Computer Networks 67 (2014) 74–88

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Survey Paper

Communication network requirements for major smart grid applications in HAN, NAN and WAN

Murat Kuzlu *, Manisa Pipattanasomporn, Saifur Rahman

Virginia Tech, Advanced Research Institute, Arlington, VA 22203, USA

ARTICLE INFO

Article history:
Received 6 August 2013
Received in revised form 19 December 2013
Accepted 31 March 2014
Available online 5 April 2014

Keywords:
Smart grid applications
Communication network requirements
Home Area Network (HAN)
Neighborhood Area Network (NAN)
Wide-Area Network (WAN)

ABSTRACT

Since the introduction of the smart grid, accelerated deployment of various smart grid technologies and applications have been experienced. This allows the traditional power grid to become more reliable, resilient, and efficient. Despite such a widespread deployment, it is still not clear which communication technology solutions are the best fit to support grid applications. This is because different smart grid applications have different network requirements – in terms of data payloads, sampling rates, latency and reliability. Based on a variety of smart grid use cases and selected standards, this paper compiles information about different communication network requirements for different smart grid applications, ranging from those used in a Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide-Area Network (WAN). Communication technologies used to support implementation of selected smart grid projects are also discussed. This paper is expected to serve as a comprehensive database of technology requirements and best practices for use by communication engineers when designing a smart grid network.

1. Introduction

The existing U.S. electric power grid was built over 100 years ago with the aim to deliver electricity from large power stations to customers [1]. In the past decade, blackouts and grid failures have become a noticeable problem, which can cause great damages and inconvenience to people's daily life [2]. There is thus a need to make the current electricity network more reliable, efficient, secure, and environmentally friendly. This can be achieved by the next-generation power grid, i.e., the smart grid, which is characterized by a two-way flow of electricity and information, creating an automated, widely distributed energy delivery network. With an emerging smart grid, various intelligent and automated applications can be enabled. These applications are such as home/building automation, automated meter reading, distribution automation, outage and restoration management and integration of electric vehicles [3].

Today's electric power grid has become a complex network of networks, comprising both power and communication infrastructures, and several thousands of intelligent electronic devices (IEDs) [4]. Communication networks provide necessary infrastructure allowing a utility to manage these devices from a central location. In the smart grid environment, heterogeneous communication technologies and architectures are involved. Communication networks should meet specific requirements, i.e., reliability, latency, bandwidth and security, depending on smart grid applications. The complexity of the smart grid may lead to difficulties in choosing appropriate communications networks as many parameters and different requirements must be taken into account depending on applications and utility expectations.

* Corresponding author. Tel.: +1 571 858 3305; fax: +1 571 858 3015.
E-mail addresses: mkuzlu@vt.edu (M. Kuzlu), mpipatta@vt.edu (M. Pipattanasomporn), srahman@vt.edu (S. Rahman).

http://dx.doi.org/10.1016/j.comnet.2014.03.029
1389-1286/

Authors in [5] provide a comprehensive tutorial about capability and requirements that the smart grid needs from both power and communications perspectives. Authors in [6] summarize application characteristics and traffic requirements of the communication infrastructure in the smart grid, while authors in [7] present a brief survey of selected transmission grid applications in terms of their bandwidth and latency requirements. Although existing wired and wireless communication technologies can be applied to the smart grid, establishing smart grid standards and protocols is an urgent issue for some devices, i.e., smart meters [8]. In the literature, smart grid technologies and standards are discussed to provide an overview of the smart grid paradigm and integration of different communication technologies [9,10]. Some studies focus on a specific standard or communication technologies, i.e., smart metering [11], power line communication (PLC) [12], and wireless communication [13,14]. Authors in [15] evaluate the network performance for a long-distance distribution line and proposed a communication architecture for distribution level applications. Additionally, selection of communication technologies for transmission-level applications has been addressed in [16].

As data size, latency and reliability requirements for different smart grid applications vary widely and are not easily obtainable to practitioners, this paper presents a comprehensive compilation of information from various use cases and smart grid-related standards on potential smart grid applications and their associated communication network requirements. These are discussed in terms of typical payload, data sampling requirements, as well as latency and reliability requirements for smart grid applications deployed in a Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide-Area Network (WAN). Additionally, the paper also discusses, based on selected smart grid projects around the world, various communication technologies that have been implemented to support real-world smart grid applications. It is the objective of this paper to provide a comprehensive database of communication technology requirements for different smart grid applications implemented at generation, transmission, distribution and customer levels.

The paper is organized as follows. Section 2 provides an overview of the smart grid communication network architecture, and compares various communication technologies that can be deployed in the smart grid environment. Section 3 discusses network requirements to support smart grid applications in HAN, NAN and WAN, as well as challenges in smart grid communications. Section 4 presents communication technologies used to support selected real-world smart grid projects.

2. Communication network architecture and various technologies for the smart grid

The smart grid is an interactive platform, consisting of a power system layer, a control layer, a communication layer, a security layer and an application layer. See Fig. 1.

This architecture represents how a smart grid can be implemented. In general, a smart grid comprises: (1) a power system layer, which refers to power generation, transmission, distribution and customer systems; (2) a power control layer, which enables smart grid monitoring, control, and management functions; (3) a communication layer, which allows two-way communications in a smart grid environment; (4) a security layer, which provides data confidentiality, integrity, authentication and availability; and (5) an application layer, which delivers various smart grid applications to customers and utilities based on an existing information infrastructure. For example, to enable a smart metering application, an electric grid must have the power system layer – which is an electric power distribution system that delivers electricity to customers; a power control layer – which is a smart meter that enables power consumption to be monitored; a communication layer – which is necessary to allow transmitting information from a customer to a utility or vise versa; and a security layer – which is necessary to address data privacy issues.

The communication layer is one of the most critical elements that enables smart grid applications. In the smart grid environment, a communication network can be represented by a hierarchical multi-layer architecture. Classified by data rate and coverage range, this architecture comprises:

- Customer premises area network, i.e., Home Area Network (HAN)/Building Area Network (BAN)/Industrial Area Network (IAN).
- Neighborhood Area Networks (NAN)/Field Area Network (FAN).
- Wide Area Network (WAN).

Data rate and communication range requirements for these networks are summarized in Fig. 2.

HAN/BAN/IAN applications include home automation and building automation, which are related to sending/receiving electrical measurement data from an appliance to a controller within a customer premises. These applications do not require data to be transmitted at high frequency and all applications occur inside residential/commercial/industrial buildings. Thus, communication requirements for HAN/BAN/IAN applications are low power consumption, low cost, simplicity, and secure communication. Communication technologies that provide data rate of up to 100 kbps with short coverage distance (up to 100 m) are generally sufficient. ZigBee, WiFi, Z-Wave, power line carrier (PLC, or known as HomePlug), Bluetooth, and Ethernet are widely used to support HAN/BAN/IAN applications.

