Smart Grid Communications Architecture: A Survey and Challenges

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Abstract: - With an increasing interest from both the academic and industrial communities, this article systematically investigates developments in communication technology for the smart grid. Smart grid can be defined as an electric system that uses information, two-way secure communication technologies and computational intelligence in an integrated fashion across the entire spectrum of the energy system from the generation to the end points of the electricity consumption. Communication networks play a critical role in smart grid, as the intelligence of this complex system is built based on information exchange across the power grid. The design of the communication network associated with the smart grid involves detailed analysis of requirements, including the choice of the most suitable technologies for each case study, and architecture for the resultant heterogeneous system.

Key-Words: - cognitive communications, demand response, heterogeneous wireless networks, smart grid.

1 Introduction

Affordable and reliable electric power is fundamental to modern society and economy. With the application of microprocessors, reliable and quality electric power is becoming increasingly important. On the other hand, the electric grid was cited by the National Academy of Engineering as the supreme engineering achievement of the 20th century [1].

The smart grid (SG) evolves the architecture of legacy grid which can be characterized as providing one-way flow of centrally generated power to end users into a more distributed, dynamic system characterized by two-way flow of power and information. Information and communication technologies (ICT) play a crucial role in the SG. The SG will involve networking vast numbers of sensors in transmission and distribution facilities, smart meters, back-office systems as well as home devices which will interact with the grid. Large amount of data traffic will be generated by meters, sensors and synchrophasors.

While networking technologies and systems have been greatly enhanced, the SG faces challenges in terms of reliability and security in both wired and wireless communication environments. Some of the key requirements of the SG from the aspects of global multimedia communications include [2]:

- Better utilization of existing assets to address long term sustainability,
- Management of distributed generation and information storage,
- Integration, communication and control across the information system to promote open system interoperability and to increase safety and operational flexibility.

From technical component’s perspective, the SG is high complex combination and integration of multiple analog and digital technologies and systems. The automation being applied to the electric grid is similar in concept to the network management and operations support systems that were applied to the telecommunication networks in the 1970s and 1980s. Applying ICT to the grid is not straightforward because it must account for constraints that did not exist in automating the telecommunications network. For example, unlike the communications network, which routes packets of information, the electric grid routes power flows that are constrained by the laws of physics. Some SG applications that control generators or substations, have latency requirements measured in milliseconds, while the consequences of failing to deliver a control packet on time can be harmful. On the other hand, applications such as communication of smart meter interval data have much less stringent requirements. Characterizing the performance requirements is crucial to understanding which communication technology should be used for various SG applications.
This article starts with a key requirement for the SG. Then, we deal with main components of the SG together with corresponding communication architecture. The importance of wireless mesh networking as well as heterogeneous network integration to coordinate the SG functions are invoked, too. Finally, an outline of the SG demand response concludes the article followed by own discussion.

2 Components of the Smart Grid

The main components of the SG are: new and advanced grid components, smart devices and smart metering, integrated communication technologies, programs for decision support and human interfaces, and advanced control systems. An overview of the main components of a SG is provided in Fig. 1.

![Fig. 1. Main components of the smart grid](image)

New and advanced grid components allow for a more efficient energy supply, better reliability and availability of power, as it was mentioned. Smart devices and smart metering include sensor networks. Sensors are used at multiple places along the grid, at transformers and substations or at user’s homes [3]. They play an outstanding role in the area of remote monitoring and they enable new business processes like real-time pricing. Control centers can immediately receive accurate information about the actual grid condition. Smart meters allow for real-time determination and information storage of energy consumption and provide the possibility to read consumption both locally and remotely [4].

Information provided by sensors and smart meters needs to be transmitted over a communication backbone, which is composed of heterogeneous technologies and applications. These can be classified into communication services group shown in Table 1, together with brief descriptions and examples. Usually, wide area networks (WANs) and local area networks (LANs) are deployed within a SG [5].

<table>
<thead>
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<th>Table 1. Smart grid communication applications and technologies</th>
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<td><strong>Core networking</strong></td>
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<td><strong>Network management</strong></td>
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The data volume in SG will increase tremendously compared to traditional grids. Tools and applications include systems based on artificial intelligence and semi-autonomous agent software, visualization technologies, alerting tools, advanced control and performance review applications as well as data and simulation applications and geographic information system (GIS). Artificial intelligence methods as well as semi-autonomous agent software, for example, contribute to minimize data volume and to create a format most effective for user comprehension whereby the software has features that learn from input and adapts. As for GIS, it provides location and spatial information and tailors them to the specific requirements for decision support systems along the SG.
Advanced control systems monitor and control essential elements of the SG. Computer-based algorithms allow efficient data collection and analysis, provide solutions to human operators and are also able to act autonomously. Faults can be detected much faster than in traditional grids, while outage times can be significantly reduced. To fulfill the purposes, the SG communications infrastructure has to integrate enabling networking technologies.

