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Review

Communication technologies for smart grid applications: A survey

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ABSTRACT

Modernization of the conventional power system is being driven by increased load, aging infrastructure and proposed legislation to increase taxation of greenhouse gas emissions. The evolving intelligent energy value chain known as the smart grid is an intricate system, which requires deliberate collaboration from various stakeholders. The smart grid is not a monolithic system but rather a collection of enabling technologies and applications with different Quality of Service (QoS) requirements. It is pivotal to any nation's economic advancement, global relevance and overall quality of life. In this article, a review of integral components of the emerging grid and communication infrastructures enabling the six smart grid applications is presented. In addition, this paper summarizes their communication and networking requirements such as payload (size and frequency), physical (PHY) and media access control (MAC) layer latency based on IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks. Also, this article highlights the need for convergence into a common protocol platform to achieve interoperability of legacy and evolving communication protocols. Additionally, challenges of communication infrastructures deployed within the “unfriendly” power system environment and critical skill gaps that exist between the power and communication domains, which may create a 'silo unit' while integrating communication technologies into the legacy power system are presented.

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1. Introduction

The need to add intelligence to the conventional power system in order to operate as a cognitive, adaptive, self-monitoring and self-healing system has become imminent (Budka et al., 2014; Hossain et al., 2012; Ho et al., 2014; Momoh, 2012). Integration and interoperability of the conventional electricity grid with communication technologies present critical constraints for the evolving smart grid (Yu and Ansari, 2016; Zin et al., 2014). The reformation of the power grid system is likely referred to as the "Third Industrial Revolution" for energy (Lo and Ansari, 2012). The legacy power system typically operates in centralized manner with a radial topology, in which a group of consumers are fed from a single power source (Kersting, 2012). This topology has a very low reliability because any power failure or trip along the path will interrupt power delivery across the network (Ho et al., 2014). Consequently, many utilities have resorted to a loop or hybrid network topology to provide alternate paths in the event of a fault (Budka et al., 2014). However, in reference to reports from U.S. Environmental Protection Agency (EPA) and Energy Information Administration (EIA), there is an unavoidable phenomena of rising temperature and swelling greenhouse gas emissions such as carbon dioxide, methane, and nitrous oxide (Friedman, 2008; EIA; EPA). It has been estimated that as much as 40% of global carbon dioxide emissions may come from power generation (The Smart Grid, 2008). Other prevailing factors such as increasing global appetite for energy, frequent power outages, security issues, global demand to build an expansive structure, electricity theft, current evolution in information and communication technologies, serve as drivers for the modernization of the power grid (Budka et al., 2014). In addition, recent blackouts (such as 2003 Northeast and 2012 Northern India blackouts) place an enormous amount of pressure on utilities to add intelligence to the conventional grid in order to have a more resilient, responsive and robust grid (U.S DOE, 2014). The smart grid is such a broad term and concept that is difficult to capture with one singular definition. The extant literature has attempted to give a concise definition to the smart grid. The United States Energy Independence and Security Act of 2007 (EISA07) provides ten characteristics that describe the evolving smart grid (United States Government, 2007). They include:

- Increased deployment of digital control and information technology to enhance grid's reliability, security and efficiency.
- Smart appliances and customer devices integration.
- Grid operations and resources optimization, with full cyber-security.
- Distributed Energy Resources (DERs) integration.
- Development and inclusion of demand response, demand-side resources and energy-efficiency resources.
- Smart technologies deployment for metering operations, grid operation and low voltage system automation.
- Integration of advanced storage system and peak-shaving technologies.
- Provision of timely information and control options to customers.
- Standards development to enable seamless communication and interoperability of equipments connected to the grid.
- Lowering unnecessary barriers to adoption of smart grid technologies, practices and services.

Also, IEEE Std 2030 defines the smart grid as the integration of power, communications, and information technologies to modernize and enhance the performance of the electric power infrastructure serving loads while supporting evolving end-use applications (IEEE Guide for Smart, 2011). In addition, it is more than a power connection system from generation to consumer, but gradually evolving into an interconnected, diverse, intricate and self-healing system (IEEE Guide for Smart, 2011). The National Institute of Standards and Technology (NIST), described the anticipated benefits and requirements of the smart grid, which are (National Institute of Standards, 2010):

- Improving the energy network reliability and quality.
- Optimizing utility asset utilization.
- Increasing consumer choice and participation.
- Presenting opportunities to improve grid security and resilience to disruption.
- Reducing greenhouse gas emissions by enabling electric vehicles and new power sources.

Furthermore, there are four cardinal landmarks which provide a guide to the realization of the smart grid (NETL Modern Grid Strategy Powering, 2008). They include:

- Advanced Metering Infrastructure (AMI) - provides customer motivation and participation.
- Advanced Asset Management (AAM) - supports asset optimization for improved efficiency.
- Advanced Distribution Operation (ADO) - for adaptive and self-healing power network.
- Advanced Transmission Operation (ATO) - to clear network congestions.

More so, just like the internet evolution, modernizing this energy value chain is one of the most outstanding technological milestones and opportunities of the 21st century. The smart grid communication system will emerge from a large number of small-scale networks which are interconnected and organized into hierarchical architecture spanning larger geographic areas (Ancillotti et al., 2013).

Analogies between the smart grid and internet networks are presented in Ho et al. (2014), IEEE Guide for Smart (2011), Ancillotti et al. (2013), Keshav and Rosenberg (2011), which are summarized in Table 1:

1.1. Motivation

This article complements and extends other surveys carried out by various authors. Ramírez and Umaña (2015) presented

Table 1
Analogy between the internet and evolving smart grid.

Network characteristic	Internet Network	Smart grid network
Content	Data (IP packet)	Data and power
Network type	Heterogeneous and complex	Heterogeneous and complex
System architecture	Hierarchical, distributed and decentralized	Hierarchical, distributed and decentralized
Transmission flow type	bidirectional flow of data	bidirectional flow of data and power
Protocol	e.g., TCP/IP, HTTP, SMTP.	e.g., Modbus, DNP3, IP, DNP3overTCP/IP.
Vulnerability/security risk	Cyber and physical	Cyber and physical
QoS requirements	Transparency and accessibility	Priority, critical and Latency
Network philosophy	Ubiquitous, adaptive and self-healing	Ubiquitous, adaptive and self-healing
Description	Network of networks	Network of networks
Services range	Multi-service	Single service
Storage cost	Low	High
Resource management	Distributed	Distributed
Scalability	Rapid and cheaper	Slow and expensive
Standards	RFCs by IETF	e.g., IEC/ANSI/IEEE

communication technologies and routing protocols deployed in a neighbourhood area network for AMI. Fang et al. (2012) divided the entire smart grid into: the smart infrastructure system, smart management system and smart protection system, with their respective challenges. Also, Lo and Ansari (2012) provided an overview of the essentials of the progressive smart grid paradigm and integration of different communications technologies for the legacy power system. Moreover, Erol-Kantarci and Mouftah (2015) reviewed the smart grid driven approaches in energy-efficient communications and data centers, with its capacity to reduce traditional electricity costs, large amount of greenhouse gas emissions and operational cost. Ye Yan et al. (2013) presented a background and motivation for communication infrastructures in smart grid such as enhanced customer experience, integration of DER, reliability, efficiency and sustainable operations to both utilities and customers. Additionally, Meng et al. (2014) addressed the design requirements (e.g., reliability, scalability and throughput), standards, network topology, gateway deployment, routing algorithms, and security for smart grid neighbourhood area network (NAN). Other related surveys were presented in Hassan and Radman (2010), Brown and Suryanarayanan (2009), Akyol et al., 2010; Yan et al. (2012), Verma et al. (2016). Brown and Suryanarayanan (2009) provided an industrial definition and technical requirement of a smart distribution system. Akyol et al. (2010) surveyed wireless communications for electric power system applications such as feeder reconfiguration and management of customer load for DR programs. Hassan and Radman (2010) briefly discussed the smart grid technologies, goals, features, benefits and challenges. Abdrabou (2014) proposed a communication network architecture for the active management of the future low-voltage distribution networks in the smart grid. Farhangi and Road (2014) discuss the importance of analysis of interface protocol and communication requirements in the layered approach for successful integration in the emerging energy chain. Yan et al. (2012) surveyed cyber security for smart grid communication networks and highlighted the need for scalable security solutions. Moreover, while these surveys and related literature have presented overviews of communication infrastructures with their motivations and challenges in smart grid, none has considered the enabling technologies for all the six smart grid applications. However, the contributions of this survey are as follows:

- A description of smart grid integral components.
- A comprehensive survey of the enabling technologies for all the six smart grid applications.
- Also, a summary of their networking requirements, considering metrics such as payload (size and frequency) and latency introduced by the PHY and MAC layers for each of the application according to IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks, is presented.
- This article highlights the need for convergence into a common protocol platform to achieve interoperability of legacy and evolving communication protocols.
- In addition, challenges of communication infrastructures deployed within the “unfriendly” power system environment and critical skill gaps that exist between the power and communication domains, which may create a 'silo unit' while integrating communication technologies into the legacy power system are described.

