latency: Most of the smart grid applications are time critical involving real-time data transferal. For example, the synchrophasor application has a round time constraint of about 10 ms. There are some other applications which are less time critical such as the AMI application which has the roundabout time of 15 min. The communication system should deliver an optimized delay performance, taking into account these variations in latency constraints.
- Reliability: The smart grid applications are mission critical and hence the underlying communication systems should be highly reliable. Based on the application criticality, the communication system should prioritize the data transmissions and deliver a reliable performance.
- Data rate: The diverse nature of the applications results in diverse data rate requirements. It is estimated that in the next few years, more number of devices would be connected to the grid and hence the communication system should be able to offer the required bandwidth to minimize the transmission losses.
- Scalability: Millions of new devices are expected to be connected to the grid in the near future. So, the communication system should be scalable in order to accommodate this rapid growth.
- Interoperability: Different applications may use different communication standards and different communication technologies. Hence, it is important to ensure interoperability between the various standards and technologies.
- Security: The data carried by the communication systems may involve information pertaining to the consumer privacy or some grid sensitive information. Therefore, the communication system must be unassailable and resilient to attacks.

In this chapter, we present a comprehensive description of the communication systems and standards for the various smart grid applications. In the first part of the chapter, we present the various communication standards that are being employed for smart grid applications. In the second part, we discuss the various smart grid communication systems which are broadly classified into two categories: wired and wireless communication systems. In the last part of the chapter, we discuss the next-generation communication technologies that may play a pivotal role in the smart grid.

9.2 Smart Grid Communication Standards

Smart grid encompasses a wide variety of devices and caters to the demands of several applications. To ensure the smooth exchange of information between these devices, several standards have been developed across the globe. These standards have been materialized due to the combined efforts of several SDO's such as the Institute of Electrical and Electronics Engineers (IEEE), the American National Standards Institute (ANSI), International Electrotechnical Commission (IEC), International Standards Organization (ISO).

The communication standard for the substation automation is specified by the IEC 61850. It also describes the communication interface between the substation equipment and the control center. The IEC 60870-5 specifies the communication standard for telecontrol and the IEC 60870-6 specifies the standard for communication between the control centers. The standard for the data associated with the teleprotection equipment is defined by the IEC 60834. The IEC 60834 is applicable both for the narrowband as well as for the wideband teleprotection systems. The IEC 61970 standards were developed for integrating the different applications developed by various vendors and to enable the external transmission and distribution systems to exchange data with the control center. The IEC 61968 standards standardize the exchange of information between the distribution management systems (DMS). Synchrophasor measurement system plays an important role in the real-time monitoring and control of the smart grid. The IEEE 37.118.2-2011 standard defines the transfer of the synchrophasor data between the end devices. The IEEE 1815-2012 standard was developed to standardize the electric power systems communications. In the following subsections, these smart grid communication standards are comprehensively explained.

9.2.1 Communication for Substation Automation: IEC 61850

The standard for communication among the substation equipment is specified by the IEC 61850 [3–15]. This standard was developed by the IEC Technical Committee 57 (TC57) Working Group 10 (WG10) for the management of power systems and their associated communication. The abstract data and the object models of the IEC 61850 can be directly mapped to the existing protocols such as the manufacturing message specification (MMS), generic object-oriented substation Event (GOOSE), sampled measured values (SMV) which can run over the local area networks (LANs) in order to achieve the required response time. This standard is described in ten separate parts and their description is given in Table 9.1.

Table 9.1 The IEC 61850 standard documents

Part no.	Title of the document	Description of the document
IEC 61850-1	Introduction and overview	This technical report gives an introduction and overview of the IEC 61850 series
IEC 61850-2	Glossary	This technical report gives glossary of the various terms and definitions used in the purview of the substation automation
IEC 61850-3	General requirements	It describes the communication requirements for communication between the substation equipment
IEC 61850-4	System and project management	It describes the requirements of the system and project management process
IEC 61850-5	Communication requirements for functions and device models	It refers to the communication requirements of the substation automation functions and the related device models
IEC 61850-6	Configuration description language for communication in electrical substations related to intelligent electronic devices (IEDs)	Specifies the file format for describing the communication-related IED configurations, parameters and communication system configurations
IEC 61850-7	Basic communication structure for substation and feeder equipment	
IEC 61850-7-1	Principles and models	Presents an overview of the communication architecture between the substation equipment
IEC 61850-7-2	Abstract Communication Service Interface (ACSI)	This part provides the definitions of the abstract services
IEC 61850-7-3	Common Data Classes (CDC)	The CDCs are the basic blocks for building larger data objects. The CDCs are defined in this part of the standard
IEC 61850-7-4	Compatible logical node classes and data classes	Specifies the compatible logic node names and data classes for communication between the IEDs
IEC 61850-8	Specific Communication Service Mapping (SCSM)	
IEC 61850-8-1	Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3	Specifies the mapping of abstract data and object models to MMS and ISO/IEC 8802-3 frames
IEC 61850-9	SCSM	
IEC 61850-9-1	Sampled values over serial unidirectional multidrop point to point link	Specifies the mapping of SMVs onto an Ethernet data frame
IEC 61850-9-2	Sampled values over ISO/IEC 8802-3	Specifies the mapping of SMVs for transmission using the ISO/IEC 8802-3
IEC 61850-10	Conformance testing	Specifies the techniques for conformance testing

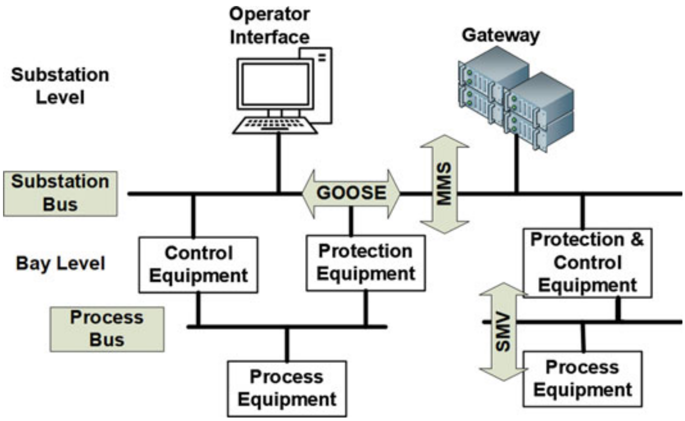

Fig. 9.1 IEC 61850 enabled substation architecture [3]

The architecture of an IEC 61850 enabled substation is shown in Fig. 9.1. The architecture consists of three levels: substation level, bay level, and process level. The substation level consists of the system operator interface for monitoring and control, etc. The bay level consists of protection and control equipment which communicate with each other using the GOOSE messages. The relationship between the bay-level equipment and the substation-level equipment is that of a client–server relationship. The communication between these levels is based on MMS and is carried by the substation bus. The third level consists of the smart equipment such as the current and voltage transformer. The process-level equipment communicates with the bay-level equipment through SMV messages using the process bus.

The protocols prior to the IEC 61850 defined the data format for transmission over the communication medium. However, the organization of data was not specified based on the application. The unique contribution of the IEC 61850 standard is that it specifies the model for organization of data such that interoperability among the devices is achieved.

The data model begins with the physical device which is connected to the network. The network address is used for identifying the device. This device consists of several logical devices (LDs). At the next level, each logical device consists of several logical nodes (LNs) which are given specific LN names. For example, the circuit breaker is identified by the LN name “XCBR”. Each LN consists of one or more than one data objects (DOs). Again, taking the example of the circuit breaker, this LN may consist of DOs such as “Loc” for determining the nature of operation (local or remote), “Pos” for position. Each DO of the LN follows the CDC specification given in the IEC 61850-7-3. The data model of the IEC 61850 is shown in Fig. 9.2.

The data model of the IEC 61850 enables the IEDs to generate application-oriented data that are identical in their structure from the network point of view. The data model must be run over the practical protocols found in the power system environment. The abstract data and objects are mapped to the ISO9506 MMS protocols, by the IEC

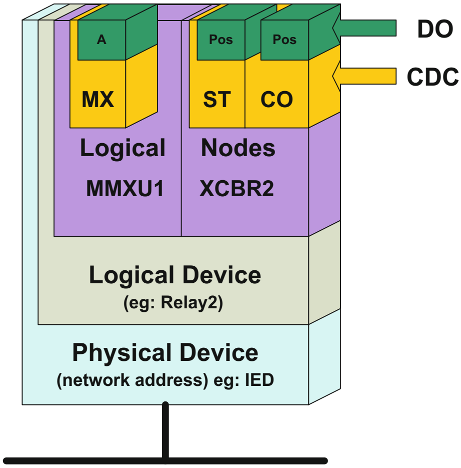

Fig. 9.2 Data model of IEC 61850 [3]

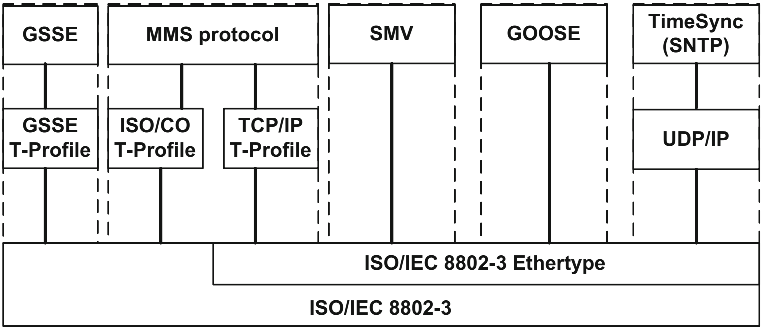

Fig. 9.3 Communication profiles of IEC 61850 [13]

61850-8-1. This is based on service mapping where the services of the ACSI are implemented using a specific MMS service.

The communication profiles defined by the IEC 61850-8-1 for the various layers of the communication stack are shown in Fig. 9.3. There are basically five kinds of communication profiles which are explained below:

- ACSI profile—For communication between the applications and servers,
- GOOSE profile—For communication on the substation bus,
- Generic Substation Status Event (GSSE) profile—For providing information exchange on substation status,
- SMV profile—For communication on the process bus,
- Time synchronization profile,
- The IEC 61850 standard has unique capabilities and offers substantial benefits to the users. Some of the key benefits of this standard are listed below:

- Lower installation cost due to minimization of wiring.
- A single SMV supported merger unit can send signals to several IEDs thereby reducing the transducer costs.
- Newer extensions can be added to substation without major impact on the existing equipment.
- Using the existing networking technology, one can obtain the substation data and therefore the integration cost is minimized.
- As the manual configuration is minimized, it reduces the commissioning cost.

9.2.2 Communication for Telecontrol: IEC 60870-5

The IEC 60870 standards are developed by the IEC TC57 WG3 for defining the systems used for supervisory control and data acquisition (SCADA) or telecontrol. The IEC 60870 consists of six parts of which the IEC 60870-5, known as the transmission protocols, is used in the smart grid [16–28]. It consists of the following separate documents:

- IEC 60870-5-1: Transmission Frame Formats,
- IEC 60870-5-2: Data Link Transmission Services,
- IEC 60870-5-3: General Structure of Application Data,
- IEC 60870-5-4: Definition and Coding of Information Elements,
- IEC 60870-5-5: Basic Application Functions,
- IEC 60870-5-6: Guidelines for Conformance Testing for the IEC 60870-5 Companion Standards,
- IEC 60870-5-7: Security Extensions to IEC 60870-5-101 and IEC 60870-5-104 Protocols (Applying IEC 62351).

The IEC TC57 has also provided the companion standards for basic telecontrol tasks, network access, protection equipment interfacing, etc., which are given below:

- IEC 60870-5-101: Transmission Protocols—Companion Standard for Basic Telecontrol Tasks,
- IEC 60870-5-102: Transmission Protocols—Companion Standard for the Transmission of Integrated Totals in Electric Power Systems,
- IEC 60870-5-103: Transmission Protocols—Companion Standard for the Informative Interface of Protection Equipment,
- IEC 60870-5-104: Transmission Protocols—Network Access for IEC 60870-5-101 Using Standard Transport Profiles,
- IEC TS 60870-5-601: Transmission Protocols—Conformance Test cases for the IEC 60870-5-101 Companion Standard,
- IEC TS 60870-5-604: Conformance Test Cases for the IEC 60870-5-104 Companion Standard.