3 Communications Architecture for the Smart Grid
The SG is usually deployed in a rather large geographical areas. Consequently, the communications infrastructure of the SG has to cover the entire region with the intention to connect a large set of nodes. The communications infrastructure is envisioned to be a multilayer structure that extends across the whole SG as shown in Fig. 2.

![Fig. 2. Multilayer structure across the smart grid](image)

In particular, home area networks (HANs) communicate with various smart devices (meters, sensors, actuators) to provide energy efficiency management and demand response. Neighborhood area networks (NANs) connect multiple HANs to local access points. Wide area networks (WANs) provide communication links between the NANs and the utility systems to transfer information.

The three-layered structure of the communications networks provides a potential operation of the SG to operate economically, efficiently, reliably, and securely. On the other hand, there are many challenges imposed on the design of SG communications architecture like [6]: energy services, interoperability, tremendous data amount, highly varying traffic, quality of service (QoS), and security.

A unique characteristic of the SG is the integration of distributed renewable energy sources (e.g., solar and wind power). For a NAN, there are two main power sources: the power from the utility and the distributed renewable energy. These power sources have two essential differences: price and availability. Balancing the usage of different energy sources will be very important for power grid stability, availability, and operation cost.

Data will flow over generation, transmission, distribution, and user networks in the SG. A variety of technologies will be used to set up the communication architecture to provide enough information to the control centers. One of the major problems of the multitiered topology of communications networks is interoperability among so many subnetworks.

The amount of data generated by smart devices will experience explosive growth in the future. This tremendous data amount places considerable load on the communications infrastructure of the SG.

There are large amounts of real-time and archival operational data in the SG. The amount of data varies tremendously during a day, so the traffic conditions change rapidly. During peak hours, the data communications requires higher data rate and more reliable services.

Different categories of data have different QoS priorities in terms of transmission latency, bandwidth, reliability, and security. Information including device’s state, load, and power pricing should flow over the communications network accurately, effectively, and reliably. A higher priority and guaranteed QoS should be provided to the meter data, while power price data used for summarizing the monthly bill for electric usage have normal priority and QoS.

The SG will use computer networks for controlling and monitoring the power infrastructures. This in turn exposes the SG to outside attacks. There are many potential threats within utilities, such as indiscretions by employees and authorization violation [7].

4 Example of Cognitive Radio Based Communication Architecture for Smart Grid
Cognitive radio based communication architecture for the SG is proposed in [6] (Fig. 3). This architecture uses cognitive radio technology to enable the communications infrastructure more economically, flexibly, efficiently and reliably.

Cognitive communications that operate in the unlicensed spectrum are applied in the HAN to coordinate the heterogeneous wireless technologies.
On the other side, cognitive communications that operate in the licensed spectrum are applied in the NAN and WAN to dynamically access the unoccupied spectrum.

The HAN is a fundamental component that enables two-way communications to provide demand response management services in the SG. Commissioning and control are two necessary functionalities in the HAN. Commissioning is specified to identify new devices and manage the forming of the self-organizing network. Control is used to maintain the communication link between devices and ensure interoperability within the SG.

The HAN consists of a cognitive home gateway (HGW), smart meters, sensors, actuators, and other intelligent devices. It usually uses a star topology with either wired technologies (e.g., PLC) or different wireless technologies (e.g., Zigbee, and WiFi).

In SG applications, the NANs will collect energy consumption information from households in a neighborhood and distribute them to a utility company through WAN. NAN cognitive gateway (NGW) connects several HGWs from multiple HANs. The HGWs are the data access points of the HANs to the outside NAN, and they also act as the cognitive nodes located in the NAN. From the technology point of view, the NGW can be considered as the cognitive radio access point to provide single-hop connection with HGWs in a hybrid access manner. The NGW manages the access of the HGWs and distributes spectrum bands to them.

In the WAN, each NGW is no longer an access point, but a cognitive node with the capability to communicate with the control center through unused frequency space. This center is connected with cognitive radio base stations (CRBS) that are dispersed over a large area (e.g., a city). In conjunction with the control center, there is a spectrum broker that plays an important role in sharing the spectrum resources among different NANs to enable coexistence of multiple NANs. In a large geographical distribution of NANs, several NGWs may not be within the geographic area covered by base stations. These NGWs have to communicate in an ad hoc mode to share unoccupied spectrum by themselves.

5 Heterogeneous Networks Integration to Coordinate the Smart Grid Functions

Heterogeneous networks achieves end-to-end integration of the corresponding technologies by using sensor network architecture. Defining the interoperability with next-generation network (NGN) as the SG backbone is of importance, too.