The rest of this survey is structured as follows: Section 2 describes the evolution of the conventional power system. Sections 3 and 4 present smart grid integral components, and smart grid applications' communication requirements respectively. Standardization of technologies for smart grid applications in Section 5. The need for convergence, challenges of communication infrastructures in power system environment, future research and closing the skill gap are discussed in Sections 6, 7, 8 and 9 respectively. This review ends with a conclusion in Section 10.

2. Power system evolution

The traditional power system is segmented into three segments with centralized operational domain. Bulk power is generated (at 30–33 kV)[1] from the generating station where it is stepped up by transformers to be transmitted at high voltages (330 kV) to cater for losses via transmission lines (Kersting, 2012). The high voltage is stepped down by transformers at substations (330/132/33 kV) and distribution stations (33/11/0.415/0.22 kV), which is then delivered to various consumers (e.g., industries, households) through feeder lines (Kersting, 2012; McDonald, 2012). In order to handle faults, short circuits and reduce outages, utilities deploy circuit breakers, relays, phasor monitoring unit (PMU), capacitor banks, switches, reclosers for the control of the power system (Kersting, 2012). Furthermore, the conventional power system monitors and controls the high (330/132 kV) and medium voltage (132/33 kV) parts of the system using supervisory control and data acquisition (SCADA) system as shown in Fig. 1 (Budka et al., 2014).

The remote terminal unit (RTU) aggregates alarms, measurements from sensors, relays and other low power devices and sends them to the SCADA master over a serial line communication (Kersting, 2012; McDonald, 2012; Ferreira et al., 2010). Proprietary

[1] range varies across countries

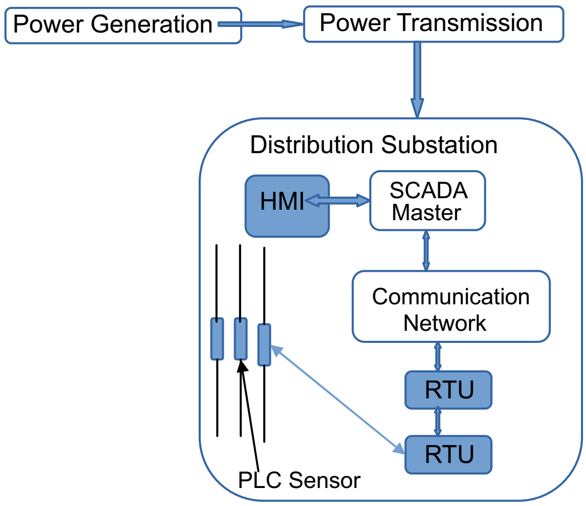

Fig. 1. Typical traditional SCADA system.

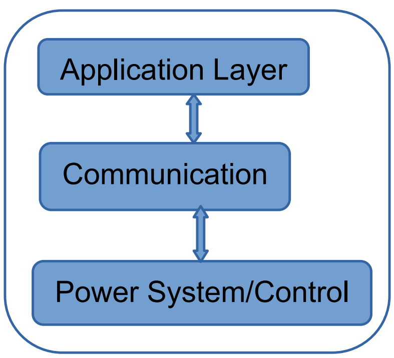

Fig. 2. Smart grid conceptual model.

protocols used are MODBUS, Landis, Harris m900 and the more recent distributed network protocol (DNP3) (Budka et al., 2014). The human-machine-interface (HMI) provides local access for engineers to perform manual control and device reconfiguration at the substation (Budka et al., 2014). However, the low-voltage feeder subsystem connecting the consumers does not come under the coverage of the SCADA system. This predisposes the distribution and the entire grid to elongated outages, blackouts, asset under-utilization, electricity theft, little or no customer participation (Ho et al., 2014). Consequently, these prevailing issues and many others drivers call for a paradigm shift in the operation of the grid. Conceptually, the evolving smart grid can be viewed as a three-layer structure in Fig. 2. The power system layer is overlaid with communication system and application layers. The interaction and integration of these layers are further elaborated in this survey.

3. Smart grid integral components

This section briefly describes smart grid integral devices.

3.1. Smart meter

The smart meter, an essential part of the customer premises network (CPN), is a resource-constrained embedded device used to measure and record energy usage, and reports alarms to the utility for billing and grid management (Ho et al., 2014). Apart from enabling remote operations such as connecting and disconnection of service, smart meters measure power flow from the DER, microgrids or storage systems (i.e. enabling bi-directional flow) (National Institute of Standards, 2010). Depuru et al. (2011) discussed the smart meter system which includes a smart meter, communication infrastructure, and control devices. The authors identified high cost of deployment and lack of proper infrastructure for synchronizing the new technology with the existing ones as major challenges. The ANSI C12.22 for smart metering with its related standards is considered as a local area network (LAN) standard for enabling point-to-point wireless connections between smart meters in North America (Farhangi, 2010). The smart meter comprises the energy meter (EM) and energy services interface (ESI). The EM measures and records the energy usage while the ESI serves as a data management gateway through which the utility interact with the customer's network (National Institute of Standards, 2010). The ESI is also used for AMI connectivity, DR signalling and transfer of energy usage to HEMS (National Institute of Standards, 2010; UCAIug Home Area Network, 2010; Emmanuel et al., 2016). In addition, the ESI is network-centric and acts as a logical gateway between the EM and loads (IEEE Guide for Smart, 2011). Latency between the EM and ESI should be very low since it provides raw data (IEEE Guide for Smart, 2011). Also, smart meters can be used as repeaters or 'hop sites' and gateways to the aggregator or concentrator unit for others because of distance or interference constraint (Hartmann et al., 2014). Furthermore, the utility company have a remote access to the smart meter via the ESI over a wireless connection for demand response (DR) signalling, AMI application, peak shaving, service disconnection and restoration (IEEE Guide for Smart, 2011). Multiple smart meters could be connected to the aggregator through technologies such as IEEE 802.11, IEEE 802.15.4g, PLC, world-wide interoperability for microwave access (WiMAX), cellular networks (2G, 3G, long-term evolution (LTE)) (IEEE Guide for Smart, 2011).

3.2. Data aggregator unit

The Data Aggregator Unit (DAU) coalesces data from various smart meters distributed in the CPN and forwards it to the service provider for billing and grid management (IEEE Guide for Smart, 2011). Control messages from the utility WAN, AMI application and DR signalling also go through the DAU as a gateway to the CPN. DAUs are part of the neighbourhood area network (NAN), with the ability to route, prioritize and manage traffic (IEEE Guide for Smart, 2011). In addition, they have the capacity to divide the topology into distinct groups with respect to the deployed technologies such as PLC and RF (Farhangi, 2010). Additionally, the aggregator can act as a cell relay or gateway with multi-interface capability. For example, a 3G, WiMAX or Fiber optic interface towards the utility and RF mesh, PLC or BPL facing the last mile network (IEEE Guide for Smart, 2011). Hartmann et al. (2014) described a practical deployment where a range of 50–150 smart meters were connected to a DAU. The connection between the DAUs and utility requires a large bandwidth technology such as fiber-optics and WiMAX (IEEE Guide for Smart, 2011).

3.3. Mobile workforce unit

The mobile workforce represents a team of field engineers that are responsible for maintenance and fault resolution and also, generates a significant amount of traffic especially during a fault situation (IEEE Guide for Smart, 2011). The workforce mobile networks can access the EM/ESI directly or through the CPN to retrieve data log in order to resolve a fault and perform preventive maintenance tasks (IEEE Guide for Smart, 2011). The WAN network can provide corporate support applications to the workforce as represented in Table 2 (Gobena et al., 2014).