The protocol uses an open TCP/IP interface to the network, for the SCADA equipment. The reference model for this is taken from the ISO–OSI model but having

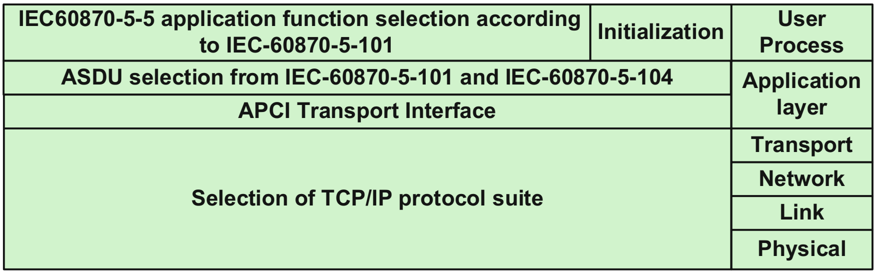

Fig. 9.4 Reference model of the protocol [23]

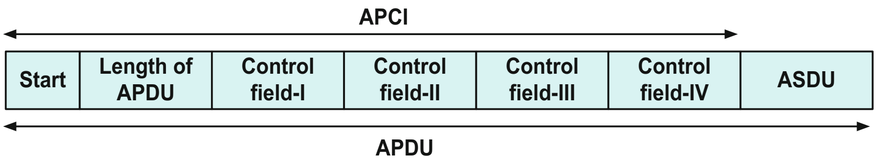

Fig. 9.5 APDU for the telecontrol companion standard [23]

only five layers. The reference model of the protocol is shown in the Fig. 9.4. The maximum length of an application service data unit (ASDU) of the IEC-60870-5-101 is 249 bytes. No initiation or termination mechanism is defined for the ASDU by the user–TCP interface. An application protocol data unit (APDU) is made of four octets of control field, an ASDU, start character and the field for length indication. The beginning and the end of the ASDU can be perceived using these fields. Thus, the maximum length of APDU is 255 bytes. The APDU for the telecontrol is shown in Fig. 9.5.

The station which initiates the connection establishment is called as the controlling station and the station that accepts the request of the controller is called as the controlled station. Connection establishment and its termination are performed over the TCP.

The IEC-60870-5-104 provides the facility of establishing more than one logical communication paths between the stations. A logical communication path is identified by a combination of two IP addresses and two port numbers. The following are the rules that apply in the event of redundant connections:

- Multiple connections between the controlled and the controlling station are permitted.
- A redundancy group is made up of *N* logical connections.
- Only one logical connection per redundancy group can be active at any instance of time.
- Supervision of all logical connection in the group using test frames.
- If the controlled station is accessed simultaneously by more than one controlling station, then they should be allotted to a separate redundancy group.

- The decision on the active logical connections is taken by the controlling station.

Another important aspect of the IEC-60870 protocol is the clock synchronization. This mitigates the use of additional circuitry at the controlling stations. The clocks of the client and the server (i.e., controller and the controlled station) must be synchronized for chronological exchange of information. At regular intervals these synchronization messages are sent by the controlling station to the controlled system.

9.2.3 IEC 60870-6 Standards for Inter-Control Center Communications

The IEC 60870-6 protocol also called as the Inter-Control Center Communications Protocol (ICCP) or as the Telecontrol Application Service Element 2 (TASE.2) specifies the communication among the control centers of the system operators, utilities, and the regional control centers. It is specified in separate documents and includes the following standards [29–40]:

- IEC 60870-6-1: Application Context and Organization of Standards,
- IEC 60870-6-2: Use of Basic Standards (OSI layers 1–4),
- IEC 60870-6-501: TASE.1 Service Definitions,
- IEC 60870-6-502: TASE.1 Protocol Definitions,
- IEC 60870-6-503 TASE.2 Services and Protocol,
- IEC 60870-6-504: TASE.1 User Conventions,
- IEC TR 60870-6-505: TASE.2 User Guide,
- IEC 60870-6-601: Functional Profile for Providing the Connection-Oriented Transport Service in an End System connected via Permanent Access to a Packet Switched Data Network,
- IEC 60870-6-602: TASE Transport Profiles,
- IEC 60870-6-701: Functional Profile for Providing the TASE.1 Application Service in End Systems,
- IEC 60870-6-702: Functional Profile for Providing the TASE.2 Application Service in End Systems,
- IEC 60870-6-802: TASE.2 Object Models.

This protocol uses the MMS to effectuate the data transfer between the control centers. The means of naming the variables, control messages, and their interpretation is specified by the MMS. The transport profiles specified by the TASE.2 include the TP4 protocol (IS 8073) and the Connectionless-mode network service protocol (CLNP) (IS 8473) along with the suitable medium specific protocols. The relationship of the TASE.2 with other members of the OSI model is shown in Fig. 9.6.

TASE.2 supports bi-directional flow of data between the two centers. It supports data pertaining to analog/measurement values, digital values, binary commands, and text messages. The data can be real time or archived and can be time tagged. In

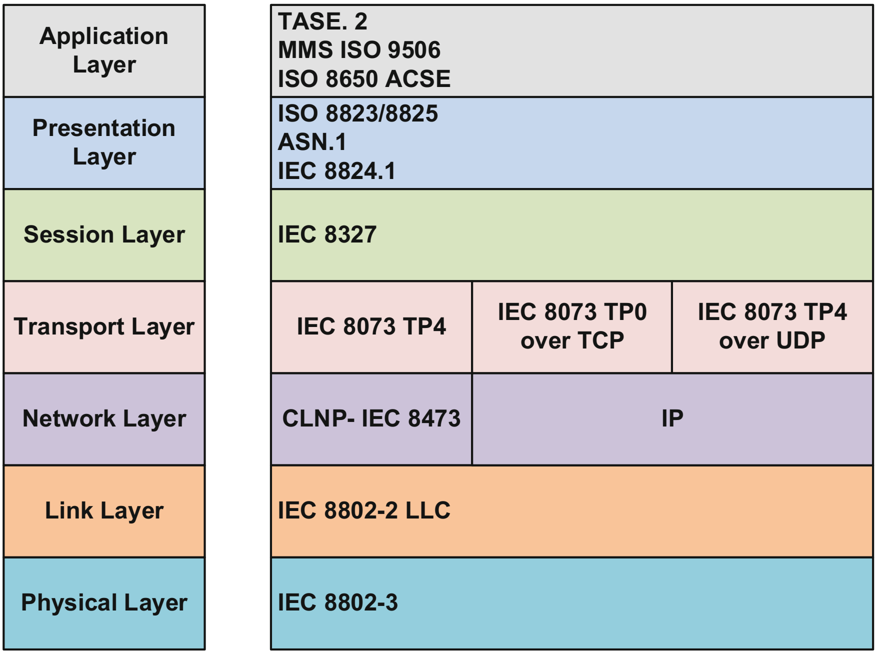

Fig. 9.6 TASE.2 relationships with other members of protocol stack [33]

addition, TASE.2 also supports more complex data such as accounting information, time series data, and schedules.

The TASE.2 uses an object-oriented method to specify the power system data objects. The protocol and the data object models are separated, which enables the data objects to be used by other protocols that support object-oriented technique. It uses the MMS messages for operating these data objects.

The TASE.2 services between the control centers are specified in terms of operations and actions. The operations are invoked by the TASE.2 client whereas the actions are invoked by the TASE.2 server. There are two other services, namely the Abort and the Conclude which can be invoked either by a client or a server. These services are run over the MMS protocol.

The connection between the two centers follows a bilateral agreement which specifies the data required to be exchanged in order to validate the connection between the two. A control center providing the data values to other control centers maintains a bilateral table for each of these centers. This table contains the entries for the data objects and the data sets that are mentioned in the bilateral agreement.

The connection establishment process between the TASE.2 server and the TASE.2 client is initiated by the latter through an association request. The client's identity is verified by the server using the client control center designation that is provided at the time of connection establishment in order to validate the existence of a bilateral agreement with the client. If an agreement exists, the server will proceed with the

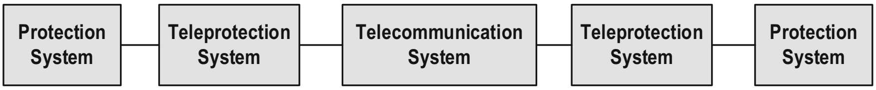

Fig. 9.7 Configuration of the systems [41]

further steps involved in the connection establishment process. If there is no such agreement, then the association request is denied.

9.2.4 IEC 60834 Standards for Teleprotection Equipment

The IEC TC57 has developed the IEC 60834 standard for the communication of the data associated with the protection equipment. This equipment generates data or information pertaining to the electrical quantities such as the amplitude and the phase. Depending on the bandwidth requirements, these systems are classified into narrowband systems and wideband systems. The narrowband systems require a unidirectional bandwidth of 4 kHz, and the wideband systems require unidirectional bandwidth of more than 4 kHz. It is specified in separate documents and includes the following standards [41, 42]:

- IEC 60834-1: Performance and Testing—Part 1: Command Systems.
- IEC 60834-2: Performance and Testing—Part 2: Analog Comparison System.

The aim of the IEC 60834-1 is to establish the performance requirements and the testing methods for the command type teleprotection equipment. The command type teleprotection equipment can be voice frequency equipment or digital equipment which is used in conjuncture with digital communication systems. The IEC 60834-2 aims to establish the performance requirements and the testing methods for the analog comparison teleprotection equipment. The protection equipment, the teleprotection system, and the telecommunication system are shown in Fig. 9.7. If the protection equipment and the teleprotection equipment are packaged into a single unit then there is no need of an interface between the two. Similar argument applies to the interface between the telecommunication system and the teleprotection equipment.

9.2.4.1 Teleprotection Command Schemes

The various types of teleprotection command schemes are explained below:

- Permissive tripping schemes: In these schemes, the teleprotection command initiates the tripping of some protection equipment. These commands operate with the permission of the local protection equipment and can be sent over a voice frequency band or as a digital signal. The communication links should be highly reliable even under adverse conditions.

- Direct tripping or inter-tripping schemes: In this scheme, the teleprotection commands do not require the permission of the local protection equipment in order to initiate the tripping. It requires high security in order to warrant proper tripping of the equipment.
- Blocking protection schemes: In this scheme, the teleprotection command received, blocks the functioning of the protection equipment. Reliability and the speed of operation are the primary considerations.

9.2.4.2 Teleprotection Performance Requirements and Testing Methods

The performance requirements of a teleprotection system depend on the protection equipment and on the communication system used. It should be highly reliable and secure. However, it is practically not feasible to design systems which are fault free. This limitation should be taken into account while designing the teleprotection equipment.

The teleprotection equipment monitors the transmission link and the end terminal, as far as possible by transmitting guard messages. Any failure in reception of these messages for a prolonged period of time is detected and an alarm is raised. An alarm is also raised if the interference in the received signal is higher than the threshold level for a prolonged time period. For digital systems, the design should not be affected by the presence of jitter at the transmitter's output or at the receiver's input.

The teleprotection system should be tested for its performance to ensure its reliable design. The testing procedures should provide a good estimate of the system performance within a reasonable amount of time. Ease of repeatability is another important criterion of the test procedures.

For analog system, the simplest means of testing is to estimate the signal-to-noise ratio (SNR) in the presence of white noise. This test procedure provides a good estimate of the systems reliability and security. For digital systems, on the other hand the bit error rate (BER) provides the estimate for the system performance.

9.2.5 IEC 61970 Standards for Energy Management Services Application Program Interface (EMS-API)

The IEC 61970 standards were developed for the purpose of application integration in the control center environment and to enable the external transmission and distribution systems to exchange data with the control center. This standard is titled as the EMS-API and it consists of the following parts [43–53]:

- IEC 61970-1 Guidelines and General Requirements,
- IEC 61970-2 Glossary,
- IEC 61970-301 Common Information Model (CIM) Base,
- IEC 61970-302 CIM Financial, Energy scheduling, and Reservations,

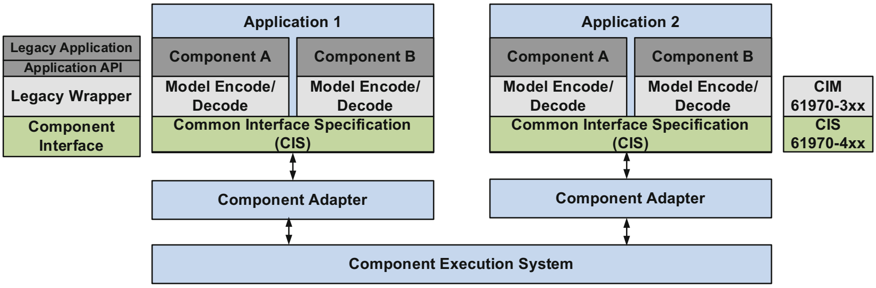

Fig. 9.8 EMS-API reference model [43]

- IEC 61970-401 Component Interface Specification (CIS) Framework,
- IEC 61970-402 CIS—Common Services,
- IEC 61970-403 CIS—Generic Data Access,
- IEC 61970-404 High-Speed Data Access (HSDA),
- IEC 61970-407 CIS—Time Series Data Access (TSDA),
- IEC 61970-453 Diagram Layout Profile,
- IEC 61970-501 Common Information Model Resource Description Framework (CIM RDF) schema.

The reference model of the EMS-API provides the linguistic for describing the solutions. It also provides the definition of the terminology and a conception of the problem's domain. Its aim is to indicate the problem space which comes under the jurisdiction of the IEC 61970 standards and which does not come under its jurisdiction. It is an abstract means of presenting the relationship between the various parts of the EMS-API standard and is specifically applicable to the control center environment. The reference model for the EMS-API model is shown in Fig. 9.8.

