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A survey of communication/networking in Smart Grids

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ABSTRACT

Smart Grid is designed to integrate advanced communication/networking technologies into electrical power grids to make them "smarter". Current situation is that most of the blackouts and voltage sags could be prevented if we have better and faster communication devices and technologies for the electrical grid. In order to make the current electrical power grid a Smart Grid, the design and implementation of a new communication infrastructure for the grid are two important fields of research. However, Smart Grid projects have only been proposed in recent years and only a few proposals for forward-looking requirements and initial research work have been offered in this field. No any systematic reviews of communication/networking in Smart Grids have been conducted yet. Therefore, we conduct a systematic review of communication/networking technologies in Smart Grid in this paper, including communication/networking architecture, different communication technologies that would be employed into this architecture, quality of service (QoS), optimizing utilization of assets, control and management, etc.

1. Introduction

The electrical power grid has contributed greatly to our daily life and industry. Currently, however, the power grid system has many issues which must be resolved. First, more voltage sags, blackouts, and overloads have occurred in the past decade than over the past 40 years [1]. Unfortunately, most of the blackouts and brownouts are occurring due to the slow response times of devices over the grid [2]. Second, as the population size has increased, the current grid has got old and worn out; thus adding new appliances into customer's houses and buildings gives more instability to the current power grid [1]. Third, the current electrical network contributes greatly to carbon emissions. The United States' power system alone produces 40% of all nationwide carbon emissions [3].

Considering both economic and environmental interests, changes must be made to such an unstable and inefficient system. It requires reliability, scalability, manageability, and extensibility, but also should be interoperable, secure, and cost effective. This electric infrastructure is called "Smart Grid". Smart Grid should be designed and implemented in such a way as to maximize the throughput of the system and to reduce consumption of the system [4]. Moreover, Smart Grid not only requires communication to be real-time, reliability, scalability, manageability, and extensibility, but also should be interoperable, secure, future-proof, and cost effective [5].

Also, the US power system is quite different from other countries in terms of decentralization. That is, the whole US power system is consisted of multiple producers and distributors who are not the same as producers. Especially, for the Smart Grid, certain customers can be producers as well, and this introduces the challenge to design and implement mechanisms to pay those customers back when they put power back in the grid. Therefore, it takes much effort to design a practical infrastructure for the above requirements.

Therefore, it is widely agreed that Smart Grid relies greatly on the design, development, and deployment of dedicated information networks that enable information communication between devices, applications, consumers and grid operators. For the desired Smart Grid, communication/networking is a key technology for achieving automation and interactivity [6]. However, no existing standardized communication/network infrastructure has been widely accepted that can be used to transform the current electrical power grid into a Smart Grid. Most organizations, companies, and researchers have proposed their own underlying strategies and applications of legacy communications for electrical grid systems [1,4,5,7]. There are many research in networking [8–174] that can be applied into Smart Grid communications.

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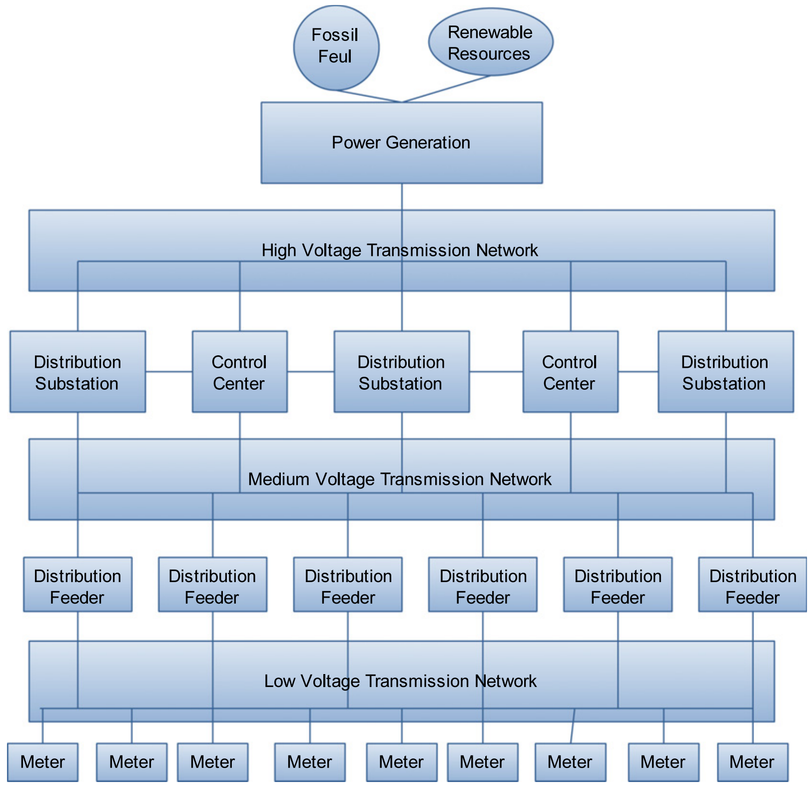

Fig. 1. Electrical grid system overview.

Smart Grids can improve energy usage levels via (1) energy feedback to users coupled with real-time pricing information and from users with energy consumption status to reduce energy usage, and (2) real-time demand response and management strategies for lowering peak demand and overall load via appliance control and energy storage mechanisms.

In this paper, we conducted a systematic literature review to identify and classify the communication and networking techniques in Smart Grid that have been proposed by other quality researchers. Every aspect in the following sections may have been or will potentially be applied into the field.

The rest of the paper is organized as follows. Section 2 briefly provides an overview of the background of Smart Grid technologies. Section 3 identifies and classifies most of existing communication and networking technologies that have been proposed to be deployed into the Smart Grid communication infrastructure. Section 4 identifies and classifies QoS issues and optimization problems in Smart Grid networking, and also concludes how the Smart Grid control the information over the whole network and the different types of data that have been transmitted. Challenges and research directions are presented in Section 5. We draw our conclusions in Section 6.

2. Electrical grid and Smart Grid

2.1. Basic electrical grid system

Electrical grid systems have four elements: electricity generation plants, transmission substations, distribution substations, and end users [4]. The recent electrical grid system works as follows. First, power bulks (or plants) generate power from wind energy, nuclear for distribution. As the power approaches customers' homes, it is stepped-down again to the voltage necessary for home use. Finally, home appliances access power through their electric meters [4]. This is shown in Fig. 1.

2.2. What is Smart Grid?

What is Smart Grid? The answers to this question vary among organizations and researchers. But they all share the common understanding that Smart Grid needs to be integrated with an information communication infrastructure in order to be "smarter".

One definition of DOE of USA is shown in Fig. 2. The bottom layer is physical energy infrastructure that distributes energy. Communication infrastructure is defined on the top of the physical energy infrastructure to entire supply chain. Computing/information technology is above the communication infrastructure for timely decision making. Smart Grid applications are on the top to create electrical system/societal values. Security is in another dimension and covers all layers.

The following paragraphs will systematically review the concept of the Smart Grid.

Generally, Smart Grid is a data communications network integrated with the electrical grid that collects and analyzes data captured in near-real-time about power transmission, distribution, and consumption [6]. Based on these data, Smart Grid technology then provides predictive information and recommendations to utilities, their suppliers, and their customers on how best to manage power [6]. From another perspective, Smart Grid is a complex system of systems, and therefore NIST (National Institute of Standards and Technology) has developed a conceptual architecture for the entire Smart Grid [4]. This conceptual architectural reference model provides a means to analyze use cases, to identify interfaces for which interoperability standards are needed, and to facilitate the development of a cyber security strategy [4].

Though it was emerged from the recent power grid system, Smart Grid has more requirements to meet and new characteristics to attain. The synthesized requirements of the desired Smart Grid are as follows:

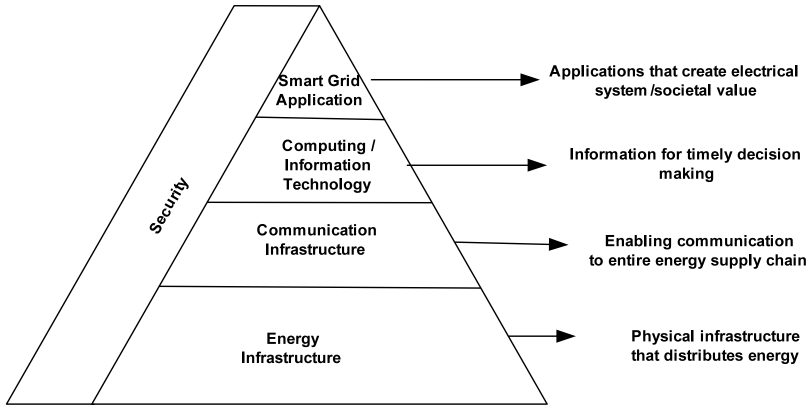

Fig. 2. Smart Grid definition.

(1) *AMI (Advanced Metering Infrastructure)*: It is designed to help customers know the real-time prices of power and optimize power usage accordingly [4,7]. Also, consumers become informed participants, and they can choose different purchasing patterns based on their needs and the Grid's demand, which can ensure the reliability of the electric power system [5].
(2) *Wide area Situational Awareness*: It is intended to monitor and manage all the components of the electric power system. For example, their behaviors and performance can be modified and predicted to avoid or to address potential emergencies [4].
(3) *IT Network Integration*: The Smart Grid scopes (generation, transmission, distribution, consumption, and control center) [1] and sub-scopes will use a variety of communication networks which are integrated from IT networks.
(4) *Interoperability*: The Smart Grid will have the capability of two or more networks, systems, devices, applications, or components to exchange and readily use information securely, effectively, and with little or no inconvenience to the user [4]. The Smart Grid will be a system of interoperable systems. That is, different systems will be able to exchange meaningful, actionable information. The systems will share a common meaning of the exchanged information, and this information will elicit agreed-upon types of responses. The reliability, fidelity, and security of information exchanges among Smart Grid systems must achieve requisite performance levels [4].
(5) *Demand Response and Consumer Efficiency*: Utilities and customers will cut their usage during peak times of power demand. Mechanisms will also be made for consumers to smartly use their power devices to lower their cost [4].

Hence, we can conclude that Smart Grid, by definitions and requirements, will have the characteristics of being more efficient, reliable, intelligent, etc. There are many challenges and issues involved in the Smart Grid communication fields. Essentially, there is an effort to make the power generation and consumption more flexible, to allow dynamic pricing, the collection of energy from small, reusable energy producers and so on. To implement this, the electric grid needs to be upgraded with communication and computation devices. Moreover, with integrating information networks into the current power grid system will come many security and privacy issues which must be addressed. Obvious vulnerabilities are introduced by IT networks. For example, hackers can steal customers' power without any trace being left their metering devices. The NIST therefore has released a guideline for addressing cyber security and privacy issues in the Smart Grid [175].

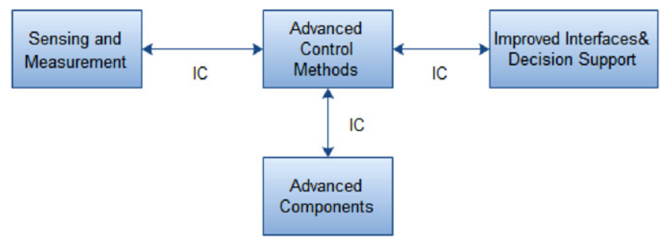

Fig. 3. Smart Grid key technology areas [5].

2.3. Key technologies

To achieve the characteristics of the desired Smart Grid addressed in the previous subsection, NETL (National Energy Technology Laboratory) described five key technology areas as follows [5,7], as well as shown in Fig. 3.

2.3.1. Integrated communications

High-speed, fully integrated, two-way communication technologies will make the modern grid a dynamic, interactive "mega-infrastructure" for real-time information and power exchange. Open architecture will create a plug-and-play environment that allows the networks' grid components to talk, listen, and interact securely.

2.3.2. Sensing and measurement

These technologies will enhance power system measurements and enable the transformation of data into information. They evaluate the health of equipment and the integrity of the grid and support advanced protective relaying; they eliminate meter estimations and prevent energy theft. They enable demand response, and they help relieve congestion.

2.3.3. Advanced components

Advanced components play an active role in determining the grid's behavior. The next generation of these power system devices will apply the latest research in materials, superconductivity, energy storage, power electronics, and microelectronics. This will produce higher power densities, greater reliability and power quality, enhanced electrical efficiency which produces major environmental gains, and improved real-time diagnostics.

2.3.4. Advanced control methods

New methods will be applied to monitor essential components, enabling a rapid diagnosis of and timely, appropriate response to any event. They will also support market pricing and enhance asset management and operations efficiency.

2.3.5. Improved interfaces and decision support

In many situations, the time available for operators to make decisions is only seconds. Thus, the modern grid will require wide, seamless, real-time use of applications and tools that enable grid operators and managers to make decisions quickly. Decision support with improved interfaces will enhance human decision making ability at all levels of the grid.

2.4. Mathematical model for the power delivery system [176]

Based on the power system architecture depicted above, Cheng et al. [176] provided a mathematical model to a quantitative description of the Smart Grid system communication requirements, which theoretically shows that building robust communication system for Smart Grid in a distributed way is possible. Following notations are defined in [176]:

- $G_l(t)$: electricity power generation of power plant l;
- $r_l^u(t)$: ramp-up function for $G_l(t)$;
- $r_l^d(t)$: ramp-down function for $G_l(t)$;
- $\Delta_i(t)$: safety margin of power plant i;
- $l_d(t)$: loss of electricity power in distance;
- $S_j(t)$: storage capacity of storage plant j;
- $l_s(t)$: loss of electricity power in storage;
- L_l: conversion loss of electricity power at level l;
- $g_{ik}(t)$: local/distributed electricity generation in branch k of power plant i;
- $u_{lmn}(t)$: electricity power consumption of utility n served by power plant l and branch m.

Then, an equation was given as follows [176]:

$$\sum_i \left[G_i(t)r_i(t) - \Delta_i(t) + \sum_k g_{ik}(t) \right] = \sum_l \left[L_1 + \sum_m \left(L_2 + \sum_n u_{lmn}(t) \right) \right] + \sum_j [s_j(t) - l_s(t)]. \quad (1)$$

By considering small time difference, the paper obtained:

$$\sum_i \left[\frac{dG_i(t)}{dt} r_i(t) + \sum_k \frac{dg_{ik}(t)}{dt} \right] = \sum_l \sum_m \sum_n \frac{du_{lmn}(t)}{dt} + \sum_j \left[\frac{ds_j(t)}{dt} - \frac{dl_s(t)}{dt} \right]. \quad (2)$$

Eq. (2) suggests that there is no need to report everything for global optimization of Smart Grid, and we only need to consider the differential values [176]. Therefore, they proposed that they can construct robust communication architectures in a distributed way.

3. Communication/networking architecture and communication technologies

As mentioned above, Smart Grid integrates information communication technologies into the electrical power grid. The Smart Grid is expected to affect all fields of the current electrical grid system, from generation, to transmission, and to distribution. But all of these fields cannot function well without an effective data communication networking system [177]. In other words, designing a communication system architecture that meets these complex requirements is the key to the successful implementation of Smart Grid in the future [177]. Based on the requirements of Smart Grid, it initially implies a need for bidirectional, real-time communication networks for data collection and processing [4]. Table 1 provides a classification of the communication/networking architecture as well as some related issues.

A Smart Grid communication includes Home Area Networks (HANs), Building Area Networks (BANs), Industrial Area Networks (IANs), and Wide Area Network (WAN). HAN is a communication network of appliances and devices within a home; NAN is a network of multiple HANs to deliver the metering data to data concentrators and to deliver control date to HANs; WAN is the largest networks for communications to/from data centers. In an HAN, appliances (such as electricity, gas, water, heat, solar panels, etc.) can be equipped with smart meters; these meters also connect smart appliances (i.e., appliances with communications and remote control functions) (such as smart dishwashers, dryers, ovens, etc.); and finally these meters connect to a metering gateway. In a NAN, many metering gateways of home areas connect each other to form a possible a wireless mesh network. A WAN connects smart metering gateways with utility and the distribution control system.

3.1. Smart Grid architecture

The challenges that we are facing to build a practical Smart Grid Communication Infrastructure would be: interoperability and scalability with many different utilities companies and user facilities and incorporation of the newly technology (Smart Meter Infrastructure).

It is important to further determine the challenges of designing communication/networking architectures of Smart Grid and to merge them into a universal model. Sood et al. [177] addressed that current IEEE standards, which govern the interconnection of Distributed Generation (DG), do not allow for the implementation of several applications which may be beneficial to the grid. They argued that IEEE Std. 929–2000 and IEEE Std. 1547–2003 implied that DR (Distributed Resource) unit of less than 250 mVA (million VA = million Watt) are not required to have monitoring and control facilities. These standards should be amended as DGs, regardless of size, so that they can be monitored, controlled, and assessed with the support of data communication [177]. Chen et al. [176] argued that a well-designed information communication structure to support the information processing will thus lead to effective electricity power usage. They argued that successful Smart Grids should be able to collect all kinds of information regarding electricity generation (centralized or distributed), consumption (instantaneous or predictive), storage (or conversion of energy into other forms), and distribution, through this communication infrastructure. Grid computing or cloud computing technologies could thus be utilized to optimize the usage of electricity [176]. Therefore, under this scenario, making Smart Grids robust and secure is the major existing challenge [176].

Before we can actually review the communication architecture infrastructure of the Smart Grid, we still need an overview of the Smart Grid architecture. There are three major sources of Smart Grid Architecture proposals:

(1) *Government & Organizations*: Provisioned requirements and blueprints of Smart Grid.
(2) *Industrial*: Proposals of communication infrastructure implementations.
(3) *Academia*: Greater focus on defining communication architecture requirements and solutions.

Table 1
List of communication/networking.

Classification	Papers	Description
Power line communication (PLC)	Application of PLC in SG consumption [181]	Application of PLC in smart power consumption
	Packet-oriented communication protocols for SG services over low-speed PLC [182]	Proposes a protocol stack based on IPv6/TCP using low-speed PLC
	Broadband over power lines could accelerate the transmission SG [183]	Challenges in transmission and distribution of SG; broadband over PL is a proposed solution
IP (or internet) based communication network	A proposed communications infrastructure for the Smart Grid [2]	Optical Media are needed for low latency; Proposes IP-based network for distribution network with AMI
	Internet protocol architecture for the Smart Grid [6]	Smart Grid technology can provide predictive information and suggestions to utilities, their suppliers, and their customers on how to utilize power better
	Why IP is the right foundation for the Smart Grid [184]	Information islands; Smart Grid communication issues and corresponding Internet architecture solutions
	Smart Grid leveraging intelligent communications to transform the power infrastructure [180]	Category of issues of Smart Grid and corresponding solutions for general, transmission, distribution, and customer aspects
Wireless networking in SG	Wireless networks for the smart energy grid: application aware networks [185]	Cellular wireless network architecture
	Control-aware wireless sensor network platform for the smart electric grid [186]	Wireless sensor networks for substations and generations
	The role of pervasive and cooperative sensor networks in Smart Grids communication [187]	Roles of ZigBee applied in Smart Grid networks
	Wireless sensor networks for domestic energy management in Smart Grids [188]	WSNs for reducing home energy consumption
	Cooperative sensor networks for voltage quality monitoring in Smart Grids [189]	WSNs applied for monitoring voltage quality in Smart Grid
	Toward a real-time cognitive radio network testbed: architecture, hardware platform, and application to Smart Grid [190]	Idea of applying cognitive radio networks to Smart Grid networking
	Frequency agility in a ZigBee network for Smart Grid application [191]	ZigBee's challenges in Smart Grid networks
	Applications of McWiLL broadband multimedia trunk communication technology in Smart Grid [192]	Application of McWiLL trunk communication in Smart Grid
Quality of services (QoS)	Smart Grid communications: QoS stovepipes or QoS interoperability? [193]	QoS interoperability, API middleware, Stovepipe system
	QoS routing in Smart Grid [194]	QoS routing for price signaling
	New IP QoS algorithm applying for communication sub-networks in Smart Grid [195]	New IP QoS algorithm for faster packet transmission in Smart Grid
Optimization	Optimizes asset utilization and operates efficiently [196]	General outlook of optimization in Smart Grids; eight aspects and challenges
	Information aggregation and optimized actuation in sensor networks: enabling smart electrical grids [197]	Application of sensor and actuator networks (SANETs) to optimize Smart Grids
	Smart Grid communication network capacity planning for power utilities [198]	Plan for communication capacity of the Smart Grid network
Control and management	Agent-based micro-storage management for the Smart Grid [199]	Agent technologies; optimization in storage of Smart Grid
	Smart Grid design for efficient and flexible power networks operation and control [200]	Intelligent functions in Smart Grid operation and control, concepts of how to evaluate them

The architectures proposed above are focused on parts of the whole Smart Grid system which are intended to address specific requirements that must be met. However, several conceptual architectures of the Smart Grid have now been proposed by national organizations and companies, such as the DOE (Department of Energy) [1], the State of West Virginia [7], NIST [4], etc.

The DOE's *Smart Grid System Report* [1] proposed that a Smart Grid's architecture should include the following scopes: Market Operators, Reliability Coordinators, Gen/Load Wholesalers, Transmission Providers, Balancing Authorities, Energy Service Retailers, Distribution Providers, and End Users (Industrial, Commercial, and Residential).

West Virginia's white paper [7] proposed that Smart Grid architecture should be composed of the following four elements: Sensing and Measurement, Advanced Control Methods, Improved Interfaces & Decision Support, and Advanced Components.

NIST proposed in the *NIST Framework and Roadmap for Smart Grid Interoperability Standards* [4] that Smart Grid architecture should include the following: Customers, Markets, Service Providers, Operations, Bulk Generation, Transmission, and Distribution. This is one the most fully described architectures proposed in recent Smart Grid literature. As depict in Fig. 4, Customers area can be further categorized into three types: Home Area Networks (HANs), Building Area Networks (BANs), and Industrial Area Networks (IANs). They can be either wired or wireless networks on customer premises (home, building and industry areas respectively) that support messaging among appliances, smart meters, electronics, energy management devices, applications, and consumers. Applications and communications in these networks may be driven by Home Energy Management Systems (HEMS), Building Automation and Control Networks (BACnet), or other energy management systems [178].

After reviewing the existing organization-proposed Smart Grid architectures [1,4,5,7,180], we conclude that a Smart Grid architecture must address the following critical issues [6]: (1) transmitting data over multiple media; (2) collecting and analyzing massive amounts of data rapidly; (3) changing and growing with the industry; (4) connecting large numbers of devices; (5) maintaining reliability; (6) connecting multiple types of systems; (7) ensuring security; and (8) maximizing return on investment.

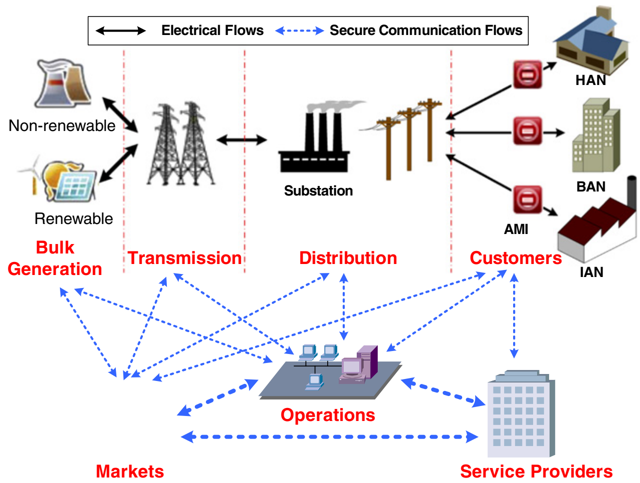

Fig. 4. Smart Grid power system architecture [179].

Based on the Smart Grid architecture, we come up with communication architecture (shown in Fig. 5) in a distributed way. It is an abstract system that only shows the different components within the communication system, and does not contain which kind of communication technology that it will employ in the future. However, we are going to explain the different communication technology for Smart Grid in later subsections.

3.2. Internet based architecture

Besides the national organizations that have proposed conceptual Smart Grid architectures, several other researchers also have proposed Smart Grid architectures with certain characteristics that they want to add to the system.

Aggarwal et al. [2] stated that the present grid allows one-way communication only from the generation system to the downstream points of distribution. Further, in Smart Grid, a point of electricity consumption can also become a point of generation [2]. Thus, communication should be able to transmit sensors' information to the control center of the grid and pass control messages to various points on the grid, resulting in the appropriate action [2]. Also, the Smart Grid needs more end-user interaction such as real-time monitoring of energy meters [2]. In this situation, there are challenges as follows:

- Latency–Stringent. If the control center misses any input from the sensors, it can produce and send a wrong result control message to the points over the grid. The latency is in the order of a few milliseconds (e.g., 10 ms) [2].
- Large number of messages–Since this adds more elements to the network, it should be able to transport more messages simultaneously without any major latency [2].

Their proposed solution to the Smart Grid communication is an IP-based network built on optic fibers. First, an IP-based network as the backbone of Smart Grid network can make use of new technologies independent of service with significantly reduced prices. Second, since optical fibers can easily support the speed of several hundred gigabits per second, they can support the increasing needs of the Smart Grid network over the long term [2].

In Cisco's definition [6], Smart Grid is a data communication network integrated into the electrical grid that collects and analyzes data captured in near-real-time about power transmission, distribution, and consumption. Then, based on the data, Smart Grid technology can provide predictive information and suggestions to utilities, their suppliers, and their customers on how to utilize power better [6]. Cisco pointed out that the challenge of communication/networking in the current Smart Grid is that the existing electrical grid is composed of isolated information "islands" [6]. At the high level, the Smart Grid can be divided into two large systems, transmission and distribution, each of which has its own specialized rules for exchanging data [184]. But the Smart Grid depends upon the fast and free exchange of data between components of the Smart Grid. Therefore, the Internet architecture addresses these issues and presents several benefits [184]:

- Transmitting data over multiple media: IP can run over any link layer network, including Ethernet, wireless networks, etc.
- Connecting large numbers of devices: IPv6 offers straightforward addressing and routing for huge networks such as the Smart Grid.
- Connecting multiple types of systems: IP is device independent. This means that IP can identify any type of system which the data is sent from and deliver it to its destination.
- Maintaining reliability: IP has more tools and applications to help manage the network.

Therefore, to achieve a certain level of interoperability and security, Cisco argued that the best standard suite of protocols for the Smart Grid is the Internet Protocol (IP) [6]. However, addressing inherited threats and vulnerabilities from the Internet is a huge challenge for securing IP-based Smart Grid. Whether follow it as a communication standard in the Smart Grid or not is still under investigation and need more research work.

In conclusion, the Internet based Smart Grid Communication/Networking Architecture is very applicable due to its scalable, secure, interoperable characteristics.

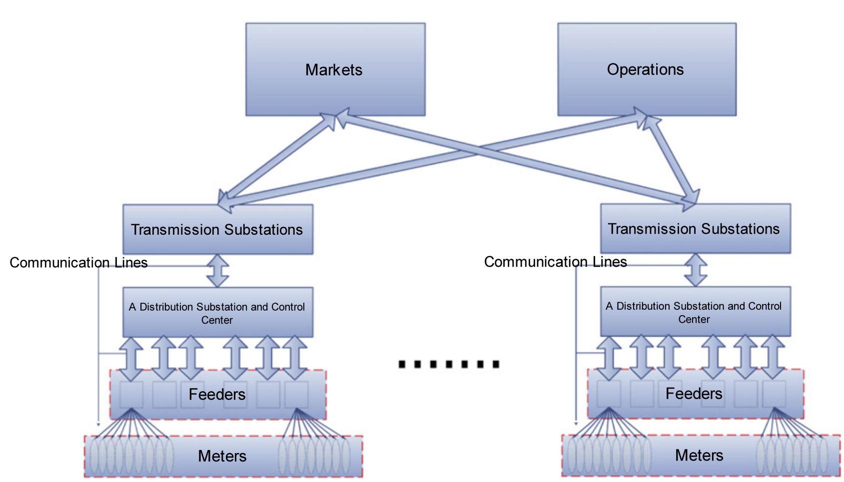

Fig. 5. Abstract Smart Grid communication architecture.

3.3. Power Line Communication architecture

Power Line Communication (PLC) systems generally operate by transmitting a modulated carrier signal on the wiring system [201]. But, as the wires were intended to deliver Alternating Current (AC), the power wire circuits only have a limited ability to carry higher frequencies. As a special case, Broadband over Power Lines (BPL), the so-called Power Line Internet, is an application of PLC technology which provides broadband Internet access through ordinary power lines. A computer would need to plug a BPL modem into an outlet in an equipped building to have high-speed Internet access [201].

Liu et al. [181] proposed a pilot simulation of a real-time two-way PLC in Smart Power Consumption. They used PLC terminals to collect data information from the AC power lines. They chose to adopt the extension of PLC technology because they believed that power lines belonged only to the utility companies, that the use of PLC technology to extend consumers' home power communication networks can effectively solve the networking issue with dramatically reduced cost of networking construction, and that it will increase the efficiency of power consumption [181]. The challenge lies in the restriction of channel characteristic; PLC still has a gap in terms of supporting high-speed data transmission. Therefore, they chose an optical composite power cable which uses power lines as a fiber optic carrier [181]. In this way, transmission media will solve the low data rate problem. Bauer et al. [182] proposed a protocol stack to build the low-speed PLC physical layer into a robust communication model.

The NETL [183] argued that the transmission of Smart Grid faces challenges. Since the transmission of Smart Grid will require broadband, low latency, secure connectivity between transmission substations and between these substations and their control center [183], the NETL Smart Grid Implementation Strategy (SGIS) team identified and tested whether the BPL could be used as potential alternative. However, BPL has only applied to distribution subsystems in Smart Grid which use Medium Voltage wires, and it has never been applied to transmission subsystems which use High Voltage (HV) wires. Working together with American Electric Power (AEP), NETL has tested the BPL network over a 69 KV, 5-mile line connecting three AEP substations [183]. The reliable communications are at over 10 MB/second, with a typical latency of about 5 ms.

In conclusion, the PLC itself has low-speed shortcomings for data communication. In order to make the Smart Grid data transmission reliable and robust, we have to either improve the transmission media or use certain technologies to make low-speed PLC communication reliable and robust.

3.4. Wireless

As mentioned earlier, Smart Grid networks can be divided into HANs, BANs, IANs, Neighborhood Area Networks (NANs), and Field Area Networks (FANs): wired and wireless networks that connect utility systems to customer premises in order to support a wide range of communication and control applications [178], including demand response and distribution automation. These networks potentially spread over wide geographic areas. Therefore, a range of wired and wireless technologies are relevant to these networks, including Cellular, RF Mesh, WLAN 802.11, WiMAX, ZigBee, McMiLL, etc., which can potentially be applied to and integrated into Smart Grid networks.

3.4.1. Cellular networks

Clark et al. [185] argued that, since distribution in Smart Grid has already deployed sensors and control devices in their networks, telecommunication wireless network technologies such as 2G, 3G, or even 4G must also be deployed in Smart Grid networks to achieve the following four characteristics: application awareness, support for large numbers of simultaneous cell connections, high service coverage, and prioritized routing of data [185]. Since the current transmission in Smart Grid uses Supervisory Control and Data Access (SCADA) as a solution to monitoring and controlling high voltage networks, fewer 3G monitoring devices are deployed here. Furthermore, 3G monitoring and control devices can also be deployed in low and medium voltage networks [185]. But the 3G solution is a temporary one because it lacks QoS and reliability in data transmission [185]. Therefore, 4G solutions such as WiMAX and Long Term Evolution (LET) must be deployed to address these issues [185]. Also, 4G can provide broader bandwidth, which makes it possible to allocate higher numbers of channels with the growing needs of Smart Grid.

3.4.2. Sensor networks

Gadze [186] proposed a hierarchical architecture of wireless embedded sensor platforms for Smart Grid, which is a multi-level, decentralized platform that addresses the potential impact of harsh power environments at the substation and generation levels, since wireless sensor communication is very unpredictable due to path loss, shadow fading, and ambient noise, which are common in substation and generator environments [186].

Erol-Kantarci and Mouftah [188] proposed a scheme called Appliance Coordination (ACORD) which uses in-home Wireless Sensor Networks (WSNs) to reduce the cost of home energy consumption. Time-Of-Use (TOU) rates and Energy Management Units (EMUs) make this scheme feasible. First, TOU rates make billing flexible and the rates differ at peak, moderate peak, and off-peak time periods [188]. Second, EMU receives and coordinates customer requests [188]. However, the following challenges exist: first, it is hard to change a customer's behavior with them being comfortable enough to accept that change; second, it is possible for dynamic pricing to cause load oscillation due to load shifting; third, the wireless channel itself might have interference, especially when appliances are trying to coordinate with each other [188].

Bisceglie et al. [189] argued that, as a consequence of the growing problems related to power quality, the system of wide area voltage monitoring is more demanding. They proposed a fully decentralized voltage quality monitoring architecture by deploying self-organizing sensor networks. In such networks, each node can compute both local and global performances by using local information and information exchanged with neighboring nodes [189].

3.4.3. ZigBee network

Ullo et al. [187] pointed out that communication infrastructures should be scalable for the future and that they should support the last-mile (from backbone node to customers location). To address this problem, he proposed that ZigBee WSNs are particularly suitable due to low cost, power, and complexity and their high level of scalability and reliability [187]. Further, Yi et al. [191] pointed out that the ZigBee channels are overlapped by wireless local area networks (WLAN) based on 802.11 specifications, which will cause significant service degradation in interference scenarios [191]. To address this issue, they proposed a frequency-agility-based scheme to mitigate interference that is composed of Interference Detection Scheme and Interference Avoid Decision algorithms.

3.4.4. Cognitive radio network

Qiu et al. [190] proposed a new way to implement real-time cognitive radio networks into the Smart Grid. They believe that cognitive radio networks can enhance the network security of the Smart Grid.

3.4.5. McWiLL network

The Multicarrier Wireless information Local Loop (McWiLL) is a wireless broadband multimedia trunk communication system which uses dynamic channel allocation and smart antennas to enhance its throughput [202]. They argued that three main issues in Smart Grid communication must be addressed as follows [192]:

- Open Integrated Communication System and Complete Communication Standards.
- Construction of Distribution Communication Networks.
- Construction of Backup Communication Systems and Emergency Dispatch Communication Systems.

After analyzing the McWiLL's benefits to the Smart Grid Communication Infrastructure, such as using shared channels to support data transmissions, rich and intuitive status display, broadband, IP-sharing, etc., they proposed an application framework of the McWiLL broadband multimedia trunk in Smart Grid [192].

Existing examples of wireless networking technologies have been applied to the Smart Grid Communication Infrastructure. However, they all share common characteristics such as real-time, reliability, scalability, low cost, low latency, etc. Existing communications architectures like PLC in the power field have been designed to be extended to meet the Smart Grid requirements. Also, there are legacy information communication networks that have been redesigned to be integrated into Smart Grid networking to meet these requirements, such as Internet based architectures. However, based on the specific requirements of Smart Grid communication infrastructures proposed by some researchers, the communication/networking technology varies from wired to wireless and from Wide Area Network (WAN) to Local Area Network (LAN), especially for the low voltage domain of the Smart Grid.

3.5. Mathematical models for communication architecture in Smart Grid [2]

We introduce a mathematical model for computing the communication bandwidth requirement before we build the communication system [2]. The result from [2] indicated that we need to use high-speed transmission media for the message congestion component in the communication system.

Assume that each electric meter generates a message per second to the distribution substation (DS), shown in Fig. 6; average length of each message is 100 bits and upper bound latency is 10 ms. The delay can be approximately by the following equation [2]:

$$T = \frac{1}{\mu c - \lambda}. \tag{3}$$

Plug in the number of messages per second $\lambda = 10^6/\text{s}$, mean length of the message $1/\mu = 100$ bits, and mean latency time $T = 10$ ms. Then the authors in [2] get the transmission line bandwidth c as 100.01 Mbps [2]. But the paper argued that this value was not meaningful if the delay varies within wide limits. For example, the delay is limited to 10 ms for 99% of the messages.

The authors further assume that packets follow the Poisson distribution at each node; and the inter-arrival time and service time are both exponentially distributed. They used formula (4) to calculate the bandwidth.

$$p_1 = P\{W_1 \le t\} = 1 - \rho e^{-\mu c(1-\rho)t}, \tag{4}$$

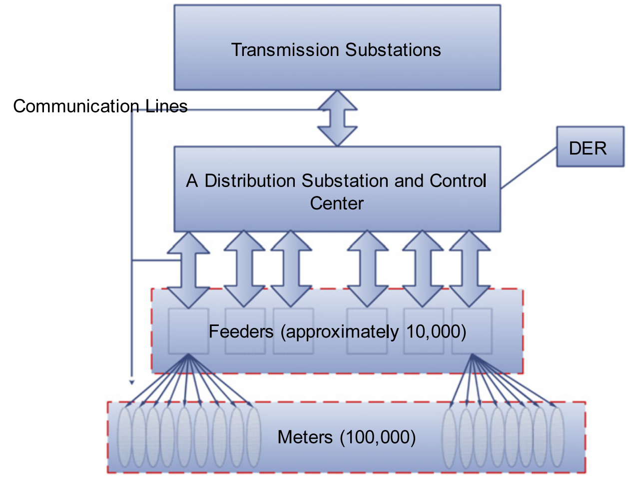

Fig. 6. Quantification of network from one distribution substation [2].

where $\rho = \lambda\bar{x}$.

In this case, $p_1 = 0.99$, and they got the bandwidth c as 100.056 Mbps. However, if the average message length is $1/\mu = 400$ bits, using formula (4), the bandwidth c is 400.086 Mbps.

Therefore, it is observed that the bandwidth requirement has grown up substantially. Thus, the authors in [2] believe that optical fiber is needed as the communication media for Smart Grid.

4. Other issues in communication/networking

Interoperability is a key requirement for data communication in the Smart Grid because there are many different types of systems, devices, communication media, and protocols within the Smart Grid system. QoS must be supported in information communication networks in the Smart Grid. Also, the Smart Grid aims to improve utilization of the grid assets and to make the electrical grid operate more efficiently. These are the two main requirements and characteristics that we will review in the section. In addition, we will also study the control and management issues in the communication and networking.

QoS and Optimization technologies are needed to be further advanced to meet the growing and further to-be-detailed requirements of the Smart Grid.

Also, with the development of communication and networking technologies, new QoS and optimization technologies must be improved accordingly.

Control and management of operations in the Smart Grid has just begun and needs to be developed by cooperation to address the increasing large number of devices integrated into the Smart Grid.

4.1. QoS

Interoperability is a key requirement for data communication in the Smart Grid [193]. Bakken and Pullman [193] argued that the Smart Grid data communication must support the interoperability of QoS across the entire power grid. They articulated that there are multiple non-functional QoS properties, such as delay, rate, confidentiality, criticality/availability, etc. [193]. In order to achieve interoperability, they built a stovepipe system which is so tightly bound together in inter-related elements that individual elements cannot be differentiated, upgraded, or refactored [193]. They then proposed middleware APIs to support the interoperability of QoS from high levels down to low levels [193].

Li and Zhang [194] argued that Smart Grid is a new technology which controls power load via price signaling. In order to have the correct real-time price of communication, they believed that degradations such as delays or outages will not be acceptable for price control [194]. Therefore, they proposed a QoS mechanism for the communication system in the Smart Grid. To do this, they first derived the QoS requirement by analyzing the dynamics of the power market and the impact of communication metrics like delay and outage on the revenue of home appliances [194]; secondly, they modeled the QoS derivation as an optimization problem that maximizes the total reward [194]; thirdly, they applied a simple greedy routing algorithm to secure the QoS [194].

Yang et al. [195] argued that traditional routers providing best-effort services cannot meet new requirements, such as exponentially growing quantities and types of traffic flow over electric power communication networks. By integrating MPLS and DiffServ, they proposed a new IP QoS algorithm applied to the Smart Grid Communication networks (MDSG) which can provide guaranteed service for IP QoS and fast-forward packets [195].

4.2. Optimization

One of the goals of the Smart Grid is to improve the overall efficiency of the whole grid [196] by optimizing the Smart Grid's asset utilization. NETL's report [196] argued that the Smart Grid will utilize the latest technologies to optimize the use of its assets over two different time periods: the short term, by how it is operated on a daily basis, and the long term through dramatically improved asset management processes. This can be achieved through the following eight characteristics [196]: improved asset utilization, reduced system losses and congestion, improved capacity planning, predictable maintenance, reduced outage duration, better customer service and work management, better operator's risk management, and increased power density.

Pendarakis et al. [197] argued that many applications of Sensor and Actuator Networks (SANETs) have emerged in the areas of energy generation and distribution. Luan et al. [198] argued that it is important to create a communication network with adequate capacity to accommodate future utility growth and new applications due to the use of AMI. They calculated data traffic profiles for the communication network based on traffic patterns, message data size, and communication protocol overheads for each application by identifying the major one [198].

QoS and Optimization are two crucial properties of Smart Grid communication/networking. Typically, the QoS algorithms aim to achieve reliable communication over the network, which must optimize the resources such as rewards and network utilization. On the other hand, optimization implies the need for QoS to secure Smart Grid's communication and guarantee that it is reliable. In this way, operational and maintenance expenses and the cost of investments will produce more effective results [196].

4.3. Control and management

Control and management of operations in the Smart Grid are also important functions for power system to achieve its characteristics, such as accommodates a wide variety of generation points, participated customers, dynamic electricity markets, optimized assets, etc.

Momoh [200] argued that the Smart Grid system should be more adaptable and secure than it has been. Customers are now demanding high power quality and reliable power supply. Therefore, they believed that the Smart Grid should use intelligent functions of advance interactions of agents, such as telecommunication, control, and optimization [200]. Since it is unclear what the concept of intelligence in the Smart Grid is and how it should be measured, they proposed the following goals of intelligent functions [200]:

- Real-time angle and voltage stability and collapse detection and prevention via intelligence-based data.
- Reactive power control based on intelligent coordination controls.
- Fault analysis and reconfiguration schemes based on intelligent switching operations.
- Power generation and load balance which use intelligent switching operation to energize loads and oscillations, and minimize demand interruption while controlling frequency.
- Distributed Generation (DG) and Demand Side Management (DSM) via a demand response strategy for peak shaving. These also include increased proliferation and control of Renewable Energy Resources (RERs).

They also noticed that there are several levels of challenges to be addressed, especially at the System Planning and Maintenance Levels. For example, there are too many decision makers, planning uncertainties, a lack of predictive real-time system controls, etc. [200].

Vytelingum et al. [199] argued that using micro-storage devices at home to save power via the Smart Grid is reducing the burning of fossil fuels. However, compared to the capacity of the Smart Grid, in-home micro-storage devices at home are facing load demanding issues [199]. To address this, they proposed an agent-based micro-storage management technique with a provided general framework within which to analyze the Nash equilibrium of an electricity grid and devise new agent-based storage learning strategies that adapt to the market conditions [199].

The control and management of Smart Grid operation is an interdisciplinary field which crosses the boundaries of communication, optimization, control, dynamic optimization techniques, and even social and environmental constraints [200].

5. Challenges and research directions

There are many challenges for Smart Grid communications, and these challenges form the potential research directions.

5.1. Interoperability

Different vendors, users, and utility companies may adopt different communication technologies. Communication of a large number of distributed energy distribution networks, power sources, and energy consumers under many different administrative domains (i.e., belonging to different organizations and users) is challenging. Therefore interoperability becomes a large challenge to make a Smart Grid work so that multiple heterogeneous communication technologies and standards could coexist in different parts of the Smart Grid. For example, in a home area, both ZigBee and WiFi could be used.

5.2. Interdisciplinary

Smart Grids include many different organizations and societies so that the research areas are interdisciplinary in nature, e.g., integration of sensor networks, actuation, and power systems, integration of communication/networking with power systems and control systems, and integration of security and power systems, etc.

5.3. Scalability

Since a Smart Grid involves millions of users, scalability becomes an issue. A technical sound solution in a small scale may not be scalable when applying into such a huge scale. Internet working between heterogeneous wired and wireless networks with seamless mobility and quality of service (QoS) requirements become important.

5.4. Security and privacy

Increased interconnection and integration also introduce cyber vulnerabilities into the grid. Failure to address these problems will hinder the modernization of the existing power system. Security issues include unauthorized smart metering data access, distributed turning off all devices by an attacker, smart metering data repudiation, stealing power without notice, attacking Smart Grid infrastructure to cause power outage, etc. There are also some concerns about privacy issues in Smart Grids, e.g., metering data can leak sensitive and private information.

Security and privacy are extreme important. Readers may refer to our survey paper [203] for further information.

5.5. Performance

First, Smart Grid communication is a very complex due to heterogeneous systems, large scale deployments, interdisciplinary areas (such as control, communication, power, etc.), and dynamic and non-deterministic systems.

Second, efficiency is important for better, fast, secure, and robust controls and communication.

5.6. Testbed

Testbeds of Smart Grids are important and essential for conducting research and test results.

5.7. Some further comments

Since the categorization of HAN, IAN, BAN, NAN, and FAN concepts was only proposed by IEEE in 2010, a great deal of networking architecture design, implementation, and testing work can be done in these area networking fields.

Furthermore, many existing and newly developed high quality, real-time, reliable wired and wireless technologies can be extended and adapted to the communication networking infrastructure of the Smart Grid.

Finally, it is crucial for the Power Society and IEEE Communication Society to cooperate and propose standards for the physical layer.

6. Conclusion

Smart Grid is a potential electrical power delivery system, with at least two important components: Firstly, a two-way, real-time, reliable, large capacity communication infrastructure to satisfy the increasing needs of the power grid, such as bill verification from customers, control and management of the power load over the whole grid, optimization of power grid assets, etc.; secondly, integrated Information Technology (IT) which processes and handles large amounts of information over the Smart Grid.

We reviewed the communication and networking technologies, including communication/networking architectures, QoS and optimization, and control and management of operations in the Smart Grid.

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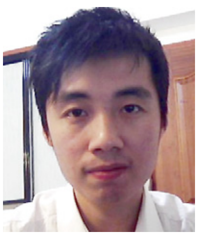

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