Table 2
Corporate support applications provided by utility WAN.

Support application	Latency	Bandwidth
Telepresence	250 ms	10–150 Mbps
IP telephony	150 ms	1–5 Mbps
IP radio	200 ms	250 kbps
Wireless mobile device	1 s	Variable

3.4. Intelligent electronic device (IED)

The traditional SCADA system was built around legacy devices such as RTU, current and voltage transformers (collectively referred to as instrument transformers) for measuring substation current and voltage respectively (Budka et al., 2014). However, with the advent of smart grid evolution, there is a proliferation of microprocessor based IEDs for both transmission and distribution SCADA systems (Ho et al., 2014; National Institute of Standards and Technology, 2012). An IED can provide multiple support functions previously delivered by a group of devices (e.g., RTU and current transformer) thereby reducing the complexity of device topology in the substation (Budka et al., 2014). Another driver for the proliferation of IEDs such as the phase monitoring units (PMUs) is the integration of DER, energy storage devices and microgrids at the customers' premises (Sanchez-Ayala et al., 2013). These devices are used for islanding, monitoring and control operations (Budka et al., 2014). In addition, in order to support smart distribution domain operation, there will be a high level deployment of IEDs outside the substation (Gellings et al., 2004). According to IEEE Std 1815-2012, an IED is placed closed to sensors or actuators to be monitored. In present power systems, the IEDs communicate using the DNP3 protocol in SCADA systems (Curtis, 2005). However, utilities around the globe are beginning to deploy IEDs using IEC 61850 standard (Yiqing, 2011).

4. Smart grid applications and their communication infrastructures overview

4.1. Advanced Metering Infrastructure (AMI)

The AMI refers to inter-related systems which allow service providers to collect, measure, and analyze energy usage data from advanced devices (such as electricity and gas meters) through an heterogeneous communication network on request (on demand) or on a pre-defined schedule for outage management, billing and power grid management (UCAIug Home Area Network, 2010; Department of Energy Communications Requirement of Smart Grid Technologies, 2010). It extends over the three hierarchical tiers (wide area network (WAN), neighbourhood area network (NAN) and home area network (HAN)) of the smart grid which enables two-way communication of power and information in support of microgrid integration and customer involvement (U.S. Department of Energy, 2011). The HAN consists of the smart meter interconnecting various home appliances, sensors, in-home display, gas meter, water meter, photovoltaic panel, EV and home energy management system (HEMS-manages energy consumption, storage and generation devices for the household) (Budka et al., 2014; Hossain et al., 2012). The NAN collects all the energy usage data from various HANs to the Utility backbone via its gateways. It is deployed within the distribution system for pricing messages, monitoring and controlling power delivery to the various consumers and determines the grid's efficiency (Budka et al., 2014; Meng et al., 2014). The WAN provides the backbone/core communication for all types of distributed area networks that exist at different segments of the grid. Table 3 summarizes the tiers with their respective coverages, data rates and possible technologies (Budka et al., 2014; Hossain et al., 2012; Saputro et al., 2012).

Furthermore, the AMI comprises communication networks from meters to local data aggregators, back-haul networks to utility data centers, meter data management system (MDMS) and then, integration of data into existing and new software application platforms (NETL Modern Grid Strategy Powering, 2008). It is different from the predecessor technology known as automatic meter reading (AMR), which uses a one-way communications for monthly meter reading and billing purposes (Department of Energy Communications Requirement of Smart Grid Technologies, 2010). Lo and Ansari (2012) presented it as a combination of distribution automation, distributed generation, NAN, smart meters, smart appliances, plug-in hybrid electric vehicle and data concentrators. The heterogeneous characteristics that exist among the various components of AMI make interoperability a major issue, with the absence of open standards (Mauri et al., 2009). Consequently, to have a successful integration and scalable AMI architecture, power system and communication technologies interoperability must be taken into full consideration during the design stage.

The AMI communications technologies provide connection between the utility, customer and the controllable electrical load, which must employ open bi-directional communication standards (NETL Modern Grid Strategy Powering, 2008). Various communication technologies are deployed in the AMI architecture, which could be wireline or wireless media depending on bandwidth requirements, reliability, cost implication and ease of installation (IEEE Guide for Smart, 2011). Wireline media include: PLC, BPL, optic fiber while internet, RF radio mesh (IEEE 802.15.4/4g), Cellular, WiMAX constitute the wireless media (IEEE Guide for Smart, 2011).

The AMI system architecture in Fig. 3 shows how information flows bi-directionally from the customer premises network (CPN) to the utility backbone office, where data collected via the various tiers of the networks are analyzed by various applications (IEEE Guide for Smart, 2011). The headend is typically an aggregation server for collecting all the data from the smart meters in the NAN and then feeds the enterprise bus, which serves the back office applications as shown in Fig. 3 (IEEE Guide for Smart, 2011). The applications include meter data management system (MDMS), asset management system (AMS), distribution management system (DMS), outage management system (OMS), customer information system (CIS) and demand response management system (DRM).

Gobena et al. (2014) presented AMI services and their communication requirements as shown below in Table 4.

Table 3
Three tiers of smart grid architecture.

Network Type	Coverage	Data rate	Standard
Home Area Network (HAN)	1–10 m	1–10 kbps	IEEE 802.15.4/802.11 & proprietary protocols—Z-wave, PLC
Neighbourhood Area Network (NAN)	10 m–10 km	10–1000 kbps	Wireless—IEEE802.11 s, RF Mesh, WiMax, cellular stds (3G, 4G, LTE) Wired—Ethernet, PLC, DOCIS
Wide Area Network (WAN)	10–100 km	10–100 Mbps	Wireless—RF Mesh, WiMax, cellular stds (3G, 4G, LTE) Wired—DSL, PON

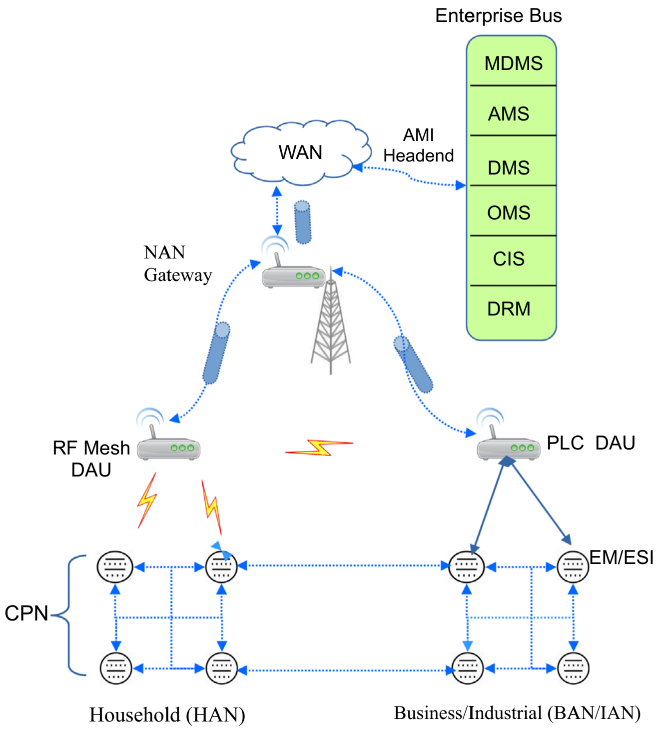

Fig. 3. AMI system architecture.

Table 4
Types of traffic in an AMI network.

AMI Service	Bandwidth	Latency
Meter Reads	10 kbps/meter (depends on size and frequency of reads)	Variable
Connects and Disconnect	500 kbps	5 s

Zhou et al. (2012) introduced a new performance metric referred to as accumulated bandwidth distance product (ABDP) to determine the aggregate communication resource usage for distributed AMI communication architectures. The proposed metric helps to solve the inherent scalability problem in the traditional AMI centralized architecture by minimizing the total cost of the system considering both the ABDP and the deployment cost of the MDMS. The conventional centralized architecture cost scales linear as $O(\lambda N)$, while the reduced distributed architecture cost is $O(\lambda^{\frac{2}{3}}N^{\frac{2}{3}})$, with λ and N representing smart meter average traffic rate and number of smart meters respectively. However, Zhou et al identified the integration of communication cost scalability and processing capacity as a possible extension to the study. Kulkarni et al. (2012) demonstrated the application of a wireless mesh network for AMI application, based on extensions proposed to the routing protocol for low-power and lossy networks (RPL) protocol using self-organizing algorithms. The self-organizing solution reduces the complexity of network management and related overheads. However, a major challenge in such a network is the deployment of aggregators especially within the radio range of other aggregators. Aggregators with global positioning systems, radio resource management and frequency resource planning are possible solutions (Kulkarni et al., 2012). Li et al. (2012) proposed a wireless communications scheme to enhance efficiency of spectrum by transmitting only when a major energy consumption change occurs and also proposed an artificial spoofing packets as a defence mechanism. Apart from the apparent benefits of wireless communication such as inexpensive units and rapid deployment, Li et al. (2012) considered the basic characteristic of the information source (i.e., the smart meter data) in order to utilize the available spectrum efficiently. Dynamics of power usage profiles across different users are expected to be considered in a future work.

Khalifa et al. (2014) presented a performance analysis of the Split and Aggregated TCP (SA-TCP) by varying parameters such as propagation delay between smart meters and utility server, network link capacity, buffering capacity of regional concentrators (RCs) and the number of RCs deployed as SA-TCP concentrators. The proposed SA-TCP showed the possibility of tuning the throughput of the AMI network to the desired value while maintaining a minimum deployment cost. It provides a solution to the performance degradation produced by the TCP congestion control. However, Khalifa et al. indicated the need to evaluate the effect of clustering smart meters in different ways while considering network characteristics. Li et al. (2013) presented an integrated solution of distribution management system and AMI network with different communication protocols and data models. As a middleware solution, it minimizes the effort of interconnecting distribution management system (DMS) applications to different AMI systems, and also, with the capability of handling the huge amount of smart meter data in terms of scalability, flexibility and performance. In addition, AMI communication technologies such as fiber-optics, hard-wired links, wireless, satellite and microwave must have sufficient bandwidth (2–5 Mbits/s), security proven and able to support current and future technologies (Sood et al., 2009).

Faisal et al. (2015) analyzed the possibility of deploying data stream mining to improve AMI security via intrusion detection system (IDS) as a secondary security measure after applying encryption, authentication and authorization. From the performance analysis carried out using existing seven state-of-the-art data streaming algorithms, Faisal et al. showed that algorithms which require less computing resources with moderate accuracy level are potential options for the smart meter IDS. On the other hand, the ones with a higher demand on computing resources and with the capacity to provide higher accuracy can be used for data aggregators and AMI headend IDSs. Yan et al. (2013) also proposed integrated authentication and confidentiality (IAC) protocol to enhance AMI network security. The IAC protocol uses mutual authentication to provide data privacy, integrity and trust services. Liu et al. (2013) proposed a key management system (KMS) based on key graph to handle hybrid transmission modes of messages, storage and smart meters with varying demand response participants. Wan et al. (2014) enhanced the work of Liu et al. (2013) by proposing a new scalable key management (SKM) which combines identity-based crypto system and efficient key tree technique. The proposed scheme has advantages of efficiency and flexibility in key management. The cost of the proposed SKM is $O(\log n)$ which is lower than $O(n)$ in the key management scheme of Liu et al. Rahman et al. (2013) presented a security analysis tool known as smart analyzer which models AMI configuration, device topology, communication features, data flows and security properties.

4.2. Demand response (DR)

This is also referred to as Demand-side management (DSM), which operates within the CPN and interact with the service providers, markets and operational regions. It is known as a grid management tool (Department of Energy Communications Requirement of Smart Grid Technologies, 2010). DR programs are designed to alter the energy consumption pattern of the customers in response to price or other forms of incentives in order to defer expansion of utility capacity (Momoh, 2012). Service providers use DR to balance energy delivered to loads over the network especially during peak periods (i.e. peak shaving) (Department of

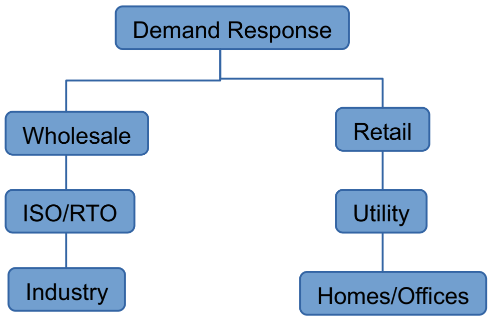

Fig. 4. Demand response types and domain.

Energy Communications Requirement Of Smart Grid Technologies, 2010). Deng et al. (2015) classified DR program into:

- Incentive-based program such as direct load control (DLC), curtailable load, demand bidding and buyback, and emergency demand reduction.
- Price based program are time-of-use (TOU), critical peak pricing (CPP), real-time pricing (RTP), and inclining block rate (IBR).

In addition DR subdivisions are shown in Fig. 4 (Department of Energy Communications Requirement of Smart Grid Technologies, 2010):

Fig. 4 shows two types of DR, wholesale and retail. The former is provided for customers (such as large industrial facilities) with a transmission-level connection to the power system via independent system operators (ISO) or Regional Transmission Organization (RTO) (IEEE Guide for Smart Grid, 2011). The latter is provided by service providers either in form of direct load control, automated DR (where CPN devices respond to the dynamic conditions on the grid), offload to microgids or local adjustment of electricity usage in response to dynamic pricing (IEEE Guide for Smart Grid, 2011). The installation of smart meters provides a two-way communication between the service provider and customer, which enables the utility to shape customers' load profile in an automated and comfortable manner (Benefits of Demand, 2006; J. M. Guerrero et al., 2013; J. Guerrero et al. 2013; Berger and Iniewski, 2012). However, reliable and efficient communication technologies are pivotal for real-time DR programs. Communication technologies for DR programs are IEEE 802.15.4, IEEE 802.11 or power-line communication (PLC) which connects users' appliances to smart meters deployed within the home, building and industrial area networks (Deng et al., 2015). Roy et al. (2014) analyzed the use of long-term evolution (LTE) multicast between the aggregator and customers' premises which provides low latency and packet drop for DR. Ebeid et al. (2015) used Smart Energy Profile 2.0 (SEP2) communication protocol to validate proposed DR protocols for smart grid. The use of internet protocols or Inter-Control Center Communication Protocol (ICCP) within the service providers' domain for data transfer to external entities that manage the data is proposed in IEC (2004). Within the WAN, protocols such as DNP3 (Curtis, 2005), IEC 61968 (IEC, 2003) and IEC 61850 (IEC 61850, 2003) could be used to transmit DR signals.

Schachinger et al. (2015) presented the use of organization for the advancement of structured information standards (OASIS) energy interoperation standard as agent communication language for data exchange (dynamic price signals and generation information) among stakeholders involved in smart grid evolution. Zheng et al. (2011) investigated the impact of packet loss during DR signalling. Also, Zheng et al. (2013) investigated the impact of communication degradation on a direct DR control program and the distribution of packet delivery ratio in a single-hop and multi-hop mesh network deployed for DR.

To maximize the evolving smart grid communication network infrastructure, DR systems can be mapped on the AMI architecture, which also depends on availability, latency, power consumption, data rate, coverage, security, interoperability and bandwidth requirements (Mohagheghi, 2012). The distribution operation to control and monitor loads is implemented via the NAN either through the smart meter or a non-smart meter black box (IEEE Guide for Smart Grid, 2011). However, for a CPN device to participate in DR programs, it must undergo commissioning, registration and enrollment on the ESI. Commissioning permits devices to exchange information (such as identity and device type), registration creates a reliable handshake between the CPN device and ESI while enrollment enlist the device for a particular DR program provided by the service provider (UCAIug Home Area Network, 2010).

4.3. Electric transportation

An electric vehicle (EV) is a vehicle that has the capacity to store electric power through its rechargeable battery pack from the grid which is used to propel one or more electric motors of the vehicle (IEEE Guide for Smart Grid, 2011). EVs can be considered as a unique HAN device (with load characteristics) and are typical examples of distributed storage systems which supply power to the grid via their charged batteries when parked at the customer's premises (UCAIug Home Area Network, 2010). EV also known as plugged-in EV and can make use of fossil fuels in an hybrid fashion. With the forthcoming carbon taxes on greenhouse gas emissions and demand for clean energy, the deployment and integration of EVs has become a major consideration in the characterization of smart grid by the EISA (United States Government, 2007). The deployment of EV interact with the grid in two modes, namely Grid-to-Vehicle (G2V) in which depleted batteries are charged by grid supply and Vehicle-to-Grid (V2G) for supplying power to grid via the batteries, acting as a DER in balancing energy supply (IEEE Guide for Smart Grid, 2011). In this section, an overview of communication technologies for only V2G as a power resource, since G2V is the conventional way of charging EV batteries is presented. The rhetorical question is still "what kind of communication technology should be used for the deployment and integration of EVs?". A reliable and scalable technology is required for a seamless bi-directional information exchange between the EVs and the utility. The choice of technology depends on these major factors: mobility, reliability, latency, bandwidth and security (Hossain et al., 2012).

Additionally, technology choice depends on the type of ancillary services (such as peak shaving and power supply to the grid) offered by the distributed EV. The V2G ancillary services are controlled and managed via direct deterministic and aggregative architectures, with different communication technologies requirements (Quinn et al., 2010). Although the direct deterministic architecture is quite simple conceptually because there is a direct link between the grid operator and vehicle, but it has issues in terms of near-term feasibility and long-term scalability. This is due to the fact that the grid operator has to deal with enormous amount of signalling and control task overhead for the large number of EVs (Quinn et al., 2010). However, considering the indirect V2G system architecture, which involves the use of aggregators or concentrators (connecting the grid with the EV) to coalesce all the ancillary services provided by the EVs into a single controllable distributed power resource. Due to high bandwidth requirement between the concentrator and grid system operator, fiber-optic and broadband technologies should suffice (Hossain et al., 2012).

Furthermore, PLC can be used to handle exchange of information between the aggregator and EVs due to reduction in cost, ease of installation and ease of retrofitting (Ferreira et al., 2010; Farhangi, 2010; Taherinejad et al., 2012). Qiu et al. (2011) and Ghassemi et al. (2010) proposed systems such as the cognitive radio and spectrum sharing for higher bandwidth and reduced latency for V2G and smart grid communications systems. Hochgraf et al. (2010) discussed the use of the GSM network and SMS text messages as options for smart grid communication, and presented a system that provides the control of thousands of mobile PEV chargers using a simple SMS text message interface. Hassan et al. (2011) presented Vehicular ad hoc network (VANET) systems requirements and implementation in a hybrid EV for inter-vehicle communications with IEEE 802.11p. Moreover, PEV public charging comes with a critical communication constraint with respect to remote billing and battery charging outside the jurisdiction of the service provider's area (Department of Energy Communications Requirement of Smart Grid Technologies, 2010). The commercial wireless provider is a viable technology option for the EV application (Alcatel-Lucent, 2010).

4.4. Distributed energy resources and storage

The global quest for a sustainable energy is currently driving the deployment and integration of DERs within the traditional power system. This creates a major concern to Utilities as these energy sources introduce a bidirectional flow of power into the grid contrary to the traditional uni-directional power flow paradigm. DERs comprises renewable and non-renewable energy resources with various possibilities such as electric power generation, conversion, storage and interconnection to the area electric power system (EPS). They consist of photovoltaic arrays, microturbines, wind turbines, fuel cells, traditional diesel and natural gas reciprocating engines, and energy storage (such as batteries) technologies (IEEE Application Guide, 2008).

The DERs with controllable load and power storage devices form a microgrid which is being deployed as alternate sources of power to meet local needs of consumers such as lighting, security and elevators during islanding due to utility blackouts (Budka et al., 2014). Consequently, the distribution system is gradually undergoing a transition from a passive to an active network, which is non-trivial to distribution system planners. The deployment of microgrids has become one of the major highlights of the evolving smart grid (European SmartGrids Technology, 2006). For example, a household with a rooftop PV solar panel can feed back excess energy generated into the macrogrid which establishes the bi-directional flow (Akinyele et al., 2015a, 2015b). For large scale deployment of these autonomous systems (microgrids) with the view of eventual integration into the utility grid, there is a need to put in place proper mechanisms for control, monitoring and synchronization over a reliable and efficient communication infrastructure. With the proliferation of embedded devices such as the intelligent electronic devices (IEDs), utilities can perform these operations to ensure a reliable and robust smart grid (Budka et al., 2014). Also, the evolving smart grid works towards the decentralization of power generation to enable two-way flow of electricity from DERs and power storage devices (Sanchez-Ayala et al., 2013).

Therefore, reliable and efficient communication technologies connecting DERs and distribution system operators (DSO) remain a critical issue as the distribution network transit from passive to active network (The Advanced Microgrid, 2014).

DERs are connected to the grid using IEDs for communication, control, monitoring and islanding (Budka et al., 2014). The emerging intelligent grid is expected to be a "properly-planned-plug-and-play" integration of smart DERs which incorporates communication infrastructure for secure exchange of information and commands (Farhangi, 2010). This intricate scenario will require reliable and scalable communication technologies for their proper integration, with stringent latency requirements between 12 and 20 ms (Gobena et al., 2014; Ho et al., 2013; Sood et al., 2009). Jaloudio et al. (2011) proposed the standard legacy SCADA protocols IEC 60870-5-104 and IEEE P181 as a communication strategy for the control of DERs in smart grids. Padilla et al. (2014) presented DNP3 over Ethernet using field programmable gate array (FPGA) as a communication architecture to integrate DERs to the power system.

The deployment of intelligent electronic devices (IEDs) with communication capability as an emerging distribution automation technology was presented in Das et al. (2015). Laverty et al. (2010) proposed the use of GPRS and existing power line communication (PLC) for connecting photovoltaic (PV) units to a low voltage (LV) data concentrator. A case study with a smart grid demonstration project known as future renewable electric energy delivery and management (FREEDM) systems with PV and storage as part of the power sources was presented by Lu et al. (2013). The widely adopted DNP3 over TCP/IP framework as a network solution was used for the emerging smart grid to support good trade-offs between simplicity, backward compatibility and efficiency (ABB, 2009; IEEE Standard for Electric Power Systems Communications, 1815-2010). Kanabar et al. (2009) presented different communication technologies between IEC 61850 based 69 kV/11 kV distribution substation IED and DER IED. GOOSE messages were studied for transfer trip and anti-islanding operations using wireline (Ethernet) and wireless (IEEE 802.11) communication technologies. Wireline provided a higher throughput and less latency which makes it suitable for a densely populated urban region while for spatially distributed DERs, wireless technology would be a better technology option for economic and technical reasons.

Lu et al. (2011) presented the integration of substation IEC 61850 standard into a (5 kW)PV/battery (10 kW h) hybrid system using the testbed at University of California Los Angeles Smart Grid Energy Research Center (UCLA SMERC). The IEC 61850 standardized communication network comprises PV and battery controllers which are IEDs that receive status information from the PV and battery and then transmit to the IEC 61850 server through abstract communication service interface (ACSI) using substation configuration language (SCL) files as shown in Fig. 5. The communication between the IEC 61850 server and client is realised via the manufacturing message specification, ISO 9506 (MMS).

IEEE Std 1547.3-2007 recommends four pivotal performance metrics to characterize communication network performance for DERs integration into the power system. They include (IEEE, 2007):

- Throughput which determines the amount of user information that can be transmitted via the network continuously expressed in kilobits per second (kbps)
- Latency is a measure of time delay in seconds.
- Reliability is measured in terms of mean time between failures for a communication network in seconds or years.
- Security is capability to guard against intrusion and unauthorized access while providing authorized access.

In addition, a comparison of technologies for communicating signals such as DER unit status, market and protective signals is presented in Table 5 (Ho et al., 2014; Whitaker et al., 2008; Engineering, 2000; Borlase, 2012; Obaidat et al., 2012; Ahson and Ilyas, 2007).

IEEE 802.11 and 802.15.4 technologies can be deployed for real-time pricing data, while the continuous-carrier PLC is mostly used in automated meter reading systems and islanding prevention (Whitaker et al., 2008). For intended islanding operations (i.e.