The CIM simplifies the process of application integration. Prior to this, interaction between the devices (from different vendors) required mapping of the objects and so interoperability was a serious problem. CIM alleviates this problem of interoperability by standardizing the process of information exchanges. The other important benefits of the CIM are:

- By providing a common semantic modeling it reduces the enterprise complexity.
- Provides a clear picture of the data mastership in the enterprise.
- Data is made available to the qualified users as per their requirement.

The CIM is described using the unified modeling language (UML), and it includes the classes for the major objects used in the EMS environment.

The CIS on the other hand provides the specification of the interfaces between the different components developed by independent vendors. A component should not only be able to access the data that is available publicly but should also be able to communicate with other components. Both these aspects are specified in the CIS. The CIS is not dependent on the underlying technology, and so it must be mapped

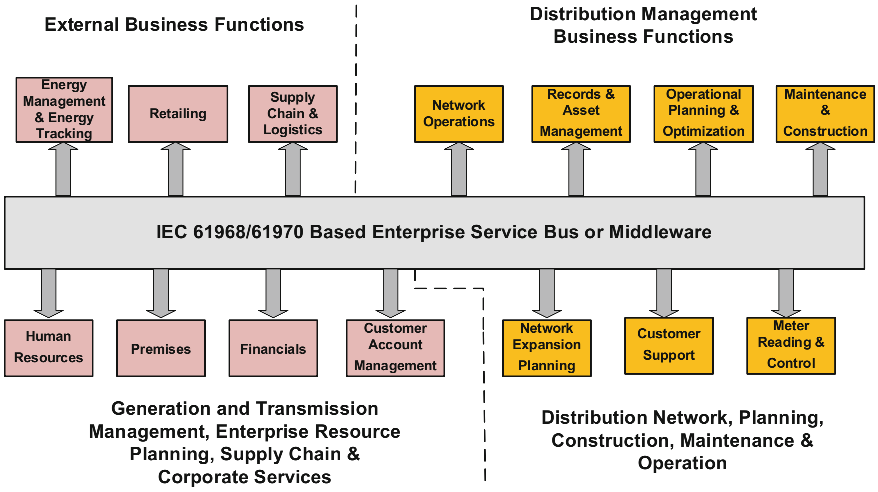

Fig. 9.9 IEC 61968 IRM [54]

to the specific technology for its practical implementation. A standardized mapping of the interface to the technology is required to warrant the interoperability.

The IEC 61970 communication profile services are required for guaranteed delivery of the network messages to their respective destinations even in the event of network failures, while maintaining or preserving the order in which the messages are sent. In the event that the message could not be delivered, a message should be sent to the source regarding the failure of delivery. Lastly, an option should be provided for selecting the quality of service (QoS) in order to prioritize the message delivery.

9.2.6 *IEC 61968—Application Integration at Electric Utilities—System Interfaces for Distribution Management Systems*

The IEC 61968 is a set of standards being developed by the IEC TC57 WG14 for standardizing the information exchange between the distribution management systems. It defines the interface reference model (IRM) for the CIM and unlike the IEC 61970 standard which defines a generic interface, it details the cases for exchange between the systems. The IEC 61968 IRM is illustrated in Fig. 9.9. The IEC 61968 has several subparts which are described in Table 9.2 [54–62].

In a typical power system, the components that exchange information are distributed across the system. This information exchange may be between different processes of the same component or between the same processes across different

Table 9.2 The IEC 61968 standard

Part no.	Title	Description
IEC 61968-1	Interface architecture and general requirements	This part forms the basis for the subsequent parts of the standard which defines the interface architecture and its requirements for the various components of the DMS
IEC 61968-2	Glossary	This part gives a glossary of the various terms and definitions used in the purview of the DMS
IEC 61968-3	Interface for network operations (NO)	It describes the NO interface architecture and its requirements
IEC 61968-4	Interfaces for records and asset management (AM)	It describes the interface architecture for records and AM
IEC 61968-6	Interfaces for maintenance and construction (MC)	It describes the interface architecture and its requirements for MC
IEC 61968-8	Interfaces for customer support (CS)	Specifies the architecture for the CS
IEC 61968-9	Interface standard for meter reading and control (MR)	Specifies the interface standard for the MR
IEC 61968-11	CIM extensions for distribution	This part extends the CIM of the IEC 61970 by providing objects required for the exchange of distribution information
IEC 61968-13	CIM RDF model exchange format for distribution	This part provides the standard for the CIM RDF model exchange format for CDPSM

components or between the different processes of different components. A middleware adapter is present in the IEC 61968 in order to extend the middleware services for providing the required support. These provide a set of APIs and have the following functionalities:

- They are distributed transparently and can interact with other applications in the network.
- They can be scaled up without degrading their functionality.
- They are highly reliable and secure.
- They are not dependent on the communication services profile.
- They can provide Business-to-Business transactions.

Interaction between the components requires a connection establishment between the two. If more than two components are involved in information exchange, then the integration system resolves the problem of differences in the protocols without the knowledge of the components.

9.2.7 IEC 62351 Standard for Cyber Security

The IEC 62351 standards were developed by the IEC TC57 for providing security for the IEC 60870, IEC 61850, IEC 61970, and the IEC 61968 standards. The goal of these standards is to provide the required security functionalities such as protection from spoofing, prevention of eavesdropping, data transfer through authentication, intrusion detection. This standard consists of several parts which are given below [63–72]:

- IEC 62351-1: Introduction,
- IEC 62351-2: Glossary,
- IEC 62351-3: Security for profiles including TCP/IP,
- IEC 62351-4: Security for Profiles including MMS,
- IEC 62351-5: Security for Profiles including IEC 60870-5,
- IEC 62351-6: Security for IEC 61850 Profiles,
- IEC 62351-7: Security through Network and System Management,
- IEC 62351-8: Role-Based Access Control,
- IEC 62351-9: Cybersecurity Key Management,
- IEC 62351-10: Security Architecture Guidelines for TC57 Systems.

The relationships between the various parts of the IEC 62351 standard and the IEC 60870, IEC 61850, IEC 61970, and the IEC 61968 standards are shown in the Fig. 9.10.

9.2.8 The Society of Automotive Engineers (SAE) Standards for Electric Vehicle Communications

The SAE started to develop the communication standards between electric vehicles and the utility grid (V2G) in 2009. There a total of 21 standards classified into four different categories. These standards are mentioned in Table 9.3 [73], and the interaction between them is shown in Fig. 9.11.

9.2.9 Standards for Advanced Metering Infrastructure (AMI)

The AMI collects the data pertaining to the user's energy consumption which is transmitted to the service provider. This helps to improve the quality of service and energy management. The AMI consists of four subsystems: the smart meter, communication subsystem, data concentrator, and meter data management system (MDMS). These subsystems are shown in Fig. 9.12.

The smart meter collects the energy consumption data which is transmitted via a suitable communication system. The data concentrator collects the metering data

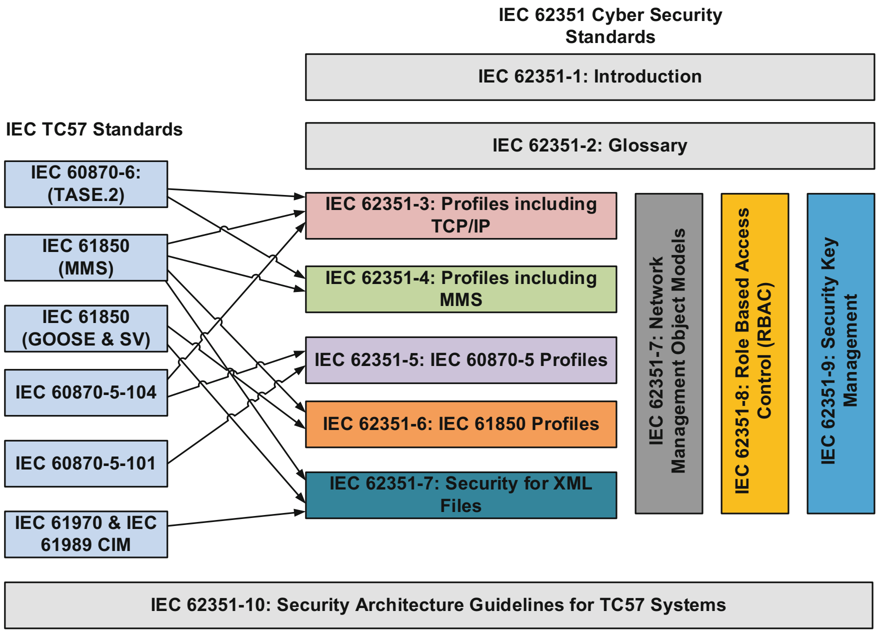

Fig. 9.10 Relationships between IEC 62351 and other IEC TC57 standards [63]

from several smart meters, arranges the data, and sends it to the MDMS. The MDMS analyzes the data and provides the requisite information to the service provider. The AMI communication standards are summarized in Table 9.4 and two of the widely used standards: IEC 62056 and the ANSI C12 are discussed briefly.

IEC 62056 Standard

The IEC 62056 standard is the successor of the IEC 61107, a widely used protocol for communication of metering data. This standard is centered on the device language message specification (DLMS) which defines the communication profile and the data objects. The procedures for information exchange between the devices are specified by the companion specification for energy metering (COMSEM). The DLMS/COMSEM specifies the communication standard across the different communication media. The DLMS/COMSEM specification is defined in four technical reports that are given below [74]:

- Green Book: COMSEM Architecture and Protocols,
  - IEC 62056-53: COMSEM Application Layer,
  - IEC 62056-47: COMSEM Transport layers for IPv4,
  - IEC 62056-46: Data Link layer using High-Level Data Link Control (HDLC),
  - IEC 62056-42: Physical Layer Services and Procedures for Connection-Oriented Asynchronous Data Exchange,

Table 9.3 The SAE J2836, J2847, J2937 and J2953 standards

Standard	Title	Description
SAE J2836/1	Use cases for communication between plug-in electric vehicles (PEVs) and the utility grid	This document establishes the use cases for V2G communications required for energy transfer and other related applications
SAE J2836/2	Communications between plug-in vehicles and off-board DC chargers	It identifies the use cases for V2G communication between electric vehicles and off-board DC charger
SAE J2836/3	PEV communicating as a distributed energy resource (DER)	This document identifies the use cases for the PEV communicating with the grid as a DER
SAE J2836/4	Use cases for diagnostic communication for PEVs	This document specifies the use cases for identifying the diagnostic communication requirements for charging or discharging an electric vehicle
SAE J2836/5	Use cases for customer communication for PEVs	This document establishes the use cases for communication between the customers and the PEVs
SAE J2836/6	Use cases for wireless charging communication for PEVs	This document establishes the use cases for V2G communication for wireless transfer of energy
SAE J2847/1	Communications between PEVs and the utility grid	This document specifies the requirements for communications between the plug-in vehicle and the grid
SAE J2847/2	Communications between PEVs and off-board DC chargers	This document specifies the requirements for communications between the plug-in vehicle and the DC chargers
SAE J2847/3	Communication for PEVs as a DER	This document specifies the communication requirements for an electric vehicle which has an onboard inverter and can communicate using SEP 2.0 protocol
SAE J2847/4	Diagnostic communication for plug-in vehicles	This document specifies the diagnostic communications for charging or discharging an electric vehicle
SAE J2847/5	Communication between PEVs and their customers	This document identifies the requirements for the customer interface and the interactions between the plug-in vehicle and the customer
SAE J2847/6	Communication between wireless charged vehicles and wireless EV chargers	This document specifies the requirements for communications messages between wirelessly charged electric vehicles and the wireless charger

(continued)

Table 9.3 (continued)

Standard	Title	Description
SAE J2931/1	Digital communications for plug-in electric vehicles	This document specifies the digital communication for the PEV
SAE J2931/2	Inband signaling communication for PEVs	This document specifies the requirements for signaling communications for PEVs
SAE J2931/3	Narrowband power line communication (NB-PLC) for PEVs	This standard specifies the MAC & PHY layer implementation of digital communications using NB-PLC
SAE J2931/4	Broadband PLC (BB-PLC) communication for PEVs	This standard specifies the MAC & PHY layer implementation of digital communications using BB-PLC
SAE J2931/5	Telematics smart grid communications between customers, PEVs, Energy service providers (ESP) and home area networks (HAN)	This document specifies the security requirements for digital communications between the customers, PEVs, ESPs and the grid
SAE J2931/6	Signaling communication for wirelessly charged electric vehicles	This document requirements describes the signaling communication requirements for supporting the wireless charging protocol of PEVs
SAE J2931/7	Security for PEV communications	This document specifies the technical requirements for standard telematics interface for facilitating the communications between the PEVs and the utility grid
SAE J2953/1	PEV interoperability with electric vehicle supply equipment (EVSE)	This document specifies the requirements by which the PEV and the EVSE can be interoperable
SAE J2953/2	Test procedures for the PEV interoperability with EVSE	This document specifies the test procedures for ensuring the interoperability between PEVs and the EVSE

  - IEC 62056-21: Direct Local Data Exchange,

- Yellow Book: COMSEM Conformance Test Process,
- Blue Book: COMSEM Identification System and Interface Objects,
  - IEC 62056-61: Object Identification System (OBIS),
  - IEC 62056-62: Interface Classes,
- White Book: COMSEM Glossary of Terms.

Two more new standards have been added to the IEC 62056 series and are mentioned as follows:

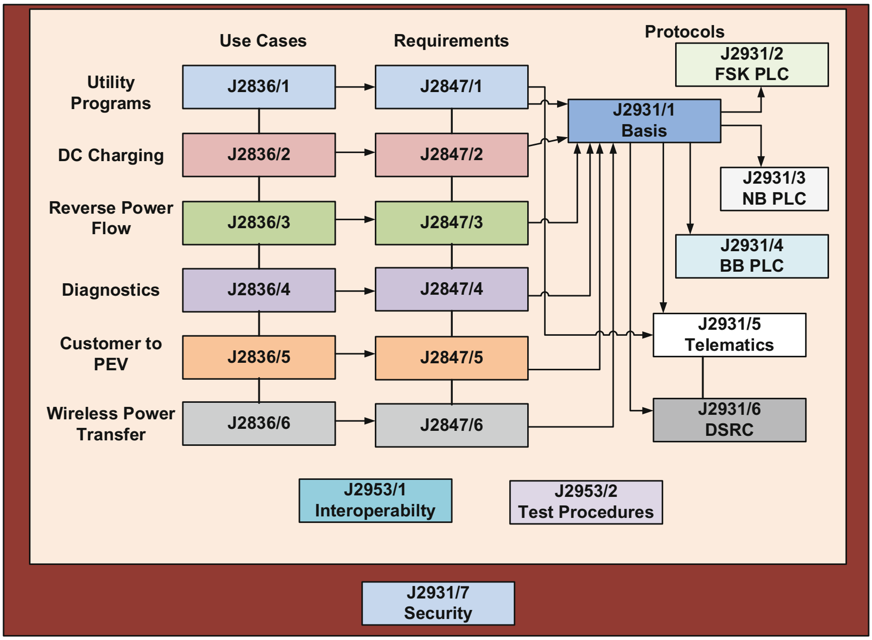

Fig. 9.11 SAE communication standards and their interactions [73]

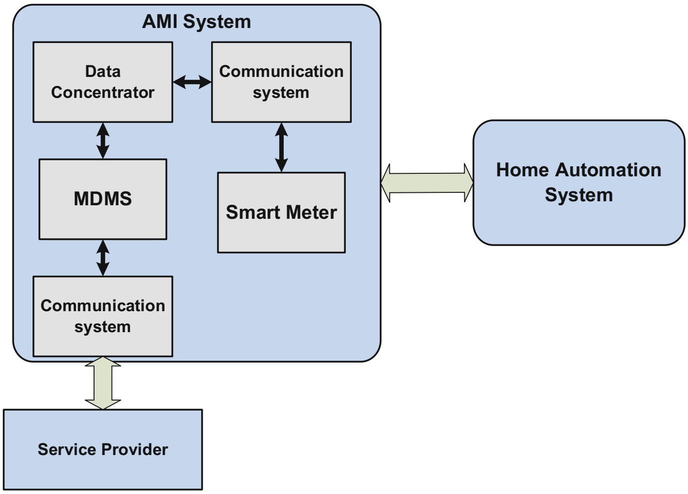

Fig. 9.12 Subsystems of an AMI system [74]

Table 9.4 The AMI standards [74]

Standard	Description
IEC 62051	Glossary: Electricity metering
IEC 62051-11, 21, 31	Requirements and test conditions for metering equipment
IEC 62053	Test requirements and test procedures for metering equipment
IEC 62054-11, 21	Tariff and load control requirements for metering equipment
IEC 62058-11, 21, 31	Inspection requirements for metering equipment
IEC 61968-9	Interfaces for meter reading
IEC 61334	NB-PLC-based automated metering
PRIME	PLC modem standard based on Iberdrola specifications for smart meters
ITU G3-PLC	PLC modem standard based on Electricite Reseau Distribution France (ERDF) specifications for smart meters
M-Bus	Standard for remotely reading of smart meters
IEC 62056	Standard for communication of metering data in Europe
ANSI C12	Standard for communication of metering data in North America

- IEC 62056-76: The Three-layer, Connection-Oriented HDLC-Based Communication Profile,
- IEC 62056-83: Communication Profile for Spread Spectrum Frequency Shift Keying (SS-FSK) Neighborhood Networks.

ANSI C12 Standards

The IEC 62056 protocol standard is used in Europe and in North America the ANSI C12 standards are used for metering purposes. The ANSI C12 standards consist of the following [74, 78]:

- ANSI C12.18: Protocol Specification for ANSI Type-2 Optical Port,
- ANSI C12.19: Utility Industry End Device Data Tables,
- ANSI C12.21: Protocol Specification for Telephone Modem Communication,
- ANSI C12.22: Protocol Specification for Interfacing to Data Communication Networks.

The data table (DT) elements for the support of appliances such as gas, water, sensors are defined in the ANSI C12.19 standards. The ANSI C12.18 standard defines the requirements for transfer of the ANSI C12.19 DT elements over a fiber optic port. Similarly, the ANSI C12.21 standard defines the requirements for the transfer of DT elements over the telephone modem and the ANSI C12.22 standard specifies the requirements or the procedures for communication over various networks.

9.2.10 IEEE C37.118.2-2011 Standard for Synchrophasor Data Transfer

Synchrophasors are time synchronized voltage and current phasors that are measured by the phasor measurement units (PMUs) at different locations in the electrical grid. These time synchronized phasors are monitored at the phasor data concentrator (PDC) for dynamic control of the power grid. The IEEE C37.118.2-2011 defines the standard for the real-time synchrophasor data transfer between the PMUs and the PDC [75]. It predecessor standards were the IEEE 1344-1995 standard and the IEEE C37.118-2005 standard. The document consists of six 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 the message formats.

A synchrophasor communication network consists of several PMUs located on the electrical buses which are distributed over a large geographical lounge. These PMUs are digital signal processing units that are capable of continuously measuring the voltage and current phasors. The measurements are further time synchronized using the reference time signal taken from the global positioning system (GPS). These time tagged measurements are then reported to the PDC for continuous monitoring and control. A simple synchrophasor measurement system is shown in Fig. 9.13.

The PMU simultaneously measures the phasors and communicates the measurements to the PDC in real time. Hence, a well-defined message format is required for homogenizing the communication process among devices developed by the different vendors. This message format is used for communicating the data between the PMU and the PDC and is shown in Fig. 9.14 and the various fields of the frame are described in Table 9.5. The synchrophasor standard defines four types of messages: data, configuration, header, and command. The command messages are received by the PMU and the remaining three types of messages are transmitted by the PMU. These different types of messages are explained below:

- Data messages: These messages are transmitted by the PMU to the PDC. These messages contain information about the synchrophasor measurements.
- Configuration messages: These messages contain information pertaining to the data types, data calibration, and other metadata for the measurement data.

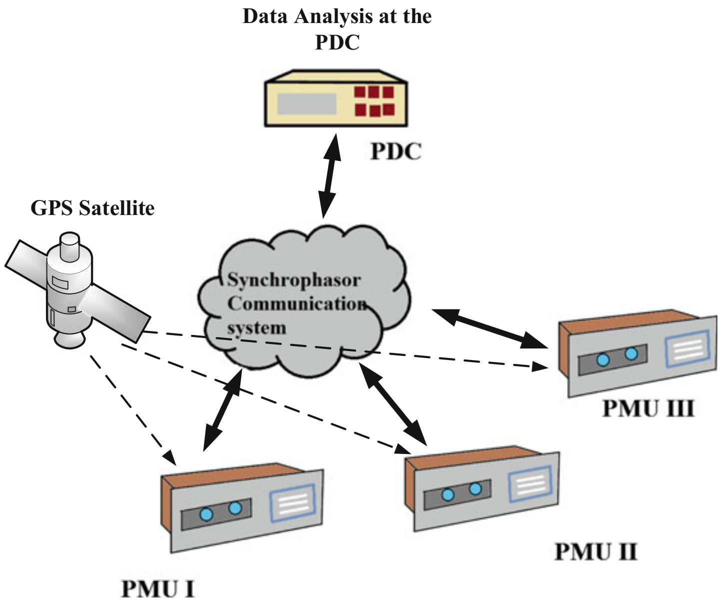

Fig. 9.13 Synchrophasor measurement system [75]

SYNC	Frame Size	IDCODE	SOC	FRACSEC	DATA 1	DATA 2	···	DATA N	CHK
2	2	2	4	4					2

Fig. 9.14 Message frame format for synchrophasor data [75]

- Header messages: These messages are provided by the user and contain human-readable information.
- Command messages: These messages are sent to the PMU for configuration and other control purposes.

9.2.11 IEEE 1815-2012 Standard for Electric Power Systems Communications- Distributed Network Protocol (DNP3)

The DNP3 was first developed by Westronic Inc. in 1992, when the IEC 60870 was still under development. It was by the IEEE in July 2013 as the IEEE 1815-2010 standard which was superseded by the current IEEE 1815-2012 standard [76]. The DNP3 standardizes the communication between the data acquisition devices and the control equipment in the electric power systems. It has a pivotal role in the SCADA systems for providing the communication between the SCADA master station and

Table 9.5 Description synchrophasor message frame [75]

Field	Size (Bytes)	Description
SYNC	2	This field marks the beginning of the frame. The first byte is AA (Hex) and the next bytes 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 (CHK)

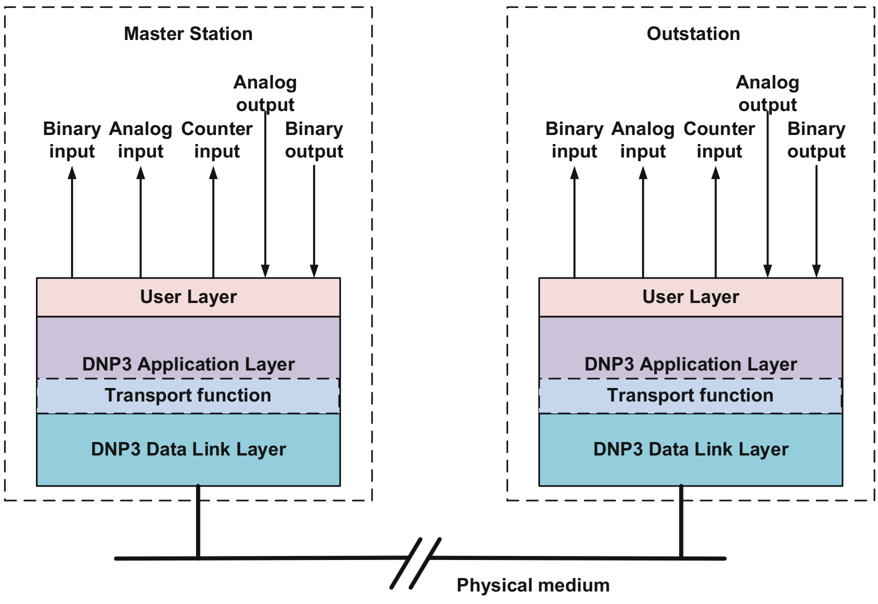

Fig. 9.15 Master-outstation model of DNP3 [76]

the Remote Terminal Units (RTUs) and the IEDs. The master-outstation model used by the DNP3 is shown in the Fig. 9.15.

The data transfer is initiated by the user layer of the master station, which makes the application layer to send an initiation request to the outstation. The request carries the information regarding the type of data that is required by the master station. The transport layer receives the application layer request and segments it into the transmission sized units. The information pertaining to the address and error detection is added at the data layer and the packets are transmitted over the physical medium. At the outstation, the reverse process is carried out. The data layer receives the packets and checks for the address and for the errors. If the packet passes the error detection, the address and the error correction is stripped and the packet is passed on to the transport layer. The transport layer combines all the data packets pertaining to a single request. The application layer of the outstation identifies what data has been requested and asks the user to provide the desired data. The user layer responds to this request and then provides the desired data to the application layer.

9.2.12 Miscellaneous Standards

Apart from the smart grid standards described in the previous subsections, there are several other standards developed for catering to the demands of different smart grid applications. These standards include the open automated demand response (OpenADR) for providing the automatic demand response, several home automation standards such as the HomePlug, HomePlug Green PHY, Utility Smart Network Access Port (U-SNAP), the IEEE 2030 standard for smart grid interoperability, the IEEE 1901 standards for communication over the electrical lines, M-bus for remote reading of electric meters, BACnet for building automation and IEC 62055 for standardizing the payment system in electrical metering. These standards are briefly described in Table 9.6.

9.3 Smart Grid Communication Systems

The communication system is a crucial integrant of the smart grid and is responsible for the flow of information across the different applications in the grid. Because of the integration of diverse and complex equipment into the grid, voluminous data is generated which has to be stored and analyzed. Thus, it is imperative that the smart grid applications should select the best possible technologies to achieve satisfactory performance. An illustration showing the mapping of the smart grid communication systems to the smart grid applications is shown in Fig. 9.16. These systems came to be broadly classified into two categories: wired communication systems and wireless communication systems [77–80].

The wired communication systems require a physical medium for transfer of data between the end devices. The most popular wired communication technologies for the smart grid are the optical communication system and the PLC system. The PLC system uses the existing electrical wires for transfer of data whereas the optical fiber communication requires the deployment of optical fiber cables for the communication feasibility.

The wireless communication technologies do not require any physical media for the transfer of signals. The rapid progress in the field of wireless communication tech-

Table 9.6 Miscellaneous standards [74, 79]

Standard	Description
OpenADR	This standard was developed by the North American research labs for effective energy management. Its main utility involves sending signals to switch off the electrical devices during the periods of peak demand
BACnet	Communication standard was developed by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) for building automation. It aims to standardize the communication process required for automation of equipment supplied by different vendors
HomePlug	This standard specifies the PLC technologies that are used for different types connecting the smart devices to the HAN
HomePlug Green PHY	This standard is developed for specification of low power PLC technologies for HANs
U-SNAP	Several incompatible standards were developed for the HAN. To standardize them, the U-SNAP was developed. Its main purpose is to enable the connectivity of any smart home appliance to the HAN. Communication protocols for connecting the smart grid devices to the HAN
IEEE 1901–2010	This standard was developed by the IEEE P1901 WG and defines the communication of high-speed data (up to 500 Mbps) using the PLC, also known as broadband over power lines (BPL). It describes the physical layer specifications and medium access control (MAC) specifications for BPL. It is mandatory for initiation of the SAE J1772 electric vehicle charging
IEEE 1901.2	This IEEE standard was approved in 2012 and it defines the narrowband PLC (less than 500 kHz) for smart grid applications
IEEE 2030	The IEEE standards association developed this as a “Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads.” It is responsible for reliable data transfer required for reliable power generation, distribution and consumption
IEC 62055	This standard aims at the standardization of payment metering systems. It discusses the system process, the system entities and the interfaces from a generic point of view. It also supports a scheme that allows the various systems and subsystems to be standardized under the IEC 62055 standard
M-Bus	M-Bus or Meter-Bus is a European standard that defines the requirements for remote reading of utility meters such as electricity or water. The architecture considers of several utility meters that are periodically accessed by the master through the M-Bus. Recently, wireless M-Bus has also been specified

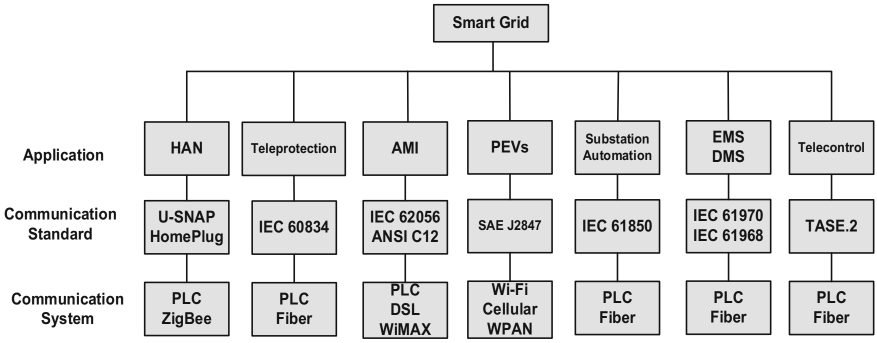

Fig. 9.16 Smart grid communication systems [79]

nologies coupled by the advancement in the signal processing technologies is paving way for their wide-scale deployment in the smart grid. The most widely used wireless communication technologies are the ZigBee, cellular technology, Worldwide Interoperability for Microwave Access (WiMAX), Wireless Local Area Networks (WLAN), satellite communication system, etc. These various smart grid communication technologies along with their relative advantages and disadvantages in the purview of smart grid are comprehensively discussed in the subsequent subsections.

9.3.1 Wired Communication Systems

9.3.1.1 PLC System

The PLC system is the most economical way for smart grid communications as it does not require additional communication media between the devices. In a smart grid, most of the devices are connected to the power line and so the power line can be used for data transfer. This is the idea behind the materialization of the PLC. The PLC system is employed for information exchange between the substations, for telecontrol, SCADA, HAN, teleprotection, etc. It is anticipated that the PLC systems would play a significant role in the future smart grid.

The PLC is further categorized into two: NB-PLC and BB-PLC. The NB-PLC operates in the lower frequency range from 3 to 500 kHz, whereas the BB-PLC operates in the higher frequency range from 2 to 100 MHz. The NB-PLC is used for low bandwidth applications such as the demand response, load control, EMS, AMI. On the other hand, the BB-PLC is used for applications that require higher bandwidth such as the home appliances [80, 81]. Recent developments in the field of multi-input–multi-output (MIMO) technology have enabled the BB-PLC to offer data rates of 1 Gbps.

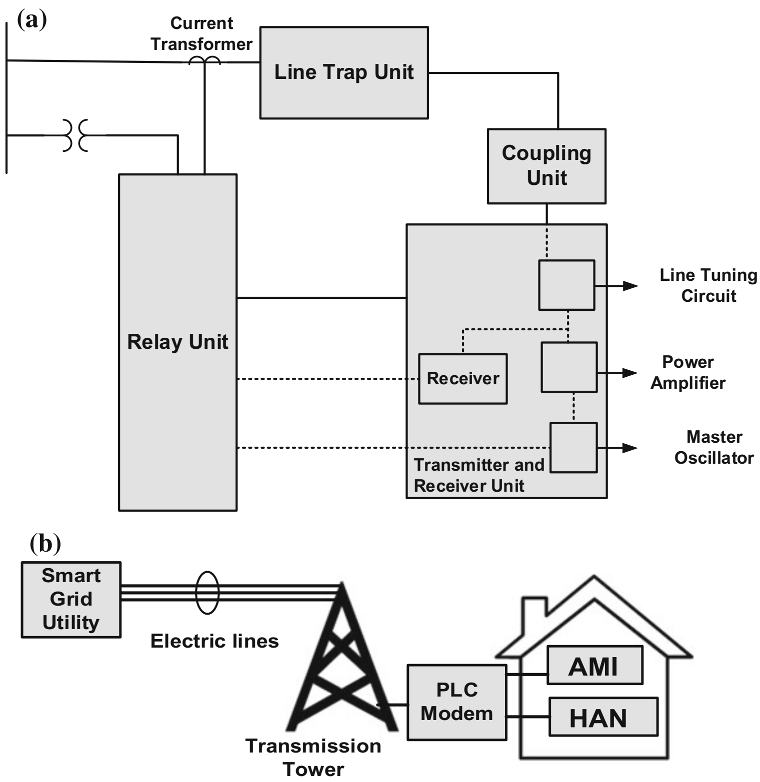

Fig. 9.17 **a** PLC System. **b** Application in AMI and HAN [80]

The PLC systems consist of coupling capacitors, line trap circuit, line tuning circuit, oscillator, power amplifier, transmitter, and receiver. A typical PLC system along with its application is shown in Fig. 9.17.

Despite having several advantages, the PLC system still suffers from severe shortcomings. The power lines are not meant for communication and so the signals undergo severe distortion due to multipath fading, frequency selective fading, and interference. These factors result in reduced SNR. Usually, the PLC is combined with other technologies such as the cellular technology to provide a hybrid solution for smart grid communication, as complete connectivity using the PLC technology is not practical because of the high sensitivity of the technology to external disturbances [79].

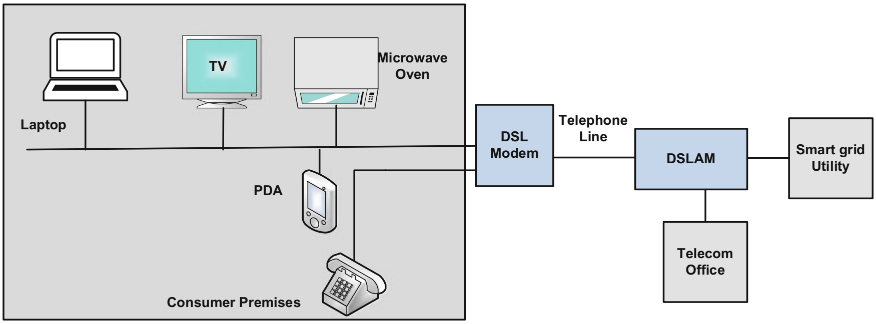

Fig. 9.18 DSL connection setup for smart grid applications [83]

9.3.1.2 Digital Subscriber Lines (DSLs)

Digital subscriber lines (DSLs) enable the transfer of digital data over the existing telephone lines, thereby significantly reducing the installation costs. It is generally employed as the last mile access for connecting the user to the network or to the DSL access multiplexer (DSLAM) which is deployed at a few hundred meters from the customer. A typical DSL connection for smart grid applications is shown in Fig. 9.18. It has a long history and even though it is being replaced by other technologies it can still be an effective smart grid communication technology owing to its high proliferation. It can be used for connecting the smart home appliances to the smart grid [82, 83]. It can also be used for the purpose of AMI and EMS applications. The various DSL technologies are mentioned in Table 9.7.

9.3.1.3 Fiber Optic Communication

The benefits of optical fibers for long-distance communication were known since the early 1990's. Since the early 2000's, the practical deployment of these fibers gained momentum owing to the substantial reduction in their cost and development in the technology. They offer high bandwidth, low attenuation, negligible interference and improved SNR which makes them the widely used wired communication technology in the smart grid [84, 85]. They find application in substation automation, teleprotection, telecontrol, V2G communications, etc. A typical fiber optic communication system is shown in Fig. 9.19.

The optical transmitter is basically a light emitting diode (LED) or a laser which converts the electrical signals into optical signals. These optical signals are then carried via the optical fibers to the receiver. At the receiver, the optical signal is converted back into the electrical signals using a photodiode. Between the transmitter and the receiver, repeaters are placed at regular intervals in order to boost the signal strength and to maintain the signal quality.

Table 9.7 DSL technologies

Name	Description
ISDN DSL	This uses Integrated Services Digital Network (ISDN) technology and provides a symmetric data rate of 144 Kbps in both the directions
High bit-rate DSL (HDSL)	Provides symmetric services of 1544 Kbps and 2018 Kbps
HDSL2	Provides up to 1544 Kbps symmetric over one pair
HDSL4	Provides up to 1544 Kbps symmetric over two pairs
Symmetric DSL (SDSL)	Proprietary technology that provides up to 1544 Kbps symmetric over one pair
Single pair high-speed DSL (G. SHDSL)	Successor of SDSL that provides up to 5696 Kbps symmetric over one pair
ANSI T1.413 Issue 2	Provides up to 8 Mbps in one direction and 1 Mbps in the reverse
ITU-T G.992.1	Provides up to 10 Mbps in one direction and 1 Mbps in the reverse
ITU-T G.992.2	Provides up to 1536 Kbps in one direction and 512 Kbps in the reverse but is more resistant to noise than the ITU-T G.992.1
Asymmetric DSL2 (ADSL2)	Provides up to 12 Mbps in one direction and 3.5 Mbps in the reverse
ADSL2+	Provides up to 24 Mbps in one direction and 3.5 Mbps in the reverse
Very high bit-rate DSL (VDSL)	Provides up to 52 Mbps in one direction and 16 Mbps in the reverse
VDSL2	Provides a combined data rate of up to 200 Mbps in both the directions

A typical example of fiber optic communication in smart grid is for the transfer of synchrophasor measurement data [85]. This is illustrated in the Fig. 9. 20. The PMUs measure the data which is modulated by the optical transceiver and transferred via the optical cable. At the PDC, these signals are demodulated back into electrical signals for subsequent analysis. Synchrophasor applications require real-time processing and hence fiber optic comes out to be an ideal communication technology.

In spite of its several advantages, this communication technology is also plagued by the problems which are common to the other wired communication technology. The biggest disadvantage is the high installation cost. Also, it requires substantial time in order to lay the fiber cables and hence they are not suitable for immediate deployment. It is also difficult to connect geographical regions that are in rocky or hilly terrain through this technology.