In NAN/FAN applications, such as smart metering, demand response and distribution automation, data are required to transmit from a large number of customers/field devices to a data concentrator/substation or vise versa. Therefore, these applications require communication technologies that support higher data rate (100 kbps–10 Mbps) and larger coverage distance (up to 10 km). NAN/FAN applications can be implemented over ZigBee mesh networks, WiFi mesh networks, PLC, as well as long distance wired and wireless technologies, such as WiMAX, Cellular, Digital Subscriber Line (DSL) and Coaxial Cable.

For WAN applications, such as wide-area control, monitoring and protection, which require transmitting a large

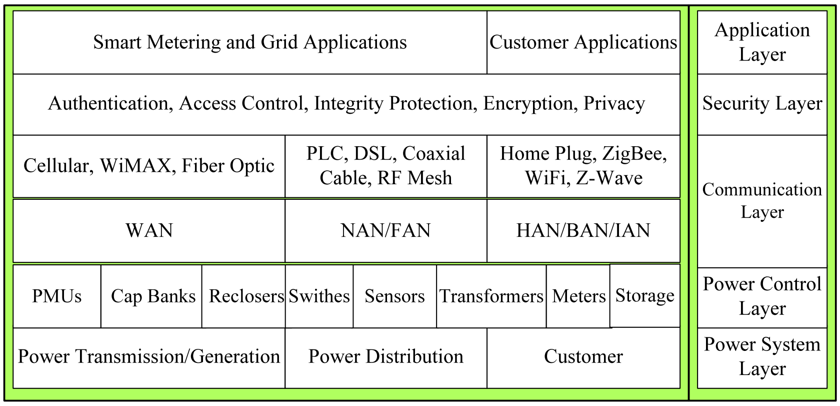

Fig. 1. The system multi-layer architecture of smart grid.

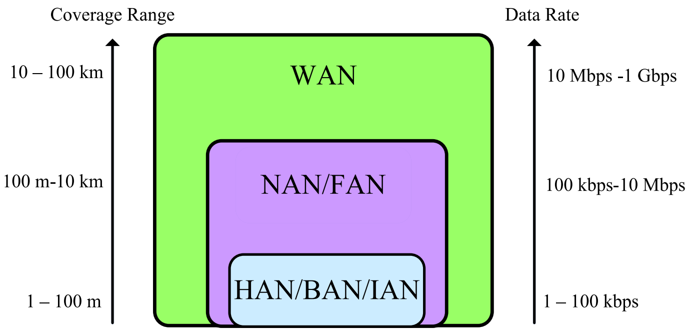

Fig. 2. Date rate and communication range requirements for smart grid communications hierarchy.

number of data points at much higher frequency (i.e., in a fraction of seconds) to allow stability control of a power system, communication technologies that support much higher data rate (10 Mbps–1 Gbps) and provide long coverage distance (up to 100 km) are therefore required. Optical communication is commonly used as a communication medium between transmission/distribution substations and a utility control center due to its high capacity and low latency. Cellular and WiMAX are also used due to their wide coverage range and high data throughput. Satellite communications can also be used to provide redundant communications at critical transmission/distribution substation sites as backup a communication mean in a remote location.

A comparison of various communication technologies that can support smart grid applications in terms of data rate and coverage distance is presented in Table 1.

As wireless technologies provide lower installation cost, more rapid deployment, higher mobility and flexibility than its wired counterparts, wireless technologies are recommended in most of the smart grid applications. Advantages and disadvantages of each technology have already been discussed in our previous study [17] in terms of their data rates and coverage ranges, and will not be repeated in this paper. Latency requirements for each network are discussed in details in Section 3 by smart grid application.

3. Smart grid applications, network requirements and challenges in smart grid communications

Smart grid is a platform consisting of different domains, including generation, transmission, distribution, customers, service providers, operations and markets, to enable various applications. The generation domain is responsible for generating electricity from other forms of energy, e.g., fossil fuels, water, wind, solar radiation and geothermal heat. The transmission domain is responsible for transferring of electrical power from generation sources to distribution systems over long distances through multiple substations. The distribution domain is the electrical interconnection between the transmission and the customer domains. It distributes electricity from/to customers. The customer domain includes residential, commercial, and industrial customers, where electricity is consumed. The service provider domain executes services to customers and utilities. The operations domain manages the movement of electricity and responsible for the operation of the power system. The market domain allows to exchanging price and balancing supply and demand within the power system. Each domain can be interactive with the other domains through different communications area networks to accomplish requirements of different smart grid applications. See Fig. 3.

Table 1
Comparison of communication technologies for the smart grid.

Technology	Standard/protocol	Max. theoretical data rate	Coverage range	Network		
				HAN/BAN/IAN	NAN/FAN	WAN
Wired communication technologies						
Fiber optic	PON	155 Mbps–2.5 Gbps	Up to 60 km			X
	WDM	40 Gbps	Up to 100 km			
	SONET/SDH	10 Gbps	Up to 100 km			
DSL	ADSL	1–8 Mbps	Up to 5 km		X	
	HDSL	2 Mbps	Up to 3.6 km			
	VDSL	15–100 Mbps	Up to 1.5 km			
Coaxial Cable	DOCSIS	172 Mbps	Up to 28 km		X	
PLC	HomePlug	14–200 Mbps	Up to 200 m	X		
	Narrowband	10–500 kbps	Up to 3 km		X	
Ethernet	802.3x	10 Mbps–10 Gbps	Up to 100 m	X	X	
Wireless communication technologies						
Z-Wave	Z-Wave	40 kbps	Up to 30 m	X		
Bluetooth	802.15.1	721 kbps	Up to 100 m	X		
ZigBee	ZigBee	250 kbps	Up to 100 m	X	X	
	ZigBee Pro	250 kbps	Up to 1600 m			
WiFi	802.11x	2–600 Mbps	Up to 100 m	X	X	
WiMAX	802.16	75 Mbps	Up to 50 km		X	X
Wireless Mesh	Various (e.g., RF mesh, 802.11, 802.15, 802.16)	Depending on selected protocols	Depending on deployment	X	X	
Cellular	2G	14.4 kbps	Up to 50 km		X	X
	2.5G	144 kbps				
	3G	2 Mbps				
	3.5G	14 Mbps				
	4G	100 Mbps				
Satellite	Satellite Internet	1 Mbps	100–6000 km			X

According to the smart grid communication infrastructure that can generally be classified into HAN, NAN and WAN based on the data rate and coverage range, smart grid applications discussed below are grouped by their data rate and coverage range required for their successful deployment. Then, challenges in smart grid communications are discussed.

3.1. Premises network applications

A premises network, i.e., HAN/BAN/IAN, is at the customer end of the network architecture. It supports communications among household appliances, electric vehicles, and other electric equipment at customer premises.

HAN provides communications for household appliances and equipment that are capable of sending and receiving signals from a smart meter, in-home displays (IHDs) and/or home energy management (HEM) systems. These applications include home automation, optimal thermostat set points for thermal zones, optimal water tank temperature set-point, controlling and managing loads and providing total electricity costs. BAN and IAN are used for commercial and industrial customers with focus on building automation, heating, ventilating, and air conditioning (HVAC), other industrial energy management applications.

A premises network is connected to other smart grid actors, e.g., an electric utility or a third-party energy service provider, via a smart meter or an Internet gateway. This enables an electric utility to perform NAN/FAN applications in residential, commercial and industrial premises, e.g., prepaid services, user information messaging, real-time pricing and control, load management, and demand response.

Table 2 summarizes these network requirements in terms of typical payload sizes, data collection requirements, reliability and latency, together with feasible communication technologies that can support such requirements.

3.2. Neighborhood Area Network applications

A Neighborhood Area Network (NAN) supports information flow between WAN and a premises area network. It enables data collection from customers in a neighborhood for transmission to an electric utility company. NAN can also be called Field Area Network (FAN) when it connects with field devices such as intelligent electronic devices (IEDs). NAN/FAN enables a range of smart grid applications, such as smart metering, load management, distribution automation, pricing, outage management and restoration or other customer-based applications [18].

NAN/FAN includes a metering network, which is a part of AMI, enabling services such as remote meter reading, control and detection of unauthorized usage. It allows electricity usage information to be transmitted from energy meters to a utility or a third-party system, and allows field devices to be controlled remotely, e.g., in distribution automation applications. NAN/FAN is connected to WAN via a backhaul network, where data from many NAN/FAN are aggregated and transported between NAN/FAN and WAN.

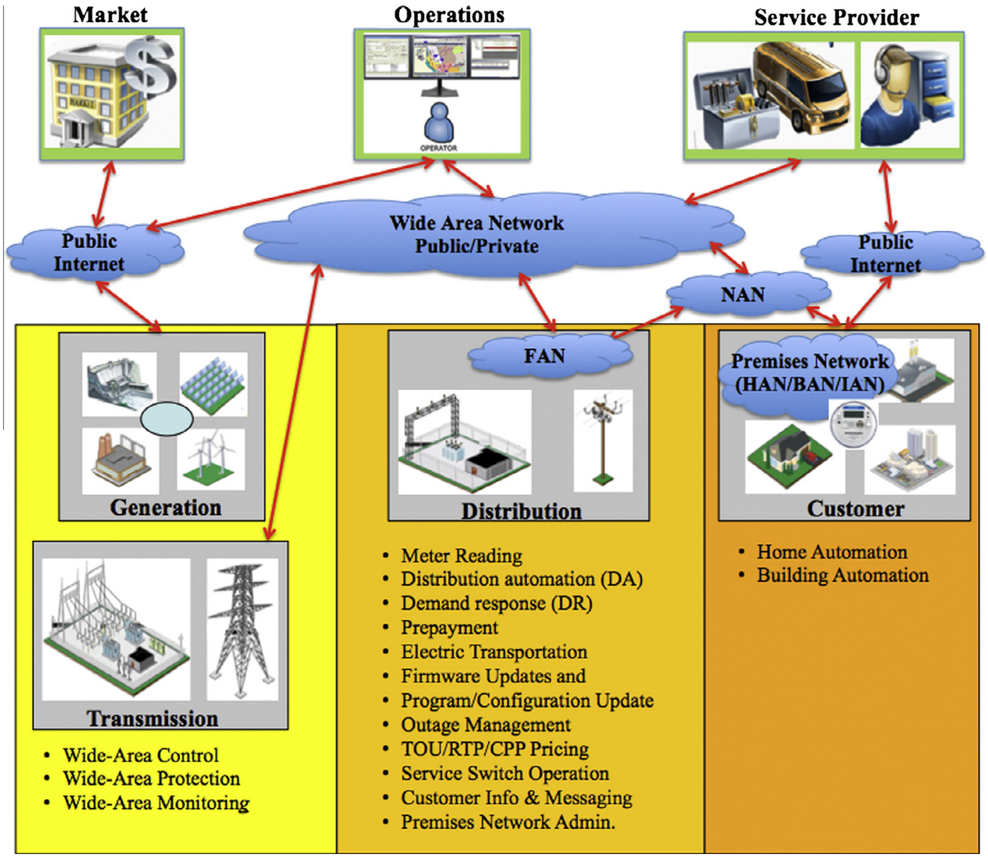

Fig. 3. Smart grid domains, intra/inter-domain interactions via communication networks, and smart grid applications in generation, transmission, distribution and customer domains.

Smart grid applications in NAN/FAN include meter reading, distribution automation (DA), demand response (DR), prepayment, electric transportation, firmware updates and program/configuration, outage and restoration management, TOU/RTP/CPP pricing, service switch operation, customer information and messaging, and premises network administration.

For these applications, communication technologies that support higher data rate and larger coverage distance (up to 10 km) than those applications in a premises area network are required. Coverage area and data rate requirements for different NAN applications can vary depending on applications [19]. For example, a typical data size requirement for scheduled meter interval reading is 1600–2400 bytes, while it is 25–1000 bytes for distribution automation applications.

Typical NAN/FAN applications are discussed below. Their network requirements in terms of typical data sizes, data sampling requirements, as well as reliability and latency requirements are summarized in Table 3, together with feasible communication technologies supporting smart grid applications in NAN/FAN. In this paper, latency requirements imply the acceptable window of data/status update delay from a transmitter to a receiver for each smart grid application.

(1) Meter reading allows a utility to collect data from electric/gas/water meters and transfer data to a central database for billing and analysis. With Advanced Metering Infrastructure (AMI), a utility can perform real-time bidirectional communications between meters and a centralized management site, thus improving meter reading accuracy, and reducing operational costs. With the ability to monitor electricity usage in real-time, customers can be informed of their own usage, thus allowing better management of their electricity consumption. Network requirements for meter reading applications vary depending on service types, e.g., on-demand meter reading, scheduled meter interval reading and bulk transfer of meter reading.
   - On-demand meter reading allows readings to be taken when needed, e.g., when a utility needs to answer customers' inquiries about their usage, or to backfill missing information. A typical payload is 100 bytes for a data transmission from a meter to a utility with a latency requirement of less than 15 s.
   - Scheduled meter interval reading provides the capability to collect usage information from a meter to an AMI head end several times a day

Table 2
Networks system requirements for HAN/BAN/IAN applications in the smart grid.

Application	Typical data size (bytes)	Typical data sampling requirement	Latency	Reliability (%)	Communication technologies											
					Wired					Wireless						
					Fiber optic	DSL	Coaxial Cable	PLC	Ethernet	Z-Wave	Bluetooth	ZigBee	WiFi	WiMAX	Wireless mesh	Cellular
Home automation	10–100	Once every configurable period (e.g., 1 min, 15 min, etc.)	Seconds	>98				X	X	X	X	X	X			
Building automation	>100	Once every configurable period (e.g., 1 min, 15 min, etc.)	Seconds	>98				X	X			X	X		X	

(e.g., 4–6 times per residential meter per day or 12–24 times per commercial/industrial meter per day) with interval usage information varying from 15 min to 1 h. Interval readings are normally taken and stored automatically at the customer-end equipment, i.e., smart meter, and later retrieved by a utility. Acceptable window of data delivery is less than 2 h for commercial/industrial meter and less than 4 h for residential meters. Payload size depends on the number of readings collected from the meter at a given time.