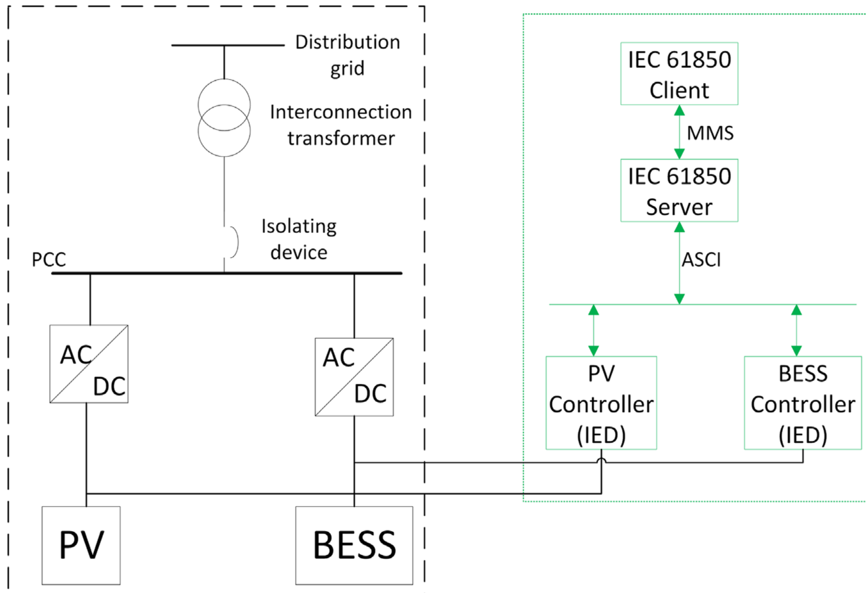

Fig. 5. DER communication configuration of the UCLA SMERC test bed.

Table 5
A comparison of communication technologies for DER.

Technology	Latency	Bandwidth	Reliability	Range	Capital cost
IEEE 802.11	2–10 ms	1–100 Mbps	Medium	100 m	Medium
IEEE 802.15.4	> 16 ms	20–250 kbps	Unknown	30–100 m	Low
Continous-carrier PLC	0.2–10 ms	Low	Unknown	< 100 miles	High
Bluetooth (Class 1)	50 ms	1–3 Mbps	Variable	< 100 m	Medium
BPLC	< 30 ms	Medium to high	Unknown	2000 ft per hop	Medium to high
Ethernet	2–10 ms	10–1000 Mbps	Medium	100 m	Medium
Copper wire	< 3 ms	200 bps	High	2–20 miles	High
IEEE 802.16 (WiMAX)	6–18 ms	30–40 Mbps	Medium	5–50 km	Medium

taking loads off the macrogrid to be powered by DER) a communications technology with exceptionally tight and low latency property (such as fiber optic and WiMAX) is required (Sood et al., 2009). However, for operations such as DER critical control, fault isolation and overcurrent protection which requires short latencies, extremely high data rates and availability, optical fiber remains the only option (Ho et al., 2014). Fiber optics is the best communication technology (with high capital cost) for medium- and low-voltage applications due to its robustness, insusceptibility to electromagnetic interferences or capacity constraints (Ho et al., 2014; Communications, 2011).

4.5. Wide-Area Situational Awareness (WASA)

The WASA application refers to the deployment of technologies to enhance the monitoring, protection and control of the power system across large geographic areas in order to mitigate the impact of disturbances and cascading blackouts in a timely manner (Ho et al., 2014). The root cause of the 2003 Northeast blackout in the U.S. was traced to inadequate WASA for utilities (U.S DOE, 2014). Synchronized phasor measurement units (PMUs) are digital devices used to measure instantaneous voltage at buses, line current and frequency for monitoring and controlling the transmission system (Sanchez-Ayala et al., 2013). The PMUs generate consistent data synchronized with global positioning system (GPS) as shown in Fig. 6 to provide useful information to help analyze the exact sequence of events causing failure and blackout (De La Ree et al., 2010). Traditionally utilities have limited wide area situation awareness to transmission system only. However, with the

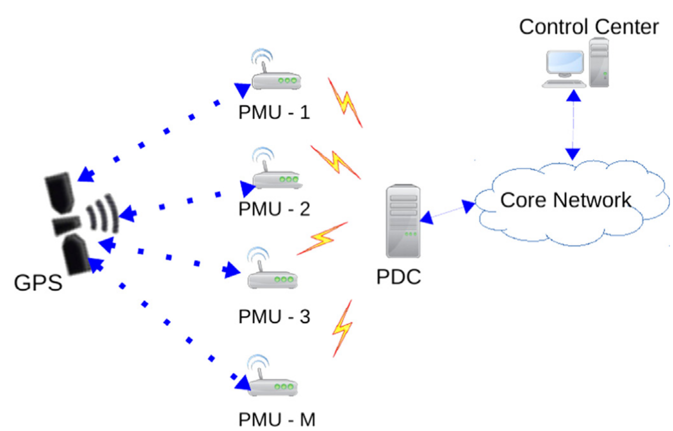

Fig. 6. Wide area PMU communication architecture.

decentralization of the electric grid and high penetration of DER, the distribution landscape faces a lots of constraints such as voltage imbalance, power quality issues and high impedance at the point of interconnection (Sanchez-Ayala et al., 2013). This evolution in the distribution system necessitates the introduction of PMUs for monitoring and controlling of the distribution segment of the grid. Sanchez-Ayala et al. (2013) discussed the use of PMUs for distribution state estimation, dynamic monitoring and protection, harmonic estimation, load modelling, parameter estimation, fault location and detection. However, the choice of adequate communications technologies for handling enormous amount of data provided by these units remains a critical issue (Sanchez-

Ayala et al., 2013). According to ETSI, PMUs are connected to the control center via broadband data connections (such as optical fibres) for high voltage network supervision considering transmission delay of <1 s and near real time for network phase information (Applicability, 2012). Khan and Khan (2012) provided performance analysis of the communication system between the PMUs and phasor data collector (PDC) over a WiMAX network. Rizzetti et al. (2014) discussed QoS (Quality of Service) methods provided in IP networks such as the use of MPLS (Multi-protocol Label Switching), RSVP (ReSource ReserVation Protocol), 802.1p and DSCP (Differentiated services code point) protocols for PMU data communication. PMU traffic has a strict traffic requirement ranging from 20 to 200 ms (Ho et al., 2014) and for historical post-fault data, latency requirements is less stringent (Department of Energy Communications Requirement of Smart Grid Technologies , 2010; Ho et al., 2013; Martin, 2011; Sychrophasor).

Jie Wu and Shil (2014) proposed a mathematical model of average identification ability of multiple line outages using PMU and formulated its placement problem. Martin (2011) highlighted the improvement in the *syn*chrophasor standard, IEEE C37.118, especially the data communication methods using the IP protocol, and mapping into the Distributed Network Protocol (DNP). Kenneth (2011) discussed latency limits in IEEE C37.118 known as dynamic compliance-performance under step changes in phase and magnitude, which is defined as delay time (T_D):

$$T_D \le 1/(4^*F_s) \tag{1}$$

where Fs is the reporting rate or frequency.

Koong Chai et al. (2015) presented a communication platform known as C-DAX based on information-centric networking (ICN) which enables efficient *syn*chrophasor measurement delivery for WASA application. Lee et al. (2013) connected PMUs to PDC via Ethernet for a microgrid monitoring system using IEC 61850 standard interface.

Amongst the various communication technologies for networking synchrophasors such as fiber optics, Ethernet, microwave and BPLC, optical fiber is a preferred choice due to its robustness, insusceptibility to electromagnetic disturbances or capacity constraints (Ho et al., 2014; Borlase, 2012; Communications Network Solutions for Smart Grids, 2011). Moreover, for networking integrated IEDs such as synchrophasors, a reliable, dedicated local area network (LAN) is required. The LAN can be created from various media such as copper, fiber optics and Ethernet (IEC 61850, 2003; Dolezilek, 2006). However, the IEC 61850 recommends the use of Ethernet LAN (with TCP/IP) for networking IEDs (IEC 61850, 2003). In addition, the North American Synchro-Phasor Initiative Network (NASPInet) specified the optical Ethernet and galvanic Ethernet interface options for connecting the phasor gateway (PG) to its WAN (Sychrophasor).

4.6. Distribution Grid Management (DGM)

The distribution landscape is experiencing a major paradigm shift in terms of operation and management due to the high level of penetration of DER, PEV, microgrids and energy storage systems. DGM places emphasis on the optimization of transformers, feeders with the distribution of other intelligent field devices (such as IEDs) and integrating them with transmission systems and customer operations (National Institute of Standards and Technology, 2012). Table 6 shows various DGM applications with their respective technologies and communication requirements (Gobena et al., 2014; Das et al., 2015; Ho et al., 2012; Smallwood and Wennermark, 2010; Chen and Sabir, 2001; McDonald, 2003).

5. Standardization of technologies for smart grid applications

The IEEE Guide for Smart Grid Interoperability, National Institute of Standards and Technology, and U.S. Department of Energy provide recommendations for communication and networking requirements such as payload (size and frequency), physical (PHY) and media access control (MAC) layer latency for smart grid applications. These are summarized below (IEEE Guide for Smart Grids, 2011; National Institute of Standards and Technology, 2012; Department of Energy Communications Requirement of Smart Grid Technologies, 2010):

5.1. AMI

Table 7 depicts the AMI hand-off communication requirements.

The *NAN* ⇔ *WAN* segment connecting the utility with the NAN, is expected to have a low latency to support advanced applications such as real-time pricing, with 500 kbps as the bandwidth (IEEE Guide for Smart Grids, 2011). The communication technologies options are Fiber optic, T1, E1, Microwave and WiMAX (Department of Energy Communications Requirement of Smart Grid Technologies, 2010). The ESI provides a secured communication interface between identified CPN devices and the service providers. The ESI provides two distinct interfaces for the AMI system which are, the utility - secured interactive interface (ensures security, integrity and availability) and utility-public broadcast channel for disseminating information provided by the utility to the general public (Department of Energy Communications Requirement of Smart Grid Technologies, 2010). One of the greatest challenges is determining what type of technology is appropriate for the AMI application, taking into consideration issues such as backward compatibility of (aging) legacy devices, interoperability of heterogeneous devices, cost and ease of installation. However, the level of AMI functionality will determine the choice of communications technologies (Department of Energy Communications Requirement of Smart Grid Technologies, 2010).

Table 6
DGM applications.

DGM application	Description	Communication requirements		Technologies
		Latency	Bandwidth	
SCADA	Grid monitoring and control (for high and medium voltage).	2–4 s	10–30 kbps	Satellite communication, Licensed Wireless DOCSIS, Fiber optic.
Distribution Automation	Automated actions for efficient DGM initiated by IEDs.	<1 s	9.6–100 kbps	Cellular M2M, Fiber optic AMI network, Unlicensed RF mesh, Satellite.
Video (Substation) Surveillance	Asset monitoring.	Few seconds	A few Mbps	Fiber optic.
Mobile Workforce	Allows field engineers access to local devices and provides voice with video access to engineers.	150 ms	250 kbps	AMI NAN/FAN network, LTE, WiMAX, GSM, EDGE, UMTS, GPRS, WCDMA, CDMA, proprietary microwave and satellite, Internet.

Table 7
AMI hand-off communication technologies.

Network Segment	Bandwidth	Latency	Payload	Technologies
CPN ⇔ NAN	10–100 kbps	* < 1 ms to 1500 ms (MAC+PHY) * 2–15 s (end-to-end application)	* Size:10–1500 bytes * Freq.:50 k packets/s to 1 packet/min	PLC, RF Mesh, Fixed point-to-multipoint (Licensed), WiMAX, BPLC, Cellular, IEEE802.15.4/4g, IEEE802.11, Ethernet.
ESI ⇔ ESI	1 kbps–30 Mbps	* < 1 ms to 1500 ms (PHY + MAC)	* Size:10–1500 bytes * Freq.:50 k packets/s to 1 packet/s	RS-232, IEEE 802.15.4, IEEE802.3, IEEE 802.11a,b,g,n, KNX/ISO-IEC 14,543–3/M-Bus
Utility ⇔ ESI	1 kbps–75 Mbps	* 10 ms to 5 s-(MAC+PHY) * 10 ms to 15 min–(End-to-end application)	* Size:10–1500 bytes * Freq.:50 k packets/s – 1 packet/min	LTE, WiMAX, GSM, EDGE, UMTS, GPRS, WCDMA, CDMA, Proprietary microwave and satellite.

Table 8
Demand response communication path.

Network Segment	Bandwidth	Latency	Payload	Technologies
ESI ⇔ Loads	1 kbps–30 Mbps	* < 1 ms to 1500 ms-(MAC+PHY) * < 4 ms to 15 s–(End-to-end application)	* Size:10–1500 bytes * Freq.:50k packets/s– 1 packet/min	ISO 16,484–5/ANSI-ASHARE 135, ISO-IEC 14,543–3, IEEE802.15.4, IEEE802.11a,b,g,n, IEEE802.3, ECHONET
Utility ⇔ ESI	1 kbps–75 Mbps	* 10 ms to 5 s-(MAC+PHY) * 10 ms to 15 min–(End-to-end application)	* Size:10–1500 bytes * Freq.:50k packets/s – 1 packet/min	LTE, WiMAX, GSM, EDGE, UMTS, GPRS, WCDMA, CDMA, Proprietary microwave and satellite.

Table 9
Communication requirements for EV.

Network Segment	Bandwidth	Latency	Payload	Technologies
ESI ⇔ PEV	1 kbps–2 Mbps (based on SAE J2293/2836/2847)	< 1500 ms (End-to-end) (based on SAE J2293/2836/2847)	* Size:10–1500 bytes * Freq.:100 packets/s– 1 packet/min (based on SAE J2293/2836/2847)	SAE J2293/2, ISO TC 57, SAE J2836, SAE J2847, ISO 16,484–5/ANSI-ASHRAE 135, ISO-IEC14543-3, IEEE 802.15.4, ZigBee SEP 2.0, IEEE 802.11, ITU-T G.hn, IEEE 1901 and IEEE 802.3.

5.1.1. DR

Table 8 shows the different communication paths (segments) for DR programs.

5.1.2. EV

The Table 9 shows the communication requirements for EV when it is physically located at the customer's premises to support functions such as storage, charging, billing, load shedding and positioning information. The bandwidth, payload and latency requirements are based on Society of Automobile Engineers (SAE) standards which are: SAE J2293, J2836 and J2847.

5.1.3. DER

Table 10 presents technologies for connecting the ESI and DER network to provide functions such as, monitoring, controlling and protecting.

6. The need for convergence

With the smart grid being a heterogeneous network, it requires convergence of the existing utility proprietary protocols (Modbus, DNP3) and evolving communication protocols into a common protocol platform. The convergence of technologies and protocols is necessary for power and data to be transmitted seamlessly, to ensure the realization of the intelligent grid in a timely, cost efficient manner. There is a growing consensus towards the convergence of communication technologies into a TCP/IP enabled network for the emerging smart grid applications (National Institute of Standards and Technology, 2012). The data centric grid requires a flexible and scalable IP-based solution to connect islands of data in the traditional power grid for efficient end-to-end communications without the burden of conversion of protocols (Bennett and Highfill, 2008; Internet, 2009; Kim et al., 2010; Lobo et al., 2008, 2009; Molderink et al., 2010; Sauter and Lobashov, 2011; Gungor and Hancke, 2009). Collier (2015) described the concept of the emerging "enernet" as convergence between the smart grid and Internet of Things (IoT). Fang et al. (2012) provided

Table 10
Communication requirements for DER.

Network Segment	Bandwidth	Latency	Payload	Technologies
ESI ⇔ DER	1 kbps–30 Mbps	* < 1 ms to 1.5 s-(MAC+PHY) * < 4 ms to 15 s–(End-to-end application	* Size:10–1500 bytes * Freq.:50 K packets/s to 1 packet/min	IEEE 802.3, IEEE 802.15.4, ZigBee SEP 2.0, IEEE 1901, IEEE 802.11a, b, g, n and IEC 61,850–7-420/IEC 61,850–8–1.

an experimental study on the delay performance of the smart grid protocol (DNP3 over TCP/IP) and showed that it cannot be directly used for time-critical situations but usable for monitoring applications. Gungor and Hancke (2009) listed the technical merits of deploying IP architecture for smart grid, they include:

- Ability to transmit data over multiple link layers such as serial lines, IEEE 802.3 and wireless radio networks.
- IP maintains end-to-end reliability.
- Aggregating and analyzing large amount of data rapidly.
- Capability to connect large number of devices.

7. Challenges of communication infrastructures in power system environment

The power system environment is such a sensitive, "unfriendly" and dynamic one which poses a significant threat to the reliability and availability of communication devices deployed within its zone of influence due to RF interference, dirt and dust, vibrations, electric arc, high humidity levels and corrosion (Gungor and Hancke, 2009; U.S. Department of Energy, 2004; Gungor and Bin Lu, 2010). Wireline communications are very susceptible to the electromagnetic environment especially in the high and medium voltage regions within the power system (IEEE Guide for Smart Grid, 2011). Consequently, wireline communications require high voltage protection against the effect of ground potential rise (McDonald, 2012). For dangerous electromagnetic environment, the use of fiber optic cable is invaluable. Mladen Kezunovic and Costas (2002) investigated the effect of the varying electrical and environmental processes in substations on wireless communication quality and noticed signal variations were due to substation location (rural or urban) rather than power delivery of substation. Additionally, the design of wireless communications should be customized for different substations to accommodate dynamic network topology (Gungor and Bin Lu, 2010). The design, deployment and integration of communications technologies must take into consideration distribution or topology of assets (such as reclosers, meters and capacitor banks) and landscape of utilities (Intelligence-based Approah Smart Grid Network Communications, 2012). However, despite the undeniable evolution in information and communication technology (ICT), utilities are quite skeptical in the deployment of these new technologies because they have not been proven within the context of real world scenarios, real loads, feeders, various consumption profile and validated for smart grid applications (Department of Energy Communications Requirement of Smart Grid Technologies, 2010). For all stakeholders involved in the evolution of smart grid, the focus must be a well defined path to migrate technologies from the four walls of the laboratory to actual field deployment (Farhangi, 2010).

8. Future research

This section presents research opportunities and challenges in the deployment of communication technologies in the emerging next-generation grid. They include:

- Interoperability of communication protocols with the existing utility legacy protocols. Since the next-generation grid represents an evolution of the electric power system equipment and communication technologies, interoperability of independently developed diverse systems within such a heterogeneous network remains a focal point for all stakeholders. In addition, as a system of systems, the smart grid interoperation will cover a bidirectional flow of electric power and information with a huge number of monitoring and control operations (IEEE Guide for Smart Grid, 2011).
- Another research focus is the smart grid security which comprises cyber and physical security. The reliance of smart grid on the rapidly evolving ICT predisposes the electric power infrastructure and end users to high levels of vulnerability and threats. As a critical system, there is a need to develop adequate smart grid security solutions such as strong encryption and access controls to prevent attackers from disrupting electrical services (IEEE Guide for Smart Grid, 2011; Obaidat et al., 2012). Also, the proliferation of the grid with resource-constrained devices such as the smart meter underpins the need to develop new lightweight and robust authentication schemes (IEEE Guide for Smart Grid, 2011; Obaidat et al., 2012).
- Environmental concerns such as the green house gas emission and demand for clean energy are major drivers for electric transportation. There is therefore, a need to explore communication technologies suitable for EV charging and networking (Obaidat et al., 2012).
- Additionally, since smart grid applications have different QoS requirements and priorities, there is a need to manage seamlessly all the various types of smart grid traffic. This QoS differentiation is pivotal to specifying communication technologies suitable for each of the application (Ho et al., 2014; Hopkinson et al., 2009; Arnold, 2011).
- Also, with the proliferation of PV/energy storage (battery) hybrid systems, there is a research need to evaluate the performance of communication systems deployed for their remote dispatch. In order to characterize such communication networks, IEEE 1547.3-2007 specifies four critical metrics which include throughput, latency, reliability and security (IEEE Std 1547.3, 2007).
- Another research area is in the development of standard language protocols for communicating with inverter-based PV/storage systems for smart grid applications (Seal and McGranaghan, 2010).
- Moreover, with the high penetration level of intermittent energy sources such as solar PV system, it is increasingly becoming a challenge for utility companies to completely exercise real-time economic dispatch with finer granularity. There is a research opportunity to use the cloud's computing fast elasticity characteristic for short-term stochastic scheduling with a granularity of seconds and minutes (Powell et al., 2012; Bakken, 2014; Mell and Grance, 2010).

9. Closing the skill gap

There is an obvious skill gap that exist among the technical domains of the smart grid which could create a "silo unit" and hamper the eventual realization of the modernized grid. The engineering profession has to undergo a major paradigm shift to retrain engineers with a broader expertise and integrated skills that can support smart grid engineering (Heydt et al., 2009). A critical question is "where will the power engineers emerge from to engineer the smart grid" (Heydt et al., 2009). There are twelve main elements of an integrative approach to smart grid design and operation such as transmission and distribution engineering, power electronics, information technology and energy conversion (Heydt et al., 2009). A typical example is in the definition of concepts in the smart grid (IEEE Guide for Smart Grid, 2011). For instance, to a power system engineer, reliability is assessed in terms of guaranteed power delivery to the consumer and measured using indices such as System Average Interruption Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). However, to a communication engineer, different indices are involved such as latency, priority, transmission errors, packet delay and arrival rate. A loss of packets reported to a power system engineer might be erroneously termed power outage (IEEE Guide for Smart Grid, 2011). Also, there is an aging workforce in most utilities which may adversely affect the stepwise progress of the emerging smart grid. There is therefore, a need for collaborative effort from all stakeholders geared towards ensuring a solid foundation for the emerging smart grid.

10. Conclusion

In this paper, integral components of the emerging grid and communications infrastructures enabling the six smart grid applications have been presented. Also, given in this article, is a summary of their communication and networking requirements such as payload (size and frequency), physical (PHY) and media access control (MAC) layer latency based on IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks. In addition, this paper has presented the need for convergence into a common protocol platform to achieve interoperability of legacy and evolving communication protocols. This will further help to achieve smart grid milestones such as adaptive and self-healing, customer motivation and participation, and asset optimization for improved efficiency. Challenges of communication infrastructures deployed within the “unfriendly” power system environment and critical skill gaps that exist between the power and communication domains, which may create a 'silo unit' while integrating communication technologies into the legacy power system, have been highlighted.

Acknowledgements

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Appendix A

Appendix - abbreviations.

AAM	Advanced Asset Management
AC	Alternating Current
ADO	Advanced Distribution Operations
AMI	Advanced Metering Infrastructure
AMR	Advanced Meter Reading
AMS	Asset Management System
ANSI	American National Standards Institute
ASCI	Abstract Communication Service Interface
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
ATO	Advanced Transmission Operations
BAN	Business Area Network
BESS	Battery Energy Storage System
BPLC	Broadband Powerline Communications
CDMA	Code-Division Multiple Access
CIS	Customer Information System
CPN	Customer Premises Network
DAU	Data Aggregator Unit
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DGM	Distribution Grid Management
DMS	Distribution Management System
DNP3	Distributed Network Protocol
DOCSIS	Data Over Cable Service Interface Specification
DRM	Demand Response Management
DSCP	Differentiated Services Code Point
DSL	Digital Subscriber Line
ECH-ONET	Energy Conservation and Homecare NETwork
EDGE	Enhanced Data for Global Evolution
EPS	Electric Power System
ESI	Energy Services Interface
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FAN	Field Area Network
GOOSE	Generic Object Oriented Substation Events
GPRS	General Packet Radio Service

GSM	Global System for Mobile communication
HAN	Home Area Network
HEMS	Home Energy Management Systems
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
IAC	Integrated Authentication and Confidentiality
IAN	Industrial Area Network
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISO	International Organization for Standardization
ITU-T G. hn	International Telecommunication Union's Telecommunication Home Networking
KNX	Konnex (Building control communication system)
LTE	Long-Term Evolution
M2M	Machine-to-Machine
MAC	Media Access Control
PDC	Phasor Data Collector
PHY	Physical
PLC	Power Line Communication
PMU	Phasor Measurement Unit
PV	Photovoltaic
NAN	Neighbourhood Area Network
RF	Radio Frequency
RFC	Request for Comments
SAE	Society of Automobile Engineers
SCADA	Supervisory Control & Data Acquisition
SEP 2.0	Smart Energy Profile 2.0
SMTP	Simple Mail Transfer Protocol
TCP	Transmission Control Protocol
WAN	Widearea Network
WCDMA	Wideband Code-Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
UMTS	Universal Mobile Telecommunications System

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