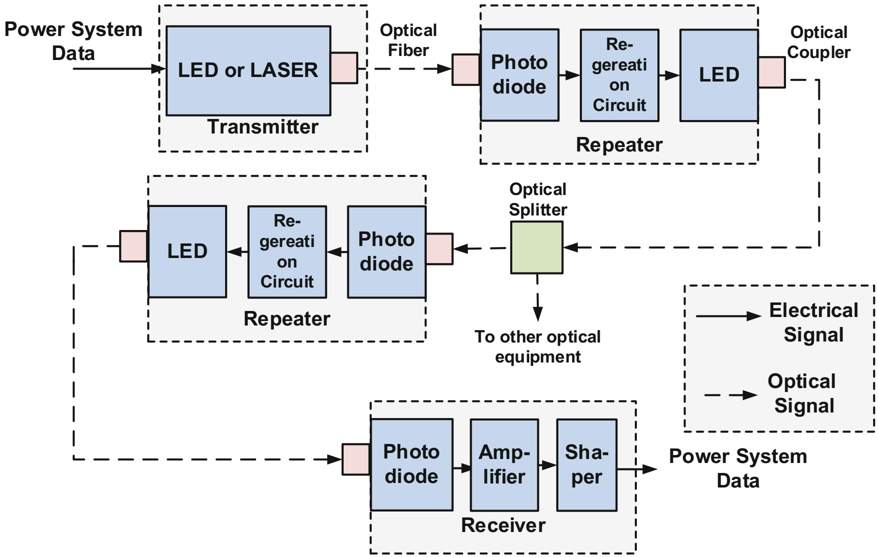

Fig. 9.19 Optical fiber communication system

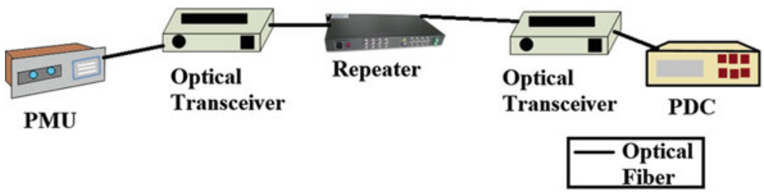

Fig. 9.20 Optical fiber communication system for synchrophasor data transfer [85]

9.3.2 Wireless Communication Systems

9.3.2.1 Cellular Communication System

Cellular communication system is another viable option for quick deployment of the communication infrastructure. These networks already exist and hence they are cost-effective solution for integration of smart grid applications [86]. The other reasons for opting it are the increased data rates, high proliferation, increase in data reliability and quality. This technology is increasingly being employed for AMI, HANs, wide area networks (WAN), V2G communication, etc. The cellular technologies that are available for the smart grid applications are shown in Table 9.8. The basic cellular communication consists of a mobile user who exchanges information with a fixed base station through a wireless link. Several such base stations are connected to a central station through the fiber optic cables. The central station acts as a gateway for

Table 9.8 Cellular technologies for smart grid applications

Technology	Data rates	Applications
Global system for mobile communications (GSM)	Up to 9.6 Kbps	HANs, AMI
General packet radio service (GPRS)	Up to 114 Kbps	HANs, AMI
Enhanced data rates for GSM evolution (EDGE)	Up to 384 Kbps	HANs, AMI
Universal mobile telecommunications system (UMTS)	Up to 2 Mbps	HANs, AMI, V2G
High-speed packet access (HSPA)	600 Kbps–10 Mbps	HANs, AMI, V2G
Long-term evolution-advanced (LTE-A)	Up to 100 Mbps	AMI, Fault Detection

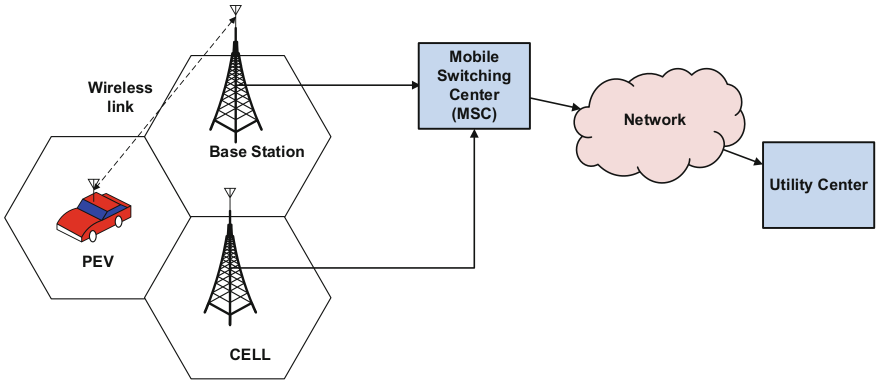

Fig. 9.21 Cellular communication system for smart grid applications

connecting to the rest of the network. This system for a typical smart grid application is shown in Fig. 9.21.

The cellular technology is one of the fastest growing technologies in the world and research is already in progress for practical deployment of the fifth-generation cellular technology (5G) which promises a data rate of 100 Gbps. However, there are a few disadvantages. Since the cellular system is simultaneously shared by many users; it cannot cater to the demands of some of the mission-critical applications that require uninterrupted services.

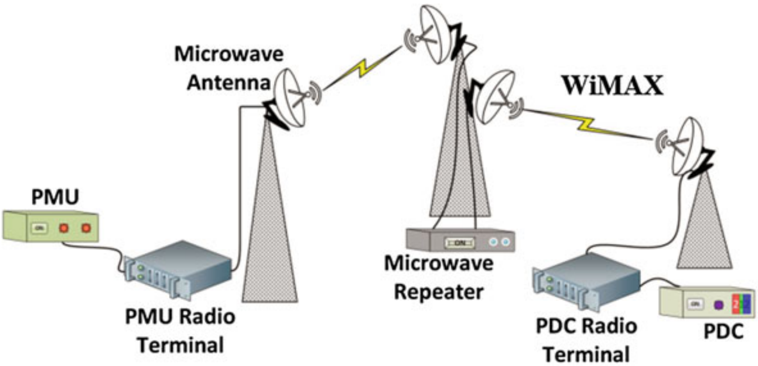

Fig. 9.22 WiMAX for synchrophasor applications [87]

9.3.2.2 WiMAX

WiMAX is another technology developed to provide wireless communication services. There are several releases of this technology which are summarized in Table 9.9. It is a major competitor to the LTE and is very similar to LTE technology. The major disadvantage of the WiMAX is that uses the Orthogonal Frequency Division Multiplexing (OFDM) technology which has a significant peak to average power ratio (PAPR). This technology may find significant application in V2G communications and can replace the optical fibers in providing high bandwidth backhaul in synchrophasor applications [87]. The alternative WiMAX communication system to the optical technology for the synchrophasor data transfer is shown in Fig. 9.22.

9.3.2.3 WLAN

WLAN is a wireless communication technology with one distinctive feature. The WLAN uses unlicensed frequency spectrum for data transfer and has emerged as a popular choice for networking in a small area. The WLAN is based on the IEEE 802.11 standards which are summarized in Table 9.10. The WLAN can be used for home automation applications and for AMI applications [86]. However, the major disadvantage of this technology is that it operates in the unlicensed frequency band and so is more susceptible to noise and interference. Another disadvantage of this technology is the limited coverage area and hence cannot be used for wide area applications.

In a WLAN, the devices are connected in two different architectures: centralized or infrastructure architecture and ad hoc architecture. In the infrastructure architecture, the devices in the LAN exchange information with each other and with the external network through the medium of a base station. On the other hand, in an ad hoc

Table 9.9 WiMAX standards

Standard	Description
IEEE 802.16	This document is currently withdrawn. It specifies the data transfer at high frequencies between 11 and 66 GHz
IEEE 802.16a	This document is currently withdrawn. It provides the specifications for 2–10 GHz frequency band
IEEE 802.16b	This document is currently withdrawn. It also includes the licensed frequency band of 5–6 GHz and discusses the aspect of QoS
IEEE 802.16c	This document is currently withdrawn. Defines the system profile for the 11–66 GHz band, for increased interoperability
IEEE 802.16d	This standard replaced all the previous standards. Presents the use of OFDM and procedures for compliance testing. This was for fixed operation
IEEE 802.16e	This standard was provided for mobile use
IEEE 802.16f	This standard defines a management information base (MIB) for the management of MAC and PHY layers
IEEE 802.16 g	This document specifies management plane procedures and services
IEEE 802.16 h	This document specifies improved coexistence mechanisms for license-exempt operation
IEEE 802.16j	This document specifies the standard for multi-hop relay
IEEE 802.16 m	Specifies the advanced air interface for fixed data rates of 1 Gbps and mobile data rates of 100 Mbps
IEEE 802.16-2012	Specifies the air interface for broadband wireless access systems
IEEE 802.16.1-2012	Specifies the air interface for WirelessMAN broadband wireless access systems
IEEE 802.16p-2012	Specifies the air interface for broadband wireless access systems to support machine-to-machine (M2 M) applications
IEEE 802.16.1b-2012	Specifies the air interface for WirelessMAN broadband wireless access systems to support M2 M applications
IEEE 802.16n-2013	Specifies the air interface for broadband wireless access systems for high reliability
IEEE 802.16.1a-2013	Specifies the air interface for WirelessMAN broadband wireless access systems for high reliability

Table 9.10 WLAN standards

Standard	Description
IEEE 802.11a	WLAN for the 5 GHz industrial, scientific, and medical (ISM) band with bandwidth of 20 MHz and data rates up to 54 Mbps
IEEE 802.11b	WLAN for the 2.4 GHz ISM band with bandwidth of 22 MHz and data rates up to 11 Mbps
IEEE 802.11e	This standard specifies the QoS and prioritization
IEEE 802.11f	This standard specifies the handover in the WLAN environment
IEEE 802.11 g	WLAN for the 2.4 GHz ISM band with bandwidth of 20 MHz and data rates up to 54 Mbps
IEEE 802.11 h	This standard specifies the power control
IEEE 802.11i	This document standardizes the authentication and encryption in WLAN
IEEE 802.11j	This document specifies the internetworking in a WLAN
IEEE 802.11 k	This document deals with the measurement reporting
IEEE 802.11n	WLAN for the 2.4 and 5 GHz ISM band with bandwidth of 40 MHz and data rates up to 150 Mbps
IEEE 802.11 s	Specifies the WLAN standard for mesh networking
IEEE 802.11ac	WLAN operating below 6 GHz with data rates up to 1 Gbps for multi-station operation and 500 Mbps on a single link
IEEE 802.11ad	WLAN providing high throughput at 60 GHz
IEEE 802.11ah	WLAN operating in the unlicensed bands below 1 GHz for long-range communications

architecture, few devices form a network and exchange information with one another. These two architectures are shown in Fig. 9.23.

9.3.2.4 Satellite Communication

Satellite communication technology has developed over the last few decades and is widely used for applications such as Direct-To-Home (DTH), geological monitoring, defense. Due to the presence of the communication equipment in the space, above the surface of the earth, this system is impervious to the natural disasters such as floods,

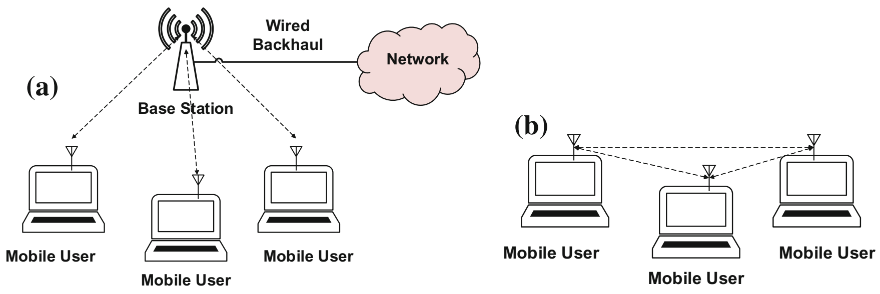

Fig. 9.23 **a** Infrastructure architecture. **b** Ad hoc networks

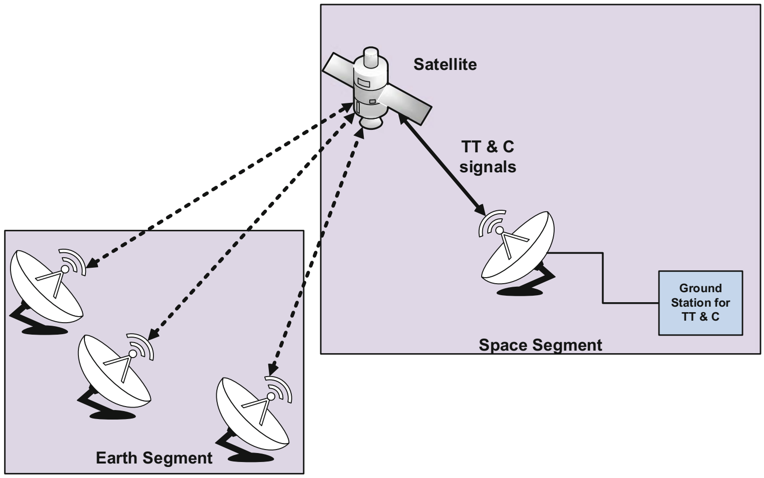

Fig. 9.24 Satellite communication

earthquakes. The satellite communication system consists of two segments: the space segment and the earth 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 the transmit and receive earth stations. These two segments are shown in Fig. 9.24.