- Bulk transfer of meter reading allows a utility to collect usage information from all meters (via AMI head end or meter data management system, MDMS) within a utility enterprise. Payload includes meter reading information from a number of meters, of which the payload size depends on the number of meters scheduled to be read.

(2) Pricing applications involve broadcasting of price information to meters and devices, e.g., smart appliances, plug-in hybrid electric vehicles (PHEVs) and load control devices, at customer premises. These are typically associated with time-of-use (TOU), real-time pricing (RTP) and critical peak pricing (CPP) programs.
- TOU programs allow customers to lower electric bills, as long as customers are able to shift their electricity usage to off-peak hours. Customers participating in this program typically accept different price schedules for different time periods, such as peak, shoulder, and off-peak.
- RTP programs offer short-term time-varying pricing information, e.g., every 5 min, 30 min or 1 h, to end-use customers. Customers can use this information to reduce electricity bills by managing their energy consumption.
- CPP programs are typically used during times of high peak demand. A utility needs to curtail loads and quickly sends CPP messages to enrolled customers for a radical load reduction. In these programs, customers are charged a higher price during a few hours and given a discounted during remaining hours.

A typical data size for such pricing applications is 100 bytes, and the data latency requirement is less than 1 min.

(3) Electric service prepayment allows customers to purchase utility services, i.e., supply of electricity, gas or water, in advance. These services are available to customers as long as the meter has credits. In traditional applications, a prepaid meter measures electrical/gas/water usage and deducts credits according to tariff programmed for customers in real time. The meter issues warnings, e.g., audible alarm sounds, when the credit reaches a threshold or zero. Then the service is disconnected within a predetermined time. Customers need to refill credits inside their prepaid meters to gain a service again.

With the smart grid and AMI, utilities do not require prepaid meters to serve prepaid customers. A smart meter can perform prepaid meter functions with the ability to remotely connect or disconnect the service. A utility can calculate available credits on a prepayment account and can initiate necessary actions, such as sending out warning messages and disconnect or reconnect commands. A typical data size for an electric service prepayment application is between 50 and 150 bytes, and the data latency requirement is less than 30 s when a utility sends information, such as price and available credit, to a customer.

(4) Demand response (DR) allows a utility to talk to devices at customer premises, such as load control devices, smart thermostats, smart appliances, PHEVs, and in-home displays, to provide load reduction during peak demand periods in the distribution grid. Typical DR applications include direct load control programs for central air conditioning systems, heat pumps, electric water heaters and/or pool pumps, as well as real-time pricing and time-of-use programs. For direct load control applications, selected devices can be turned ON/OFF by a load controller installed at a customer premise with commands sent by a utility. These commands may be unicast,

Table 3
Networks system requirements for NAN applications in the smart grid.

	Application	Typical data size (bytes)	Typical data sampling requirement	Latency	Reliability (%)	Communication technologies
1a	Meter reading – on-demand from meters to utility)	100	As needed (7 am–10 pm)	<15 s	>98	Wired: DSL, Coaxial Cable, PLC, Ethernet Wireless: ZigBee mesh, WiFi mesh, WiMAX, Wireless mesh, Cellular
1b	Meter reading – scheduled interval (from meters to AMI head end)	1600–2400	4–6 times per residential meter per day (24 × 7) 12–24 times per commercial/ industrial meter per day	<4 h <2 h	>98	
1c	Meter reading – bulk transfer from AMI head end to utility)	MB	*x* per day for a group of meters (6 am–6 pm)	<1 h	>99.5	
2a	Pricing-TOU (from utility to meters)	100	1 per device per price data broadcast event 4 per year (24 × 7)	<1 min	>98	
2b	Pricing-RTP (from utility to meters)	100	1 per device per price data broadcast event 6 per day (24 × 7)	<1 min	>98	
2c	Pricing-CPP (from utility to meters)	100	1 per device price data broadcast event 2 per year (24 × 7)	<1 min	>98	
3	Electric service prepayment (from utility to customers)	50–150	25 times per prepay meter per month (7 am–10 pm)	<30 s	>98	
4	Demand response – DLC (from utility to customer devices, e.g., smart appliance, PHEV, and load control device)	100	1 per device per broadcast request event (24 × 7)	<1 min	>99.5	
5	Service switch operation (from utility to meters)	25	1–2 per 1000 electric meters per day (8 am–8 pm)	<1 min	>98	
6a	Distribution automation – distribution system monitoring and maintenance data from field devices to DMS)	100–1000	CBC: 1 per device per hour (24 × 7)	<5 s	>99.5	
			Feeder fault detector: 1 per device per week (24 × 7) Recloser: 1 per device per 12 h (24 × 7) Switch: 1 per device per 12 h (24 × 7) VR: 1 per device per hour (24 × 7)			
6b	Distribution automation – Volt/VAR control (command from DMS to field devices)	150–250	Open/close CBC: 1 per device per 12 h (24 × 7)	<5 s	>99.5	
			Open/close Switch: 1 per device per week (24 × 7) Step up/down VR: 1 per device per 2 h (24 × 7)			
6c	Distribution automation – distribution system demand response (DSDR) (command from DMS to field devices)	150–250	Open/close CBC: 1 per device per 5 min	<4 s	>99.5	
			Open/close switch: 1 per device per 12 h Step up/down VR: 1 per device per 5 min (1–6 h duration, 4–8 times a year)			
6d	Distribution automation – fault detection, clearing, isolation and restoration (FCIR) (command from DMS to field devices)	25	1 per device per isolation/ reconfiguration event (<5 s, within <1.5 min of fault event)	<5 s	>99.5	
7	Outage and Restoration Management (ORM) (from meters to OMS)	25	1 per meter per power lost/ power returned event (24 × 7)	<20 s	>98	

Table 3 (*continued*)

	Application	Typical data size (bytes)	Typical data sampling requirement	Latency	Reliability (%)	Communication technologies
8	Distribution customer storage (charge/discharge command from DAC to the storage)	25	2–6 per dispatch period per day (discharge: 5 am–9 am or 3 pm–7 pm; charge: 10 pm–5 am)	<5 s	>99.5	
9a	Electric transportation (utility sends price info to PHEV)	255	1 per PHEV per 2–4 day (7 am–10 pm)	<15 s	>98	
9b	Electric transportation (utility interrogates PHEV charge status)	100	2–4 per PHEV per day (7 am–10 pm)	<15 s	>98	
10a	Firmware updates (from utility to devices)	400k–2000k	1 per device per broadcast event (24 × 7)	<2 min–7 days	>98	
10b	Program/configuration update (from utility to devices)	25k–50k	1 per device per broadcast event (24 × 7)	<5 min–3 days	>98	
11	Customer information and messaging customers request account info from utility/utility responds to customers)	50/200	As needed (7 am–10 pm)	<15 s	>99	
12	Premises network administration (from utility to customer devices)	25	As needed (24 × 7)	<20 s	>98	

multicast or broadcast depending on the required load reduction amount. A typical data size for DR applications is 100 bytes, and the data latency requirement is less than 1 min.

(5) Utility service switch operation allows a utility to turn an electrical/gas/water service ON/OFF at customer premises. This feature enables a utility to switch a service without having to roll a service truck. This can be particularly useful for reducing service time and costs for establishing or terminating services. These applications include sending a service switch operation (service enabling/service cancelling) commands to a meter. For these applications, a typical data size is 25 bytes, and the data latency requirement is less than 1 min.

(6) Distribution automation (DA) provides real-time operation information of grid structure, automation control, data communication and information management, to monitor and control the distribution grid. DA systems help utilities make the most of their distribution assets by allowing control of distribution-level devices, such as capacitor bank controllers (CBC), fault detectors, reclosers, switches, and voltage regulators (VR). DA applications and their requirements may vary from utility to utility. Major DA applications include distribution system monitoring and maintenance, Volt/VAR control, distribution system demand response (DSDR) and fault detection, clearing, isolation and restoration (FCIR).
   - Distribution system monitoring and maintenance includes self-diagnostics on equipment, polling equipment status (open/closed, active/inactive) at scheduled intervals, and retrieving sensor data to monitor equipment conditions. Equipment to be monitored may include CBCs, fault detectors, reclosers, switches and voltage regulators.
   - Volt/VAR control aims to reduce energy loss, adjust voltage along a distribution circuit, and compensate load power factor. For a distribution system, Volt/VAR management includes both monitoring of feeder line devices, and their control.
   - DSDR applications aims to reduce distribution grid voltage to help manage system load during peak periods. It involves control of capacitor banks, automated feeder switches and voltage regulators.
   - FCIR applications manage the detection, isolation, and restoration of a power grid after the occurrence of a fault on a section of the grid to minimize the effect of service interruptions to customers.

The DA system consists of intelligent communications and automation devices and low-latency network communications backbone. It is generally built on open standard systems and protocols such as IP-based communications and SCADA interfaces. A typical data size for DA applications ranges from 25 bytes to 1000 bytes, and the data latency requirement is less than 4–5 s while the reliability requirement is high, i.e., more than 99.5%.

(7) Outage and Restoration Management (ORM) allows an electric utility to detect an outage as soon as the power is lost via devices, such as smart meters and outage detection units. These devices can also report over and under voltage situations. Typically, an additional interface module is added to a smart meter to enable the outage detection function. A utility usually places more than one outage detection units on every branch of a distribution network to avoid false alarms. The ORM application allows an

electric meter to send a message to a utility's Outage Management System (OMS) when the meter loses its mains power, and when the meter detects that the mains power has been restored. For this application, a typical payload is 25 bytes, and the data latency requirement is less than 20 s.

(8) Distribution customer storage applications arise as a technological solution that can address operational challenges by providing power, energy and fast response time to a distribution network allowing an efficient integration of renewable sources. These storage applications include the use of storage devices installed along distribution feeder circuits or laterals for peak load shaving, voltage support, power quality, demand control, and interruption protection. A typical data size is 25 bytes for a charge/discharge command from a Distribution Application Controller (DAC) to a distribution customer storage, and the data latency requirement is less than 5 s for distribution customer storage applications.

(9) Electric transportation applications involve both electricity flow from vehicles to the power grid (vehicle-to-grid, V2G) and electricity flow from the power grid to vehicles (grid-to-vehicle, G2V). These applications allow various electric vehicle technologies (based on battery, hybrid, plug-in hybrid, fuel cell, and plug-in fuel cell) to become mobile distributed generation resources. Electric transportation applications may include a utility sending inquiries to acquire knowledge of vehicle battery state-of-charge, informing vehicles about electricity prices; as well as an electric vehicle sending messages back to a utility in response to received commands. A typical payload is 100–255 bytes for electric transportation applications, and the data latency requirement is less than 15 s.

(10) Firmware updates and program/configuration changes allow utilities to upgrade firmware and change program/configuration on their devices to incorporate new functionalities and settings. Specifically, firmware updates aim to fix bugs or enhance features of a background program that runs in devices. Utilities usually perform firmware upgrades to accommodate changing application requirements and strengthen device security. Program/configuration updates aim to change current program/configuration settings in devices. These devices may include Data Aggregation Points (DAP), NAN/FAN gateways, and DA devices, e.g., regulators, capacitor banks, sensors, switches, reclosers and relays. A typical data size is 400k–2000k bytes, and the data latency requirement can be up to 7 days for firmware update applications; while the typical data size is 25–50 Kbytes, and the data latency requirement can be up to 3 days for program/configuration update applications.

(11) Customer information and messaging applications allow a customer an access to their account information, historical electricity consumption data and outage information. This information is sent to an appropriate operational data warehouse (ODW) and web portal via the Internet or an extranet gateway, which is connected to a utility's internal network. These applications are provided by a utility or a third-party service provider. A typical payload is 50 bytes for a customer request of account information from a utility; and is 200 bytes for a response from a utility to a customer. The data latency requirement is less than 15 s for these applications.

(12) Premises network administration applications allow customers to connect/remove premises area network devices (e.g., smart meters, PHEV, smart appliances and load control devices) to/from a network. These can be accomplished using an interactive voice response (IVR) or a web portal, etc. A typical data size is 25 bytes, and the data latency requirement is less than 20 s for these applications.

3.3. Wide Area Network applications

Wide Area Network (WAN) supports real-time monitoring, control and protection applications, which can help prevent cascading outages with real-time information related to the state of the power grid. It also provides communication links for smart grid backbones; and covers long-haul distances from NAN/FAN to a control center.

WAN applications, including wide-area monitoring, wide-area control and wide-area protection, have been identified as the next-generation solution to improve power system planning, operation and protection in the smart grid. These applications involve the use of system-wide information and selected local information to counteract the propagation of large disturbances [20]. Wide-area monitoring, control and protection applications offer higher data resolution and shorter response time than classical supervisory control and data acquisition (SCADA) and energy management (EMS) systems. While SCADA/EMS provides a measurement update interval of several seconds or even minutes, wide-area monitoring, control and protection applications provide high-resolution data, i.e., 60 samples per second. Three domains of WAN applications are explained in further details below.

(1) Wide-area protection provides a fully automatic protection to protect power systems against widespread blackouts, transmission congestion and stressed conditions, or unexpected events. Wide-area protection applications generally involve load shedding and adaptive islanding. Wide-area protection systems are useful to deal with unpredicted contingencies that need very short reaction time to prevent widespread failures or blackouts.

(2) Wide-area control provides automatic self-healing capabilities that exceed functionalities delivered by local control and responds faster than manual control by a control center. It provides a flexible platform for rapid implementation of generator tripping and reactive power compensation switching for transient stability and voltage support of a large power system [21]. It serves as an additional layer to prevent possible blackouts and facilitates electrical commerce by providing a real-time insta-

bility control. Wide-area control applications involve control of fast controllable equipment, e.g., high-voltage direct current (HVDC) and flexible-AC transmission system (FACTS) devices. Additionally, these applications also include wide-area damping control with respect to oscillations in large-scale electrical transmission systems [22], voltage stability control to sustain active and reactive power flows for transmission corridors [23], and frequency stability control to prevent possible damage to generation and load side equipment [24].

While wide-area protection and control applications offer more advanced protection/control systems as compared with traditional power systems, more stringent performance and availability requirements are needed. For example, the required response time for wide-area protection and control applications should be in the range of milliseconds to minutes (e.g., <0.1 s–<2 min), and the communication system reliability requirement should be very high (e.g., >99.9%). Their typical message size can vary depending upon communication protocols implemented. Typical protocols used for these applications include MIRRORED BITS, IEC 61850 Generic Object-Oriented Substation Event (GOOSE), and ETHERCAT communications [25]. For the MIRRORED BITS communication protocol, the message size is 4 bytes in length due to its simple design. For the GOOSE message, roughly 157 bytes of data are required. On the other hand, a message size of 64 bytes is required for the EtherCAT communications.

(3) Wide-area monitoring aims at providing system data in real-time from a group of intelligent electronic devices (IEDs) and PMUs. IEDs transmit snapshots of device status and measurement data to SCADA/EMS over a WAN. PMUs, on the other hand, enable time-synchronized snapshots of a power network including voltage and current phase angles, i.e., wide-area measurements. Availability of wide-area measurements enables enhanced stability assessment with respect to state estimation, system parameter estimation and post-fault analysis. Examples of wide-area monitoring applications include monitoring of power frequency oscillation and system voltage stability. Thus, wide-area monitoring provides the power grid opportunities to improve voltage stability and detect frequency oscillations/instability [26].

For wide-area monitoring applications, a minimum message size containing measurements made by a PMU is 52 bytes. This information can be obtained from the IEEE Standard for Synchrophasors for Power Systems (IEEE Std. C37.118), which defines measurement and data transmission formats for real-time data reporting in electric power systems [27]. Similar to those for wide-area protection and control applications, the required response time for wide-area monitoring applications is also in the range of milliseconds to minutes, and communication system reliability requirement is very high.

Table 4 that summarizes primary requirements by these applications in terms of their typical data sizes, sampling rates, as well as reliability and latency requirements, together with communication technologies that can support these applications [28].

3.4. Challenges in smart grid communications

Many challenges exist that are associated with upgrading communication infrastructures to enable a wide range

Table 4
Network requirements for wide-area protection, control and monitoring applications.

Application	Typical data size (bytes)	Typical data sampling requirement	Latency	Reliability (%)	Communication technologies
Wide-area protection					
Adaptive islanding	4–157	Once every 0.1 s	<0.1 s	>99.9	Wired:
Predictive under frequency load shedding		Once every 0.1 s	<0.1 s	>99.9	– Fiber optic
Wide-area control					
Wide-area voltage stability control	4–157	Once every 0.5–5 s	<5 s	>99.9	Wireless:
FACTS and HVDC control		Once every 30 s–2 min	<2 min	>99.9	– WiMAX
Cascading failure control		Once every 0.5–5 s	<5 s	>99.9	– Cellular
Precalculation transient stability control		Once every 30 s–2 min	<2 min	>99.9	
Closed-loop transient stability control		Once every 0.02–0.1 s	<0.1 s	>99.9	
Wide-area power oscillation damping control		Once every 0.1 s	<0.1 s	>99.9	
Wide-area monitoring					
Local power oscillation monitoring	>52	Once every 0.1 s	<30 s	>99.9	
Wide-area power oscillation monitoring		Once every 0.1 s	<0.1 s	>99.9	
Local voltage stability monitoring		Once every 0.5–5 s	<30 s	>99.9	
Wide-area voltage stability monitoring		Once every 0.5–5 s	<5 s	>99.9	
PMU-based state estimation		Once every 0.1 s	<0.1 s	>99.9	
Dynamic state estimation		Once every 0.02–0.1 s	<0.1 s	>99.9	
PMU-assisted state estimation		Once every 30 s–2 min	<2 min	>99.9	

of smart grid applications. In general, key challenges of smart grid communications are:

Firstly, it is the lack of necessary interoperability standards that can hamper effective deployment of communication networks in the smart grid environment. This is because the use of proprietary networking solutions and protocols are preferred by utility/customer systems in today's environment. Integrating these networks with future versions of software and hardware is the key challenge, which may lead many utilities to consider the adoption of IP-based networking to address the interoperability issue [29]. For example, interoperability and integration with the utility system are major challenges to full-scale deployment of HAN applications. The interoperability is outside the control of the utility and can be solved by designing a system using common protocols, e.g., Smart Energy Profile (SEP) and software/firmware updates. To solve the integration issue, utilities prefer to connect the customer premises via a HAN gateway device, e.g., smart meter or Internet gateway.

Secondly, communications networks deployed in an existing electric power grid are based on decade-old technologies that were designed without considering the need to collect information from and support a large number of customers or devices. This is closely related to challenges in realizing NAN/FAN applications, which will involve the upgrade of existing communication technologies that can serve a large number of customers and field devices and span a large coverage area of different terrain characteristics. For example, to transmit electrical usage information from a number of smart meters to an electric utility, a data from a smart meter needs to be routed to a data concentrator in a neighborhood. The uplink from homes to a data concentrator in an urban area is typically realized using a private network solution consisting of RF mesh and cellular technologies. To enable a utility to perform direct load control on a number of end-use equipment (downlink), a popular technology for deployment can be based on RF mesh networks in unlicensed 900 MHz bands.

Thirdly, latency requirements can become the most important issue in the data collection and transmission, specifically for wide area control and protection applications. This is because WAN applications are associated with the need for the most stringent communication network requirements in terms of bandwidth, latency, and reliability. The data are required to be transmitted to a control center, and control commands are required to be issued and implemented within a few milliseconds to prevent cascading outages in real-time. To meet such high requirements for WAN applications, utilities generally prefer to use private networks consisting of the fiber optic communication because of its ability to deliver high data rates for long-distance communications. Data compression is another solution to improve the efficiency of data flow and hence reducing latency. Congestion management can also be used to reduce latency under the condition of heavy traffic as it allows data classification and prioritization of communication channels for emergency situations [30].

Lastly, with integration of information and communication technology (ICT) to the power grid and emerging smart grid applications, e.g., smart metering, pricing, demand response, wide-area measurement, many concerns arise related to cyber security and data privacy. The most comprehensive smart grid security discussions are provided in NIST Guidelines for Smart Grid Cyber Security (NISTIR 7628) [31]. In the NIST report, smart grid cyber security topics are presented in three main categories: Vol. 1 – Smart grid cyber strategy, architecture, and high-level requirements; Vol 2. – Privacy and the smart grid; and Vol. 3 – Supportive analyses and references. Selected other publications [32,33] also discuss cyber security and privacy issues in the smart grid, such as power and control system security, accountability, integrity, confidentiality and data sharing. Authors in [34] develop a framework to detect malicious activities by proposing an algorithm to place grid sensors to enhance detection performance and provide network observability. In addition, as the electric power grid has become a more complex network comprising a large number of customers/field devices, the trend is to design a smart grid communication infrastructure to support and allow implementation of autonomous distributed network operation as discussed in [35]. This can be deemed as another possible challenge in designing and implementing smart grid communications.

4. Smart grid projects for major smart grid applications

It is understood that a successful smart grid project starts with a well-designed communications network and systems architecture. Selecting the right communication technologies is the fundamental component of this success. In various real-world smart grid implementations to be discussed below, many different communication technologies are deployed. In practice, an electric utility chooses to implement communication technologies that best fit its requirements after having evaluated current system infrastructures, technology standards, application requirements, and future scaling requirements. In the past several years, many countries including the U.S., several European countries and China have launched many smart grid projects [36,37]. Selected smart grid projects are discussed below with the emphasis on their communication aspects. This information is summarized in Table 5.

In the U.S., the Austin Energy's AMI project is one of the first fully operational smart grid projects. As of 2012, approximately 500,000 devices are deployed, including 86,000 smart thermostats, 410,000 smart meters, 2500 sensors and 3000 computers and network elements [38]. Austin Energy uses a combination of Cellnet + Hunt's Radio Frequency (RF) mesh network and optical fiber to allow a variety of smart grid functions, including AMI, distribution automation, SCADA and multi-service utility meter operation. The network also supports time-of-use pricing, distribution automation, load management, and outage management applications. Data transmission is based on a robust, peer-to-peer mesh network utilizing a 902–928 MHz unlicensed frequency band.

The City of Glendale Water and Power Utility initiated its AMI project in 2010, focusing on installation of advanced meters, use of customer systems and in-home displays, installation of distribution automation equipment, and

Table 5
Various types of example projects from various countries.

Organization	Region, country	Applications	Technologies	Notes
Austin Energy	Texas, USA	– AMI – Metering reading – Pricing – Distribution automation – Service switch operation – Demand response	Optical fiber and RF mesh network	Smart grid project with 410,000 smart meters, 86,000 smart thermostats, 2500 sensors, 3000 computers and network elements
City of Glendale Water and Power	California, USA	– AMI – Metering reading – Pricing – Distribution automation – Distribution energy storage – Customer info and messaging – Home display	Ethernet/Internet, wireless mesh network	Smart grid project with 86,526 smart meters, AMI communication systems, MDMS, 80,000 HANs, customer web portal access, 30,000 in-home displays, 1.5 MW of distributed energy storage devices and distribution automation equipment
Baltimore Gas and Electric Company	Maryland, USA	– AMI – Metering reading – Pricing – Customer information and messaging – Demand response (DLC)	Optical fiber, RF mesh network	Smart grid project with 1,272,911 smart meters, AMI communication systems, MDMS, customer web portal access for residential/small commercial customers, and 400,000 direct load control devices
AC Propulsion, Inc.	California, USA	– Electric transportation	Cellular (CDPD)	V2G demonstration project with VW Beetle EV, equipped with a wireless modem. Remote dispatch of V2G functions over the Internet
Duke Energy Carolinas, LLC	North Carolina and South Carolina, USA	– Electric transmission systems – Wide area monitoring	Optical fiber	PMU deployment with communication system modernization project with the installation of 102 PMUs, 2 phasor data concentrators, and the upgrade of existing serial-based communications infrastructure
Eandis and Infrax	Flanders, Belgium	– Advanced Metering Management (AMM) – Meter reading	PLC, DSL, Cellular (GPRS)	Pilot project, two-way communication between central systems and electricity and gas meters and 36,000 smart communication gateways
Acea Distribuzione	Roma, Italy	– AMM – Meter reading	PLC, Cellular (GPRS)	One of Europe's largest smart metering projects, gas and water meters, serving 1.5 million households
Public Power Corporation	Larissa, Greece	– Demand response	Wi-Fi, BPL	A large-scale pilot project, remote monitoring and control of irrigation pumps during peak hours
China Southern Power Grid	Southern China	– AMI – Meter reading – Pricing – Demand response	Cellular (2G and 3G)	Large-scale AMR project, monitor end-users' electricity usage in real-time, to both prepare accurate bills and estimate ongoing demand

management of distributed energy storage was started in 2010. Its AMI system includes deployment of 86,526 smart meters, 80,000 HANs and 30,000 in-home displays. A meter data management system (MDMS) is deployed to provide customers access to data about their electricity usage and enable dynamic rate programs [39]. In this case, a combination of Ethernet/Internet protocol backhaul and a local wireless mesh radio frequency network is used to support two-way communication between meters and utility data systems and allows for monitoring and control of select distribution automation equipment. The company uses Tropos WiFi mesh into Ethernet/Fiber network for backhaul communications, and 900 MHz mesh to Itron cell relay collectors for its meter communication network.

Baltimore Gas and Electric Company (BG&E) initiated its smart grid project in 2010, including Advanced Metering Infrastructure (AMI), implementation of a customer web portal and home energy management, and installation of a new customer care and billing system. The project includes enhancement of its communication infrastructure, as well as deployment of about 1.3 million smart meters, and 400,000 Direct Load Control (DLC) devices to cycle air conditioning units and electric hot water heaters during peak periods as part of a new load management plan [40]. BG&E's communication infrastructure to support its NAN/FAN applications includes a two-way mesh radio frequency network consisting of approximately 1200 access points and relays designed to remotely connect smart meters to back-office systems. The company selects Verizon for its backhaul communications.

A V2G demonstration project initiated by AC Propulsion, Inc. was launched in California, USA. In this project, VW Beetle electric vehicles are equipped with a wireless modem to allow remote dispatch of V2G functions over the Internet. Control commands can be sent wirelessly to the vehicle based on current power need and knowledge of the vehicle battery current state-of-charge (SOC). Commands received by the vehicle over a wireless modem are interpreted to control AC line current to/from the system. The vehicle automatically maintains the battery SOC to comply with the driver usage requirement. The wireless link between the aggregator server and the vehicle is an always-on TCP/IP connection. The wireless data service is based on the CDPD (cellular digital packet data) system and is provided by AT&T Wireless [41].

A PMU deployment and communication system modernization project was started by Duke Energy Carolinas, LLC in North Carolina and South Carolina in 2010. This project includes the installation of 102 PMUs and 2 phasor data concentrators (PDC), and the upgrade of existing serial-based communications infrastructure. The PMU deployment provides high-resolution monitoring that improves grid operators' ability to visualize and manage the transmission system, improving reliability and grid operations. The company upgrades the existing synchronous optical networking (SONET) WAN backbone to a redundant 6 node optical carrier (OC)-3 ring and existing serial communications systems to IP-based communications at substations to deliver PMU data to PDC [42].

In Europe, a pilot project was initiated by Eandis and Infrax for an Advanced Metering Management (AMM) system in the region of Flanders, Belgium in 2011. Automated two-way communication between central systems and electricity/gas meters are enabled using approximately 36,000 communication gateways. A combination of PLC, DSL/LAN networks and mobile networks (General Packet Radio Service, GPRS) are utilized to set up communications between customers and an electric utility [43].

One of the European largest smart metering projects had been completed by Acea Distribuzione – the largest municipal utility in Italy. The implementation of the integrated AMM system began in 2004 to improve energy efficiency in Italy's capital, serving roughly 1.5 million households. The system includes high accuracy bi-directional meters and smart grid applications such as network operation control, and the ability to monitor low and medium voltage line status automatically. The system has also been designed to be extended to gas and water meters [44]. The company uses the Oracle Utilities MDMS system to support its AMM project, as well as uses PLC and GPRS to support its metering communication network.

A large-scale pilot project was initiated by Amperion Greece for the Public Power Corporation (PPC) to provide remote monitoring and control of irrigation pumps. The objective of the project is to reduce electricity consumption during peak hours and to detect power outages and electrical network availability in Larissa, a rural area in central Greece. The project provides a broadband access to the area encompassing a 107-km medium voltage power grid where broad power line (BPL) units installed. The BPL units were organized into cells to allow network scalability. A hybrid wireless-broadband over power lines (W-BPL) solution, combining the power distribution grid with Wi-Fi technology, is deployed in the project; and the Wi-Fi interface enables point-to-point connections to neighboring BPL cells. The W-BPL network is connected to the Network Operating Center (NOC) installed inside substations. The NOC provides the connection to the utility's remote operating center via a virtual private network (VPN) [45].

In China, an Advanced Metering Infrastructure (AMI) system was initiated to collect electricity usage information from all meters across its vast infrastructure of Huawei, Hongdian and China Mobile for China Southern Power Grid. The system allows to monitor end-use electricity usage in real-time for accurate billings and estimation of electrical demand. Additionally, the system can also detect faults on the meter and control them remotely and monitor its electricity network, i.e., substations, power lines and primary nodes. Embedded subscriber identification modules (SIMs), which can be connected to a single data collection and communication terminal, were used to remotely collect data across meters and the power grid via cellular 2G and 3G networks. The SIM information is embedded directly into the communication module's software to avoid end users from removing the SIM card and taking the meter out-of-service [46,47].

Overall, communication technologies selected can vary from country to country and from utility to utility in order to meet specific reliability, performance, security, coverage, scalability, manageability and cost requirements for a particular smart grid application. It is worth noting that wireless communications technologies, specifically RF mesh, are preferred for NAN/FAN applications in the U.S., while PLC is the dominant technology for NAN/FAN applications in Europe. This is because of the difference in electric power distribution infrastructures and wiring topologies in the U.S. and European countries. An electric power distribution system in the U.S. relies on a number of small secondary transformers – each of which serves a small number of houses, i.e., 2–7 houses. On the other hand, an electric power distribution system in European countries utilizes large secondary transformers – each of which commonly serves 100 houses or more. As a heavy attenuation can occur with PLC when communication signals on a medium-voltage line passes through a secondary transformer onto a low-voltage line, this makes it more difficult for electric utilities in the U.S. to employ PLC to serve their smart grid applications. For WAN applications, fiber optic has always been the commonly chosen technology. This is due to its ability to provide reliable and high-performance communications.

5. Conclusion

This paper compiles network requirements for major smart grid applications, ranging from home/building automation, smart metering, distribution automation, to wide-area monitoring, control and protection from a variety of smart grid use cases and selected standards. With respect to network requirements, communication technologies with low cost and power consumption are required for customer premises area network applications; those with high reliability and low latency are required for NAN/FAN applications; and those with very high reliability/security and extremely low latency are required for WAN applications. The paper also discusses real-world examples of smart grid applications and associated communication technologies. It is expected that this paper can provide an insight into communication network requirements for a variety of smart grid applications. This can be particularly useful for utility engineers when designing their smart grid networks and associated applications.

Acknowledgement

This work was supported in part by the U.S. National Science Foundation under Grant ECCS-1232076.

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Murat Kuzlu joined Virginia Tech's Department of Electrical and Computer Engineering as a post-doctoral fellow in 2011. He received his B.Sc., M.Sc., and Ph.D. degrees in Electronics and Telecommunications Engineering from Kocaeli University, Turkey, in 2001, 2004, and 2010, respectively. From 2005 to 2006, he worked as a Global Network Product Support Engineer at the Nortel Networks, Turkey. In 2006, he joined the Energy Institute of TUBITAK-MAM (Scientific and Technological Research Council of Turkey – The Marmara Research Center), where he worked as a senior researcher at the Power Electronic Technologies Department. His research interests include smart grid, demand response, smart metering systems, wireless communication and embedded systems.

Manisa Pipattanasomporn joined Virginia Tech's Department of Electrical and Computer Engineering as an assistant professor in 2006. She manages multiple research grants from the U.S. National Science Foundation, the U.S. Department of Defense and the U.S. Department of Energy, on research topics related to smart grid, microgrid, energy efficiency, load control, renewable energy and electric vehicles. She received her Ph.D. in electrical engineering from Virginia Tech in 2004, the M.S. degree in Energy Economics and Planning from Asian Institute of Technology (AIT), Thailand in 2001 and a B.S. degree from the Electrical Engineering Department, Chulalongkorn University, Thailand in 1999. Her research interests include renewable energy systems, energy efficiency, distributed energy resources, and the smart grid.

Saifur Rahman is the director of the Advanced Research Institute at Virginia Tech where he is the Joseph Loring Professor of electrical and computer engineering. He also directs the Center for Energy and the Global Environment at the university. In 2013 he is serving as the vice president for Publications of the IEEE Power & Energy Society and a member of its Governing Board. He is a member-at-large of the IEEE-USA Energy Policy Committee. Professor Rahman is currently the chair of the US National Science Foundation Advisory Committee for International Science and Engineering. Between 1996 and 1999 he served as a program director in engineering at NSF. In 2006 he served as the vice president of the IEEE Publications Board, and a member of the IEEE Board of Governors. He is a distinguished lecturer of IEEE PES, and has published in the areas of smart grid, conventional and renewable energy systems, load forecasting, uncertainty evaluation and infrastructure planning.