The main component of the SG is the sensor network which consists of a system of distributed nodes that interact among themselves and with the infrastructure in order to acquire, process, transfer and provide information extracted from the physical world [8].

The smart meter is the bridge between user behavior and power consumption metering. Distribution management system (DMS) is required for analyzing, control and provide enough useful information to the utility. The SG is also composed of legacy remote terminal units (RTUs) that can perform sensor network gateway functions acting as intermediate points in the medium voltage network. The sensor network gateway is the bridge between the sensor network and the back-end system. Therefore, it provides necessary interfaces to other sensor nodes as well as interfaces to existing ICT infrastructures.

Advanced metering infrastructure (AMI) consists of smart meters, data management, communication network and applications. Along with distributed energy resource (DER) and advanced distributed automation (ADA), AMI is one of the three main anchors of SG. Usually, (GIS) as well as consumer information system (CIS) contribute with tools and important processes. The information recollected...
and processed by DMS must be reported to a supervisory control and data acquisition system (SCADA).

Heterogeneous networks manage and collect information from established IEDs for control and automation purposes in real-time. Thus, SG needs to communicate many different types of devices, with different needs for QoS over different physical media. The IEDs involved in these processes can be situated in different locations due to the decentralized architecture. As an example, electrical substation elements are connected to the substation’s Ethernet network. As for sensors, they can be installed along electrical cables communicated through wireless sensor standards (e.g., IEEE 802.11s). Communications from the control center to energy meters and between substations can be carried out over a high variety of technologies such as PLC, Universal Mobile Telecommunications System (UMTS), general packet radio service (GPRS) or WiMAX. Standardized, open information models and communication services for all data exchanges are needed in the SG. Thus, SG will be supported by a highly heterogeneous data network.

PLC technology uses the power grid for transmitting data. However, the characteristics of the PLC medium make it especially difficult to ensure a given QoS. This technology has to overcome some problems like: unpredictable frequency and time dependence of impedance, attenuation and transmission characteristics, impulse and background noise and their wide variability, limited bandwidth, and harmonic interference. For example, the variability of the channel is especially troublesome for QoS because it can suddenly bring the bandwidth down.

Besides PLC protocol, several access technologies can be integrated into the resulting SG architecture. Some options for integration are IEEE standards for mesh personal area networks (WPANs), wireless local area networks (WLANs), wireless metropolitan area networks (WMANs) and wireless regional area networks (WRANs).

Traditional wireless systems use point-to-point or point-to-multipoint technologies. Mesh networks are an alternative to these topologies. There are some reasons for it. For example, it is easy to associate new nodes in the network thanks to the fact of self-configuration and self-organization capabilities. Secondly, a mesh network is a robust system as there will almost always be an alternative path to the destination. Taking into account the large scenario in which the SG is going to be deployed, different technologies will be needed in order to cover all the area. Some WPAN standards are presented as wireless communication candidate technologies that work within mesh networks.

IEEE 802.15.4 defines the medium access control (MAC) and physical (PHY) layers in low-rate personal area networks (LR-PANs) [9]. In 2008, the Smart Utility Networks (SUN) Task Group 4g (TG4g) was created within the 802.15 group. The role of TG4g is to define new PHY layers to provide a global standard that facilitates very large scale process control applications such as the utility SG. IEEE 802.15.5 is the WPAN mesh standard approved in March 2009. This working group was established in order to define mesh architecture in IEEE 802.15.4 based WPAN. There exist different proposals regarding routing in LR-WPAN networks. Nevertheless, these algorithms are not fully optimal.

A draft from IEEE 802.11 working group for mesh networks that defines how wireless devices can be connected to create ad hoc networks. The implementation should be over the physical layer in the IEEE 802.11g/n. A combination of IEEE 802.11n and IEEE 802.11s could be also a feasible solution for ubiquitous sensor networks.

IEEE 802.16 is a standard technology for wireless wideband access. Among its advantages, the ease of installation is by far the most important aspect. This technology supports either point-to-multipoint or mesh topologies. In mesh topologies, it is not necessary that all the nodes are connected to the central node. In this way, active nodes periodically announce mesh network configuration messages, which contain information about the base station identifier and channel in use.

IEEE 802.22 uses the existing gaps in the TV frequency spectrum between 54 and 862 MHz [10]. The development of this standard is based on the use of cognitive radio techniques in order to give broadband access in sparsely populated areas that cannot be economically served by wireline means, or other wireless solutions at higher frequencies.