In smart grid, this technology can be used for the exchange of power system data, between the systems that are separated by a large geographical sprawl such as the wide area measurement system (WAMS) or the PMU [74]. The major disadvantage of the technology is the delay. Since the signals have to travel several hundreds of kilometers, this technology is not suitable for real-time monitoring and control applications.

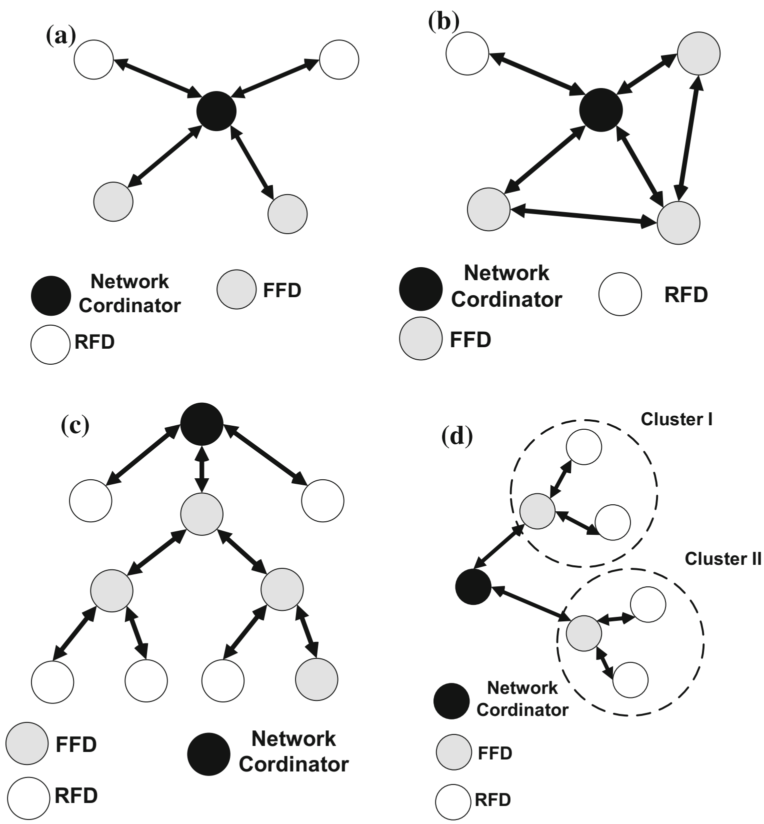

Fig. 9.25 ZigBee network topologies. **a** Star. **b** Mesh. **c** Tree. **d** Cluster tree

9.3.2.5 ZigBee

ZigBee is another wireless communication technology which is based on the IEEE 802.15.4 standard and is used for creating personal area networks (PANs) suitable for low power, low range and low-cost applications [88, 89]. It operates in the 2.4 GHz unlicensed frequency band and provides data rates of 250 Kbps. In smart grid, this technology is used for creating home automation networks and in wireless sensor networks (WSNs). In a ZigBee, the devices can be connected in four different architectures: mesh topology, star topology, tree topology, and cluster tree topology. These four topologies are shown in Fig. 9.25.

Each network consists of at least one full function device (FFD) which can communicate with one another. One of the FFDs acts as a coordinator for the network. It also consists of reduced function devices (RFD) which communicate with the FFD and have modest communication capabilities.

The disadvantage of this technology is that it operates in the unlicensed frequency band and hence is susceptible to noise and interference problems.

9.4 Challenges and Future Technologies

9.4.1 Challenges

As mentioned earlier, the smart grid is an interconnection of several sophisticated devices interacting with diverse communication requirements. Smart grid communication technology has progressed over the past few decades, and this has enhanced the materialization of several smart grid applications. However, there exist major challenges to the existing smart grid technologies are as follows [90]:

- High reliability: Most of the smart grid applications are mission critical, requiring availability of more than 99.9999%. The operational downtime for the existing communication technologies must be considerably minimized in order to fulfill this requirement.
- Low latency: Most of the smart grid applications are real time, requiring a round time of a few milliseconds. One solution is the use of dedicated communication systems for the smart grid applications, which comes at an increased system cost. So, the challenge is to minimize the communication time and at the same time, sharing the communication resources with other applications. This requires optimization of communication resources and improved protocols.
- Enhanced security: Smart grid communication technologies such as the WLAN, ZigBee operate in the open medium and are accessible to all. The cybersecurity standards must be considerably enhanced to prevent unauthorized access to power system data.
- Higher data rates: With more and more devices getting incorporated into the smart grid, the need for providing higher data rates without compromising with the QoS is another challenge for research community.
- Interoperability: Even though considerable effort has been put into standardizing the communication process in the smart grid, there still exist diverse standards and technologies in the market.
- Renewable resources: With the proliferation of renewable sources into the existing power grid, the monitoring of power flow and energy management would become more complicated. Since the consumers would be able to generate power, the AMI should be more effective to accommodate this dynamic nature.

9.4.2 Future Technologies

The potential technologies that are expected to transform the smart grid are the Internet of Things (IoT) and 5G. A brief description of these two technologies is presented below:

IoT

The IoT is a recent technology that aims at creating a network of intelligent devices that are connected to the Internet. These devices are embedded system with power signal processing capabilities that can sense, analyze, monitor, and control the surrounding physical parameters. Thus, the purpose of the smart grid can be achieved using the IoT [91]. There are three major applications of IoT in a smart grid. The first important application is the deployment of IoT devices for measurement of the grid parameters. The next major application is the storage and analysis of the power grid data for monitoring. Finally, the third application of the IoT is the implementation of the control action for the smooth operation of the grid.

The smart grid consists of four major domains: power generation, transmission, distribution, and consumption. In power generation, the IoT devices can be deployed for monitoring the quality of power generation, health status of the generators, the level of unwanted emissions, etc. In the field of power transmission, the IoT devices can be used for detection of faults in the transmission lines and in the distribution sector the IoT devices can be used for load management, automation of power distribution, and monitoring of the substation equipment. Finally, at the consumption level, the IoT devices can be employed for effective monitoring of the home appliances, energy consumption management, charging of the PEVs and for AMI applications. Smart devices are low power consuming wireless sensors, RFID tags, scanners, etc. The IoT also provides platform for cloud storage and cloud analytics thereby considerably reducing the latency and can be a viable alternative for real-time applications. The potential applications of IoT in the smart grid are illustrated in Fig. 9.26.

5G

The 5G technology is the next generation cellular standard and can offer data rates much higher than the existing 3G and 4G standards. It is expected to connect the devices wirelessly. This technology is envisioned to provide a reliability of 99.999% with a latency of 1 ms which is ten times smaller than the previous standard. It is also expected to provide data rates up to 10 Gbps and provide 100% coverage. The main application of the 5G in the smart grid is: V2G, real-time monitoring, and control using WAMS, fault detection, etc.

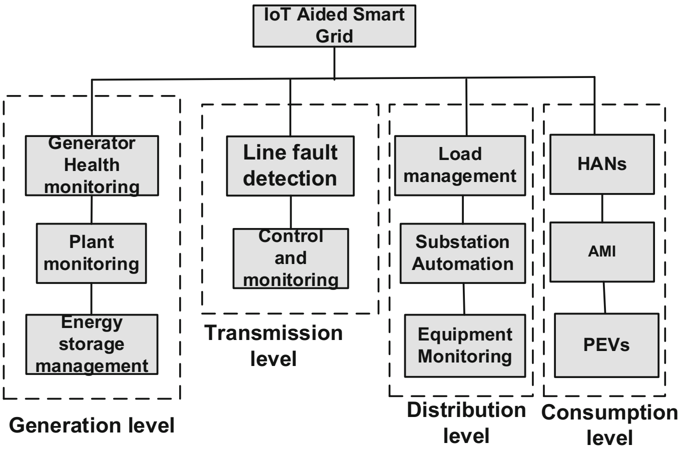

Fig. 9.26 IoT-based smart grid [91]

9.5 Conclusion

The smart grid communication system is responsible for the flow of information across the various smart grid devices. This chapter provides a comprehensive discussion of the various smart grid communication standards and smart grid communication systems. Communication standards for substation automation, teleprotection, cybersecurity, EMS, DMS, V2G, AMI, synchrophasor data transfer, and the DNP3 have been comprehensively presented. Several other miscellaneous communication standards such as the OpenADR, BACnet, IEEE 1901 standard have been briefly described. Next, the communication technologies for the smart grid application such as PLC, optical fiber, WLAN, ZigBee have been discussed. These technologies have been mapped to the various smart grid applications. Even though the smart grid can enhance the quality of power generation and distribution, there are several major challenges that are to be addressed such as the as the standardization of the diverse smart grid technologies, enhancement of reliability, minimization of latency. Finally, two future smart grid technologies, namely IoT and 5G have been briefly discussed.

References

1. W. Wang, Y. Xu, M. Khanna, A survey on the communication architectures in smart grid. Comput. Netw. **55**(15), 3604–3629 (2011)
2. M. Kuzlu, M. Pipattanasomporn, S. Rahman, Communication network requirements for major smart grid applications in HAN, NAN and WAN. Comput. Netw. **67**, 74–88 (2014)
3. M. Adamiak, D. Baigent, R. Mackiewicz, in *IEC 61850 Communication Networks and Systems in Substations* (2010)

4. IEC, IEC61850-1, in *Communication Network and Systems in Substations-Part 1: Introduction and Overview* (International Electrotechnical Commission, 2003)
5. IEC, IEC61850-2, in *Communication Network and Systems in Substations-Part 2: Glossary* (International Electrotechnical Commission, 2003)
6. IEC, IEC 61850-3, in *Communication Network and Systems in Substations-Part 3: General Requirements* (International Electrotechnical Commission, 2003)
7. IEC, IEC 61850-4, in *Communication Network and Systems in Substations-Part 4: System and Project Management* (International Electrotechnical Commission, 2003)
8. IEC, IEC 61850-5, in *Communication Networks and Systems in Substation-Part 5: Communication Requirement for Functions and Device Models* (International Electrotechnical Commission, 2003)
9. IEC, IEC 61850-7-1, in *Communication Networks and Systems in Substation-Part 7-1: Basic Communication Structure for Substation and Feeder Equipment-Principles and Models* (International Electrotechnical Commission, 2003)
10. IEC, IEC 61850-7-2, in *Communication Networks and Systems in Substation Part 7-2: Basic Communication Structure for Substation and Feeder Equipment-Abstract Communication Service Interface (ACSI)* (International Electrotechnical Commission, 2003)
11. IEC, IEC 61850-7-3, in *Communication Networks and Systems in Substation Part 7-3: Basic Communication Structure for Substation and Feeder Equipment-Common Data Classes* (International Electrotechnical Commission, 2003)
12. IEC, IEC 61850-7-4, in *Communication Networks and Systems in Substation Part 7-4: Basic Communication Structure for Substation and Feeder Equipment-Compatible Logical Node Classes and Data Classes* (International Electrotechnical Commission, 2003)
13. IEC, IEC 61850-8-1, in *Communication Networks and Systems in Substation—Part 8-1: Specific Communication Service Mapping (SCSM)-Mapping to MMS (ISO/IEC 9506-1 and ISO/IEC 9506-2) and to ISO/IEC 8802-3* (International Electrotechnical Commission, 2003)
14. IEC, IEC 61850-9-1, in *Communication Networks and Systems in Substation—Part 9-1: Specific Communication Service Mapping (SCSM)-Sampled Values Over Serial Unidirectional Multidrop Point to Point Link* (International Electrotechnical Commission, 2003)
15. IEC, IEC 61850-9-2, in *Communication Networks and Systems in Substation—Part 9-2: Specific Communication Service Mapping (SCSM)-Sampled Values Over ISO/IEC 8802-3* (International Electrotechnical Commission, 2003)
16. IEC, IEC 60870-5-1, in *Telecontrol Equipment and Systems–Part 5-1: Transmission Protocols - Transmission Frame Formats* (International Electrotechnical Commission, 1990)
17. IEC, IEC 60870-5-2, in *Telecontrol Equipment and Systems–Part 5-2: Transmission Protocols—Data Link Transmission Services* (International Electrotechnical Commission, 1992)
18. IEC, IEC 60870-5-3, in *Telecontrol Equipment and Systems–Part 5-3: Transmission Protocols—General Structure of Application Data* (International Electrotechnical Commission, 1992)
19. IEC, IEC 60870-5-4, in *Telecontrol Equipment and Systems–Part 5-4: Transmission Protocols—Definition and Coding of Information Elements* (International Electrotechnical Commission, 1993)
20. IEC, IEC 60870-5-5, in *Telecontrol Equipment and Systems–Part 5-5: Transmission Protocols—Basic Application Functions* (International Electrotechnical Commission, 1995)
21. IEC, IEC 60870-5-6, in *Telecontrol Equipment and Systems–Part 5-6: Guidelines for Conformance Testing for the IEC 60870-5 Companion Standards* (International Electrotechnical Commission, 2006)
22. IEC, IEC 60870-5-7, in *Telecontrol equipment and systems—Part 5-7: Transmission protocols—Security extensions to IEC 60870-5-101 and IEC 60870-5-104 protocols (applying IEC 62351)* (International Electrotechnical Commission, 2013)
23. IEC, IEC 60870-5-101, in *Telecontrol Equipment and Systems–Part 5-101: Transmission Protocols—Companion Standard for Basic Telecontrol Tasks* (International Electrotechnical Commission, 1995)
24. IEC, IEC 60870-5-102, in *Telecontrol Equipment and Systems–Part 5-102: Companion Standard for the Transmission of Integrated Totals in Electric Power Systems* (International Electrotechnical Commission, 1996)

25. IEC, IEC 60870-5-103, in *Telecontrol Equipment and Systems–Part 5-103: Transmission Protocols—Companion Standard for the Informative Interface of Protection Equipment* (International Electrotechnical Commission, 1997)
26. IEC, IEC 60870-5-104, in *Telecontrol Equipment and Systems–Part 5-104: Transmission Protocols—Network Access for IEC 60870-5-101 Using Standard Transport Profiles* (International Electrotechnical Commission, 2006)
27. IEC, IEC 60870-5-601, in *Telecontrol Equipment and Systems—Part 5-601: Transmission Protocols—Conformance Test Cases for the IEC 60870-5-101 Companion Standard* (International Electrotechnical Commission, 2015)
28. IEC, IEC 60870-5-604, in *Telecontrol Equipment and Systems—Part 5-604: Conformance Test Cases for the IEC 60870-5-104 Companion Standard* (International Electrotechnical Commission, 2016)
29. IEC, IEC TR 60870-6-1, in *Telecontrol Equipment and Systems—Part 6: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—Section 1: Application Context and Organization of Standards* (International Electrotechnical Commission, 1995)
30. IEC, IEC 60870-6-2, in *Telecontrol Equipment and Systems—Part 6: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—Section 2: Use of Basic Standards (OSI layers 1–4)* (International Electrotechnical Commission, 1995)
31. IEC, IEC 60870-6-501, in *Telecontrol Equipment and Systems—Part 6: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—Section 501: TASE.1 Service Definitions* (International Electrotechnical Commission, 1995)
32. IEC, IEC 60870-6-502, in *Telecontrol Equipment and Systems—Part 6: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—Section 502: TASE.1 Protocol Definitions* (International Electrotechnical Commission, 1995)
33. IEC, IEC 60870-6-503, in *Telecontrol Equipment and Systems—Part 6-503: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—TASE.2 Services and Protocol* (International Electrotechnical Commission, 2014)
34. IEC, IEC 60870-6-504, in *Telecontrol Equipment and Systems—Part 6-504: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—TASE.1 User Conventions* (International Electrotechnical Commission, 1998)
35. IEC, IEC 60870-6-505, in *Telecontrol Equipment and Systems—Part 6-505: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—TASE.2 User Guide* (International Electrotechnical Commission, 2002)
36. IEC, IEC 60870-6-601, in *Telecontrol Equipment and Systems—Part 6: Telecontrol Protocol's Compatible with ISO Standards and ITU-T Recommendations—Section 601: Functional Profile for Providing the Connection-Oriented Transport Service in an End System Connected via Permanent Access to a Packet Switched Data Network* (International Electrotechnical Commission, 1994)
37. IEC, IEC 60870-6-602, in *Telecontrol equipment and systems—Part 6-602: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—TASE Transport Profiles* (International Electrotechnical Commission, 2001)
38. IEC, IEC 60870-6-701, in *Telecontrol Equipment and Systems—Part 6-701: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—Functional Profile for Providing the TASE.1 Application Service in End Systems* (International Electrotechnical Commission, 1998)
39. IEC, IEC 60870-6-702, in *Telecontrol Equipment and Systems—Part 6-702: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—Functional Profile for Providing the TASE.2 Application Service in End Systems* (International Electrotechnical Commission, 2014)
40. IEC, IEC 60870-6-802, in *Telecontrol Equipment and Systems—Part 6-802: Telecontrol Protocols Compatible with ISO Standards and ITU-T Recommendations—TASE.2 Object Models* (International Electrotechnical Commission, 2014)
41. IEC, IEC 60834-1, in *Teleprotection Equipment of Power Systems—Performance and Testing—Part 1: Command Systems* (International Electrotechnical Commission, 1999)

42. IEC, IEC 60834-2, in *Teleprotection Equipment of Power Systems—Performance and Testing—Part 2: Analogue Comparison System* (International Electrotechnical Commission, 1993)
43. IEC, IEC 61970-1, in *Energy Management System Application Program Interface (EMS-API)—Part 1: Guidelines and General Requirements* (International Electrotechnical Commission, 2005)
44. IEC, IEC TS 61970-2, in *Energy Management System Application Program Interface (EMS-API)—Part 2: Glossary* (International Electrotechnical Commission, 2004)
45. IEC, IEC 61970-301, in *Energy Management System Application Program Interface (EMS-API), Part 301: Common Information Model (CIM) Base* (International Electrotechnical Commission, 2016)
46. IEC, IEC 61970-302, in *Energy Management System Application Program Interface (EMSAPI), Part 302: Common Information Model (CIM) Financial, Energy Scheduling and Reservations* (International Electrotechnical Commission, 1999)
47. IEC, IEC TS 61970-401, in *Energy Management System Application Program Interface (EMS-API), Part 401: Component Interface Specification (CIS) Framework* (International Electrotechnical Commission, 2005)
48. IEC, IEC TS 61970-402, in *Energy Management System Application Program Interface (EMS-API), Part 402: Component Interface Specification (CIS)—Common Services* (International Electrotechnical Commission, 2009)
49. IEC, IEC TS 61970-402, in *Energy Management System Application Program Interface (EMS-API), Part 403: Component Interface Specification (CIS)—Generic Data Access* (International Electrotechnical Commission, 2009)
50. IEC, IEC 61970-404, in *Energy Management System Application Program Interface (EMS-API), Part 404: High Speed Data Access (HSDA)* (International Electrotechnical Commission, 2007)
51. IEC, IEC 61970-407, in *Energy Management System Application Program Interface (EMS-API), Part 407: Time Series Data Access (TSDA)* (International Electrotechnical Commission, 2007)
52. IEC, IEC 61970-453, in *Energy Management System Application Program Interface (EMS-API)—Part 453: Diagram Layout Profile* (International Electrotechnical Commission, 2014)
53. IEC, IEC 61970-501, in *Energy Management System Application Program Interface (EMS-API)—Part 501: Common Information Model Resource Description Framework (CIM RDF) Schema* (International Electrotechnical Commission, 2006)
54. IEC, IEC 61968-1, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 1: Introduction and General Requirements* (International Electrotechnical Commission, 2003)
55. IEC, IEC 61968-2, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 2: Glossary* (International Electrotechnical Commission, 2003)
56. IEC, IEC 61968-3, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 3: Interface for Network Operations* (International Electrotechnical Commission, 2004)
57. IEC, IEC 61968-4, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 4: Interfaces for Records and Asset Management* (International Electrotechnical Commission, 2007)
58. IEC, IEC 61968-6, in *Application Integration at Electric Utilities—System Interfaces for Distribution Management—Part 6: Interfaces for Maintenance and Construction* (International Electrotechnical Commission, 2015)
59. IEC, IEC 61968-8, in *Application Integration at Electric Utilities—System Interfaces for Distribution Management—Part 8: Interfaces for Customer Operations* (International Electrotechnical Commission, 2015)
60. IEC, IEC61968-9, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 9: Interface Standard for Meter Reading and Control* (International Electrotechnical Commission, 2008)

61. IEC, IEC61968-11, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 11: Common Information Model (CIM) Extensions for Distribution* (International Electrotechnical Commission, 2008)
62. IEC, IEC61968-13, in *Application Integration at Electric Ultilities-System Interfaces for Distribution Management-Part 13: Common Information Model (CIM) RDF Model Exchange Format for Distribution* (International Electrotechnical Commission, 2008)
63. IEC, IEC 62351-1, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 1: Introduction to the Security Issues* (International Electrotechnical Commission, 2007)
64. IEC, IEC 62351-2, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 2: Glossary of Terms* (International Electrotechnical Commission, 2008)
65. IEC, IEC 62351-3, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 3: Security for Any Profiles Including TCP/IP* (International Electrotechnical Commission, 2007)
66. IEC, IEC 62351-4, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 4: Security for Any Profiles Including MMS* (International Electrotechnical Commission, 2007)
67. IEC, IEC 62351-5, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 5: Security for IEC 60870-5 and Derivatives* (International Electrotechnical Commission, 2009)
68. IEC, IEC 62351-6, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security-Part 6: Security for IEC 61850 Profiles* (International Electrotechnical Commission, 2007)
69. IEC, IEC 62351-7, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security, Part 7: Network and System Management (NSM) Data Object Models* (International Electrotechnical Commission, 2010)
70. IEC, IEC 62351-8, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 8: Role-Based Access Control* (International Electrotechnical Commission, 2011)
71. IEC, IEC 62351-9, in *Power Systems Management and Associated Information Exchange—-Data and Communications Security—Part 9: Cyber Security Key Management for Power System Equipment* (International Electrotechnical Commission, 2017)
72. IEC, IEC TR 62351-10, in *Power Systems Management and Associated Information Exchange—Data and Communications Security—Part 10: Security Architecture Guidelines* (International Electrotechnical Commission, 2017)
73. SAE International. http://www.standards.sae.org/. Accessed 15 Sept 2017
74. T. Sato, D.M. Kammen, B. Duan, M. Macuha, Z. Zhou, J. Wu, S.A. Asfaw, in *Smart Grid Standards: Specifications, Requirements, and Technologies* (Wiley, 2015)
75. IEEE Std C37.118.2-2011, in *IEEE Standard for Synchrophasor Data Transfer for Power Systems* (Institute of Electrical and Electronics Engineers, 2011)
76. IEEE Std 1815-2012, in *IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3)—Redline* (Institute of Electrical and Electronics Engineers, 2012)
77. IEC https://www.webstore.iec.ch/. Accessed 15 Sept 2017
78. NEMA http://www.nema.org/stds/. Accessed 15 Sept 2017
79. V.C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, G.P. Hancke, Smart grid technologies: communication technologies and standards. IEEE Trans. Ind. Inform. **7**(4), 529–539 (2011)
80. L.T. Berger, A. Schwager, J.J. Escudero-Garzás, Power line communications for smart grid applications. J. Electr. Comput. Eng. **2013**, 3 (2013)
81. S. Galli, A. Scaglione, Z. Wang, Power Line communications and the smart grid, in *First IEEE International Conference on Smart Grid Communications* (Gaithersburg, MD, 2010), pp. 303–308

82. M.F. Baba, Smart grid with ADSL connection for solving peak blackouts in West Bank, in *First International Conference on Renewable Energies and Vehicular Technology* (Hammamet, 2012), pp. 270–273
83. N. Andreadou, M.O. Guardiola, G. Fulli, Telecommunication technologies for smart grid projects with focus on smart metering applications. Energies **9**(5), 375 (2016)
84. M. Li, L. Zhang, Y. Wu, H. Chi, Comprehensive assessment of optical network in power grid, in *15th IEEE International Conference on Optical Communications and Networks (ICOCN)* (2016), pp. 1–3
85. B. Appasani, D.K. Mohanta, Co-optimal placement of PMUs and their communication infrastructure for minimization of propagation delay in WAMS, in *IEEE Transactions on Industrial Informatics* (2018)
86. V.C. Gungor, F.C. Lambert, A survey on communication networks for electric system automation. Comput. Netw. **50**(7), 877–897 (2006)
87. B. Appasani, D.K. Mohanta, Optimal placement of synchrophasor sensors for risk hedging in a smart grid. IEEE Sens. J. **17**(23), 7857–7865 (2017)
88. C. Gezer, C. Buratti, A ZigBee smart energy implementation for energy efficient buildings, in *IEEE 73rd Vehicular Technology Conference (VTC Spring)* (2011), pp. 1–5
89. A.Y. Mulla, J.J. Baviskar, F.S. Kazi, S.R. Wagh, Implementation of ZigBee/802.15.4 in smart grid communication and analysis of power consumption: a case study, in *Annual IEEE India Conference (INDICON)* (2014), pp. 1–7
90. R. Ma, H.H. Chen, Y.R. Huang, W. Meng, Smart grid communication: its challenges and opportunities. IEEE Trans. Smart Grid **4**(1), 36–46 (2013)
91. Y. Saleem, N. Crespi, M.H. Rehmani, R. Copeland, Internet of things-aided smart grid: technologies, architectures, applications, prototypes, and future research directions. arXiv preprint arXiv:1704.08977 (2017)