### 6 Smart Grid Demand Response

One of the approaches being used to reduce the peak demand and improve the system reliability is demand response (DR), in which the end users modify their electricity consumption patterns in response to price variations. DR has been used in commercial and industrial sectors for some time to increase the health and stability of the grid. With the emerging SG, DR now has the potential to be expanded into residential electricity markets on a large scale. The SG adds intelligence and
bidirectional communication capabilities to today’s power grid, enabling utilities to provide real-time pricing (RTP) information to their customers and collect the real-time usage from their customers. [11]

SG consists of sensing, communication, control and actuation systems which enable pervasive monitoring and control of the power grid. These features enable utilities to accurately predict, monitor and control the electricity flows throughout the grid.

Various wireless schemes (e.g. GPRS, IEEE 802.11) have been used to enable meters to automatically transmit data back to the utility. Automatic meter reading (AMR) is unidirectional, without capability for the utility to send data to the meter, thereby limiting its usefulness. This deficiency led to the development of advanced metering infrastructure (AMI), which provides bidirectional communication between the utility and meters installed in residences.

HANs comprise smart appliances which can communicate with one another or an home energy controller (HEC) to enable residents to automatically monitor and control home energy usage. The widespread availability of low-cost wireless technologies has accelerated the deployment of HANs by facilitating the addition of communication capabilities to household appliances. In fact, smart appliances are home appliances that combine embedded computing, sensing, and communication capabilities to enable intelligent decision making. Sensing capabilities enable these devices to measure their usage, communication capabilities enable the reporting of their energy consumption to the HEC, while their actuation abilities enable them to respond to commands from the HEC.

Block scheme of system interconnecting HAN and AMI is shown in Fig. 4. Here, a DR architecture is centered on a HEC. RTP and DR signals are sent to the smart meter over the electric utilities NAN, with the neighborhood transformer serving as the aggregation point for all the smart meters in that region.

Smart devices report their current operating status to the HEC, while the operating modes of dumb appliances can be inferred using power measurements transmitted by attached smart plugs. This data enables the HEC to determine when loads are in standby mode and switch them off. The location of the scheduling intelligence in the HEC enables complex scheduling to be applied in each load individually. Authentication is a critical security service in SG networks, and it mainly involves the smart meters in different component networks of the SG.

![Fig. 4. Home area network and advanced metering infrastructure interconnection](image)

7 Discussion and Conclusions

According to the definition of Strategic Deployment Document of the European Smart Grids Technology Platform, a SG is an electricity network that can intelligently integrate the actions of all users connected to it in order to efficiently deliver sustainable, economic, and secure electricity supplies.

In different segments of a power grid, different communication technologies are applied to meet the unique specific requirements. In a power transmission segment, wired communications over power lines or optical cables are adopted to ensure robustness of the backbone. However, in power distribution segment that provide power directly to the end users, both wired and wireless communications should be considered.

In order to achieve cost-effective and flexible control and monitoring of end devices, efficient dispatching of power, and dynamic integration of distributed energy resources with power grid, wireless communications and networking functionalities must be embedded into various electric equipment. Capability of wireless networking among various electric equipment is one of the key technologies that drive the evaluation of a conventional power distribution network into a SG.

The development of the SG will mean a drastic change in power use and administration. Users will become active participants in energy management and will be able to control their consumption. On the other hand, utilities will be able to control demand peaks and manage the grid efficiently from generation to distribution.

Different types of wireless networks are available, but which one is the suitable for a SG,
depends on the system architecture and varieties of communication modules and links. The multihop wireless networking is definitely necessary, as electric equipment out of range of each other need to exchange information. First of all, in order to simplify network organization and maintenance the entire environment needs to be self-organized. Moreover, communications modules may pertain heterogeneous nature in terms of coverage, computing power and power efficiency. Wireless mesh networks (WMNs) are considered as important networking for SG. However, when WMNs are applied in SG wireless infrastructure, a few challenging issues still remains (e.g. security level). Without effective measures to prevent security attacks, the primary of users and confidentiality of grid information cannot be guaranteed.

Wired communication technologies are not full suitable for SG communications. Optical networks are reliable, but deploying fibers to connect all end devices is too expensive. PLCs are constrained by some shortcomings: (a) they are not flexible for peer-to-peer communications among electric devices, (b) throughput may not be sufficient for frequent data exchange, and (c) high speed signals cannot pass through transformers.

In an SG, various electric devices need to have P2P communications, so mesh networking capability is a viable option. However, a WLAN can only support one-hop point-to-multipoint communications. Thus, WLAN is not enough for an smart distribution grid. The better solution is to build WMNs based on WLAN technologies. Next issue is that SG communications architecture needs to support different types of wireless applications. In this scenario, technologies based on IEEE 802.11 with high-gain antenna may be necessary. As a result, SG communications networks must be capable of integrating heterogeneous wireless networks. As for PLCs, they will be utilized as much as possible, particular to enhance reliability and security. WMNs can easily integrate heterogeneous networks to fulfill different functions such as sensing, monitoring, data collection, control and pricing.

References: