Communication Architecture for Smart Grid Applications

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***Abstract*—The need to add intelligence to the existing power grid in order to operate as a cognitive, self-monitoring and self-healing system has become imminent. The monolithic energy value chain comes with a lot of constraints such as elongated outage, electricity theft and low equipment optimization. The next-generation grid is a data-centric network with heterogeneous hierarchical interconnected layers. Network devices in the emerging grid need a standard platform for proper integration, monitoring and control. In this paper, a holistic smart grid architectural landscape that clearly separates the power and communication domains to enable "evolving smart grid" engineers provide efficient networking solutions is presented. The communication routes and device topologies for the six smart grid applications are described based on the IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks. Also, the deployments of intelligent electronic devices for microgrid control, monitoring and islanding operations are highlighted.**

***Index Terms*—self-healing, distributed energy resources, intelligent electronic devices, islanding, smart grid.**

I. Introduction

The 21st century demand for clean energy supply in order to reduce green house gas emission places a great responsibility on traditional utility for a paradigm shift in the operation of the power system. Power generating plants emits about 40% of carbon (iv) oxide [1]. In addition, power service providers are encumbered with aging infrastructure, electricity theft and the control of the non-SCADA (Supervisory Control and Data Acquisition) zone of the power system [2]. The non-SCADA zone, which is the low voltage distribution domain, is not presently controlled and monitored by the traditional power grid. This zone also known as the last-mile communication suffers from asset under-optimization, prolonged blackouts and most times requires a personal call by customers for system restoration [2]. The dynamic device topology varies from one utility to another, which makes it difficult to propose a single solution to service providers. Terrain and geographical features such as mountains and harsh weather conditions, coupled with security issues (cyber and physical), make deployment and integration of the communication technologies a hurdle for service providers [3]. Consequently, the modernization of this energy value chain presents a unique opportunity and challenge for utilities globally.

Simply stated, the evolving smart grid will be an aggregation of microgrids with "plug-and-play" capability [4]. A set of features describing the smart grid by the United States Energy Independence and Security Act of 2007 (EISA07) include [5]:

- Increased customer participation by making available well-timed information and control options.
- Standards development for device interoperability and cross-layer communications.
- Deployment and integration of microgrids, variable distributed energy resources (DERs) and energy storage systems.
- Secured optimization of utility resources and operations.
- Digitizing control, measurement and monitoring technologies to enhance reliability, resiliency, availability and security of the power grid.

These characteristics require a reliable, scalable architectural design to realize a bidirectional flow of power and information over the energy network.

Sauter *et al.* [6] investigated an end-to-end communication architecture consisting of IP-based and field-level networks for metering and SCADA applications. Budka *et al.* [7] presented a smart grid architecture that support applications such as SCADA, mobile workforce and demand response, with their diverse quality of service requirements. Also, Zaballos *et al.* [8] proposed a heterogeneous communication architecture for the smart grid based on power line communication and wireless networks. Similarly, a wireless multihop network with a cellular frequency-reuse that prioritized data transfer using a position-based quality-of-service (QoS)-aware routing protocol has been proposed for active monitoring and control in smart grids [9]. Various surveys on potential communication architectures for smart grids have also been published (e.g. [10], [11]) discussing the likely applications and communication requirements.

However, this paper proposes a holistic smart grid architectural landscape that clearly demarcates the power and communication domains to enable "evolving smart grid" engineers provide efficient networking solutions. The communication paths and device topologies for the six smart grid applications are fully described based on IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks. This article also highlights the deployments of intelligent electronic devices for microgrid control, monitoring and islanding operations are highlighted.

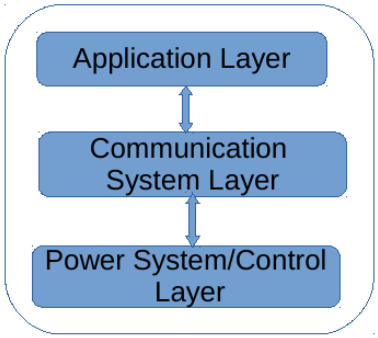

Fig. 1. Smart grid conceptual model

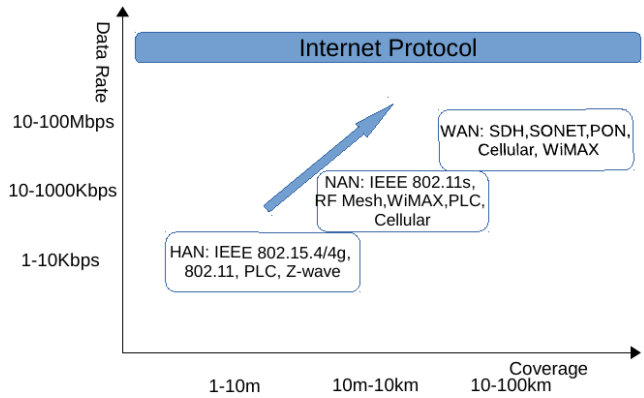

Fig. 2. Three tiers of smart grid network

II. The Next-Generation Grid

Conceptually, the smart grid can be viewed as a hierarchical three-layer interconnected structure as shown in Fig. 1. The power system layer of the smart grid consists of decentralized generation from renewable and non-renewable sources, high voltage (HV/330KV) to medium voltage (MV/132KV) transmission and MV to low voltage (LV/33-0.24KV) distribution domains. The transmission path is monitored and controlled by a class of device known as intelligent electronic device (IED) such as the phasor monitoring unit (PMU) for measuring instantaneous bus voltage, line current and frequency [12]. Other devices include digital disturbance recorders, reclosers and capacitor banks. Moreover, sensors, automated feeder switches and capacitor controllers are used to control and monitor the distribution domain. However, there will be an increase in PMU deployment in the more dynamic distribution system as a result of proliferation of intermittent DER, energy storage and microgrids distributed across the grid [12], [13].

Service providers show skepticism in this changing landscape because of constraints that come along with such integration, which are system imbalance, voltage fluctuation and high impedance at the point of interconnection [12], [13]. Furthermore, considering the previously stated smart grid features of adaptivity, self-monitoring, and self-healing, a careful selection of heterogeneous technologies will play a pivotal role in the realization of the next-generation grid.

The smart grid being a data-centric network generates a large volume of operational data which could be real-time or archival, and static (nodal diagrams) or dynamic (switching orders) [13]. Therefore, the integration of communication technologies for the evolving smart grid is a non-trivial issue. It implies that a robust architecture is required to provide support for devices generating the data and system managing them [14]. In this paper, we aim to highlight the technology options for each smart grid application.

III. Three Tiers of the Smart Grid Network

The smart grid network is divided into three tiers which are:

A. The Home Area Network (HAN)

An integral part of the HAN is the smart meter which aggregates sensor information from various home devices (e.g. refrigerators, washing machine, heaters, cookers and gas meters) and also sends control messages to these devices for managing the consumption profile [15]. There is widespread usage of power line communication (PLC) within the HAN for direct load control, building automation and metering by utilities [16] due to low cost of deployment. However, PLC has some critical deployment constraints such as electromagnetic field emissions, noise, interoperability and fluctuation of impedance. Other technologies used within the premises include proprietary Z-wave, Homeplug, IEEE 802.15.4 and other standards by the ZigBee Alliance. Besides HANs, the customer premises network (CPN) also includes industrial area networks (IANs) [14], [15].

B. Neighbourhood Area Network (NAN)

A NAN is a collection of smart meters and concentrators, and falls within the last mile communication of the smart grid. There is a variation in the number of smart meters per concentrator depending on the technology deployed and network topology [14]. It provides a gateway for the utility's wide area network (WAN) to have access to the customer's premises for advanced metering infrastructure (AMI) and demand response applications. The NAN operates within a communication range of 10m to 10km and provides support from 10 to 1000 Kbps [14] as shown in Fig. 2. Amongst the predominant technologies deployed within the NAN, the IEEE 802.11s mesh network offers self-configuration capability with high speed and reliability [17]. However, in an attempt to solve interoperability issues, utility companies, vendors and researchers unanimously agreed on the need to come up with a unified standard for Smart Metering Utility Networks (SUN). This collaborative effort led to the standardization of IEEE 802.15.4g for SUN devices, providing data rates of 40-1000Kbps and a frame size of 1500 octets [18]. Likewise, the Field Area Network (FAN) is a collection of IED units such as the PMU at the substation domain.

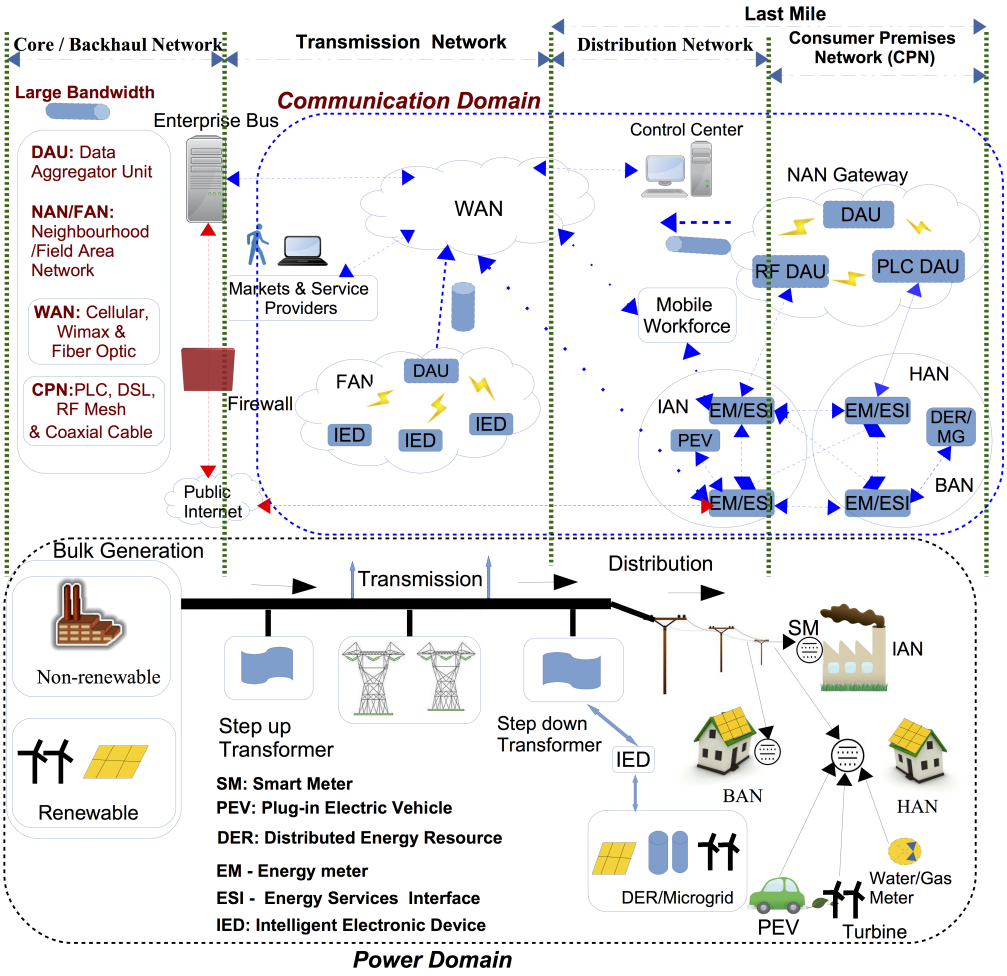

Fig. 3. A proposed smart grid architecture

C. Wide Area Network (WAN)

The WAN provides a two-way backbone communication link for all the smart grid applications [14]. The voluminous data from the NAN and FAN are sent to the service providers, data and control centres through high-bandwidth media. The WAN covers the transmission and distribution domains between 10 and 100 km range. Alternative technologies for this tier include WiMAX, Synchronous Digital Hierarchy (SDH) and Passive Optical Network (PON). Fibre optics remains the first choice for this segment because it is not susceptible to electromagnetic interferences and with very high transmission capacity, albeit costly to deploy.

IV. Integral Architectural Components

In this paper, we also describe some components which are at the very core of the proposed smart grid architecture, as depicted in Fig. 3. They include:

1) Smart Meter: At the very core of smart grid applications is a resource constrained (in terms of storage ability, processing power and limited bandwidth) device known as the *smart meter* [14], [15]. The aforementioned constraints are due to regulatory specifications from standard bodies, such as the Federal Communications Commission (FCC) and American National Standards Institute (ANSI), on meter size (form factor), cost implications, heat dissipation and smart meter operational performance [19].

The smart meter consists of the energy meter (EM) which measures, records and transfers the energy usage, and the energy services interface (ESI) serving as the data management gateway. The ESI provides network control for smart meters distributed across the network. The service providers interact with the customers via the ESI for Demand Response (DR) programs, two-way advanced metering infrastructure (AMI) and transfer of energy information to the Home Energy Management System (HEMS) [15], [20].

More importantly, smart meters are grid management tools used to monitor the power quality of the grid periodically and provide support for plug-in electric vehicle (PEV) charging [21]. The architecture also shows mesh and peer-to-peer topologies with smart meters providing multiple gateways and serving as relay nodes or forwarders to communicate with the data aggregator unit (DAU). The mesh topology ensures easy scalability, self-healing, and reliability by creating redundant paths as well as reducing congestion, for optimal performance

in the network during peak periods [2]. SUN devices have average range hop-to-hop coverage area of 100m (none line-of-sight) and up to 1 km for line-of-sight connection [22].

2) Data Aggregator Unit: The data aggregator unit (DAU) or the concentrator is a multi-interface unit which aggregates data from the various smart meters distributed across the network and forwards it to the utility company for billing and grid management [14]. Also, from the architecture in Fig. 3, the concentrator acts the NAN gateway through which control messages are received from the service providers to be sent to the customers. It has the capacity to divide the NAN into smaller autonomous networks with respect to the technologies deployed such as RF mesh or PLC [4]. Additionally, the DAU routes, prioritize and manage traffic [14]. Due to high bandwidth requirement towards the utility, cellular (3G/4G/LTE), WiMAX, and fiber optics are candidate technologies, while for the last mile network, RF mesh or PLC options are deployed. The architecture also depicts various DAU deployment scenarios with a mesh topology for reliability, scalability and optimum network performance. For a large scale deployment of smart meters in urban areas, multiple DAU units are required to reduce network congestion [17].

3) Intelligent Electronic Device (IED): The FAN connects IEDs which perform control and measurement operations for transformers and circuit breakers at the HV/MV SCADA substation domain [14]. IED units are fast replacing the conventional Remote Terminal Units (RTUs), current and voltage transformers used in the current power system [14], [20]. They have the capacity to support operations previously provided by the aforementioned traditional devices, thereby reducing the complex of device topology at the substation [2]. However, there will be a large scale deployment of IEDs in the non-SCADA region towards the customers' premises as a result of proliferation of variable DER, microgrid and energy storage system in the low-voltage distribution system [12]. This will enhance the automation of the dynamic low-voltage distribution system.

The IEEE Std 1815-2012 stipulates that an IED should be located close to the devices being monitored. Currently, the IED communicates using the distributed network protocol (DNP3) in SCADA systems but utility companies have started deploying IED units using IEC 61850 standard.

V. Smart Grid Application Communication Paths

We now present six representative smart grid applications and their communication paths in the proposed architecture.

1) The Advanced Metering Infrastructure (AMI) Communication Path: The AMI application has evolved over the years. Its predecessor technology known as the Automatic Meter Reading (AMR) uses a one-way communication for monthly meter reading and billing [14]. However, the AMI enables a bi-directional flow of data amongst the three hierarchical interconnected network tiers (HAN, NAN and WAN) of the smart grid, which could be on demand or scheduled [14].

Command, configuration and control messages flow from the utility company to the endpoints (smart meters) at the customers premises and event messages, such as "fault", are sent from the customers to the utility. Furthermore, from the architecture in Fig. 3, the utility company has remote access to the smart meter via the ESI over a wireless connection (via GSM, UMTS, LTE, WiMAX and Microwave) [14]. This is used for AMI support services such as energy data measurement request, service disconnection and restoration, firmware download and other forms of queries. Typically, AMI communication path is mapped to the WAN-NAN-HAN link as shown Fig. 4 below which is extracted from the architecture.

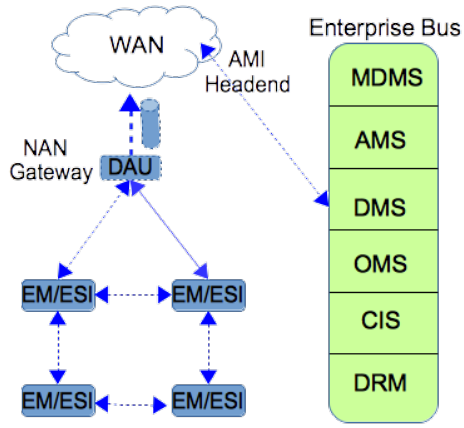

Fig. 4. AMI communication path

The DAU is a multi-interface unit, which means it can accommodate both wireline (PLC) and wireless (radio) technologies such as IEEE 802.15.4g [14]. The topology configuration is a function of the technology adopted. A PLC will form a tree-like topology with immediate hops to the DAU, while a radio technology creates a mesh topology with several hops to the DAU [14]. The coalesced data from the various smart meters (periodic, on-demand or event driven) distributed across the network is sent via large bandwidth media such as WiMAX, optical fiber and cellular to the Meter Data Management System (MDMS) of the enterprise bus for billing and grid management purposes [14]. The smart meter reports power outages to the Outage Management System (OMS) component of the enterprise bus. Other applications on the enterprise bus include Asset Management System (AMS), Distribution Management System (DMS), Customer Information System and Demand Response Management (DRM).

In addition, the AMI headend server generates data traffic such as energy meter read request, software download, modification of configuration and other queries in a point-to-point (P2P) or point-to-multipoint (P2MP) communication [21]. The headend connects to the DAUs and MDMS over an IP connection at the service provider's data center. The Extensive Markup Language (XML), is used for commands, meter data exchange and replies between the MDMS and the headend [2].

2) Demand Response (DR) Communication Path: DR programs are designed by the utility companies to influence the consumption profile of consumers in response to price, reliability of grid or other types of incentives such as the

dynamic pricing [15]. Service providers also make use of DR for peak shaving to balance the network load by shutting down some devices during peak periods. For optimization purpose, the DR programs are routed via the AMI network considering critical communication requirements such as latency, availability, reliability and bandwidth. Devices (such as heaters and air conditioners) which are meant to participate in DR programs must go through commissioning, registration and enrolment processes on the ESI [15]. In order to provide services such as management of energy consumption, HVAC and lighting control, a bidirectional link is established between the ESI and designated loads using communications technology compliant with IEEE 802.15.4, IEEE 802.11 series and IEEE 802.3 standards. The proposed architecture shows a direct load control DR program from the utility to customer's premises via a wireless communication over cellular network or Internet.

3) Plug-in Electric Vehicle (PEV) Communication Path: A PEV uses power generated from its rechargeable battery to propel its motors [14]. In this paper, it is assumed that the PEV is parked at the customer's premises and therefore, becomes part of the HAN. The interaction with the grid is in two modes, namely, grid-to-vehicle (G2V) for charging depleted batteries and vehicle-to-grid (V2G), where PEV acts as a power resource for the grid. The Electric Vehicle Supply Equipment (EVSE) is the electrical connector and interface between the grid and PEV batteries specified byapplicable Society of Automotive Engineers (SAE) standard [15]. Plug-in electric vehicle (PEV) can be deployed as a load within the customer premises network to provide support functions such as billing, location information and charging [14]. It can also be deployed as an energy storage system capable of feeding back power to the grid through its charged batteries. The connection between the ESI and PEV is established through technologies such as SAE J2293/2, SAE J2836/J2847, IEEE 802.3, and IEEE 802.15.4 [14].

4) Distributed Energy Resource (DER) and Storage Communication Path: As stated previously, the demand for clean energy supply and maintaining a balance between power supply and demand bring to focus the deployment and integration of DER and storage systems. DER represents variable renewable energy resources distributed across the energy network which includes PV panel, wind turbine and small hydro [14]. Energy storage systems store electric energy from the grid and discharge back to the grid to compensate insufficient macro grid supply; examples are PEV batteries and supercapacitors.

The deployment of DER and storage systems are part of smart grid agenda to decentralize power generation. Conceptually, the evolving smart grid will be an integration of distributed microgrids in a "plug-and-play" fashion [4]. However, the intermittent nature of power generated by the DER is a critical potential source of system imbalance, and service degradation. Therefore, the IED has emerged as a potential tool for monitoring and controlling the operations of the DER by the utility company as shown in the architecture. More importantly, in an attempt to make the distribution system smart and maintain grid integrity, the IED such as the PMU will have a significant role in helping to monitor the health of the dynamic distribution system.

The proposed architecture shows a deployment scenario where a DER is connected to the premises through a smart meter to compare energy generated locally and supplied from the utility grid. Excess energy is fed back into the grid when local generation exceeds the amount consumed. The DER connects to the ESI to provide support for operations, such as, islanding, diagnosing, protecting, starting and stopping the DER. KNX/ISO-IEC 14543-3, BACnet/ISO, Ethernet, Homeplug and IEC 61850-7 are examples of communication technologies used to connect the devices [14].

5) Wide-Area Monitoring, Protection and Control (WAMPAC) Communication Path: The WAMPAC system provides a time-synchronised display of the electrical state and performance of the transmission system over a large geographic area [14]. The objectives of WAMPAC include optimization of energy-network units, performance as well as prediction, avoidance and providing the appropriate response to possible points of failure [20]. Inadequate provision for efficient WAMPAC for utility company can lead to elongated blackouts and costly restoration [12]. PMU units are largely deployed in the transmission domain for WAMPAC. They are typical digital devices for measuring line current, bus voltages and frequency to ascertain the electrical health and integrity of the grid [12], [13]. Utilities rely on the consistent data generated by the PMU for proper analysis of the sequence of events leading to power system failure.

Rapid evolution in the distribution landscape due to the proliferation of the DER will lead to large scale deployment of PMU units distributed across the emerging smart grid. The PMU generates huge amounts of data which are sent to the phasor data collector (PDC) and therefore would require high bandwidth media for PMU-to-PDC peer and PDC to control centre connection. For a microgrid monitoring setup, a PMU can be connected to the PDC via an Ethernet cable [23]. Since the PMU network requires a high bandwidth, fibre optics and WiMAX are choice technologies for WAMPAC [14].

6) Distribution Grid Management (DGM) Communication Path: There is a prevailing need to monitor and control the dynamic distribution system in the emerging smart grid due to high rate of influx of the DER, energy storage systems and microgrids [14]. Less than 10% of power network elements, such as, distribution transformers and ring main unit (RMU) are monitored and controlled in most utilities. DGM covers Distribution Automation (initiated by the IED connected to the feeder devices, such as, recloser, line switches and capacitor bank), video surveillance (for asset monitoring), mobile workforce and smart meters deployed at the customer's premises. mobile workforce (field engineers) access to the grid by logging into the ESI gateway locally or remotely using various wireless technologies. This is done in order to retrieve data for repair and maintenance operations. Additionally, the utility's workforce use WAN to dispatch field engineers for daily maintenance operations either through the AMI-NAN/FAN, public 3G/WiMAX or substation hotspots.

VI. Architectural Features

Table I presents architectural features which provides a guide for a timely realization of the smart grid [14].

TABLE I
ARCHITECTURAL FEATURES

Feature	Definition
Scalability	Easy expansion and extension of the architecture.
Ubiquity	Location independent access grant to authorized users.
Interoperability	Secure external exchange of information between two or more networks or devices.
Integrity	Guarantees operation during outages and reliability.
Standardization	Open and well defined connection of network elements.
Upgradeability	Remote software, configuration and algorithms upgrade.

As an addendum, the Internet serves as an alternative architectural route (as shown in Fig. 3) that transverses all hierarchical levels (HAN/NAN/WAN) capable of providing communication links for smart grid applications such as AMI and DR. However, Authority Having Jurisdiction (AHJ) over the grid and utility companies (despite the security provided by firewall) remain skeptical to its usage because it increases the vulnerability of the evolving smart grid [14]. More so, Fig. 2 shows a proposed use of Internet Protocol (IP) technology for end-to-end communication of smart grid network elements. There is a growing consensus amongst the stakeholders (e.g., utility companies, researchers and governments) on the use of IP for a number of reasons such as the maturity, scalability, interoperability with proprietary protocols, availability, widespread usage and reliability of the protocol [20]. However, more research needs to be conducted into the suitability of IP-based networks for smart grid applications considering their respective communication requirements such as latency, bandwidth, throughput and packet delay.

VII. Conclusion

There is an inevitable demand on the power industry to modernize its operation and effectively integrate the evolving information and communication technologies. However, a reliable and scalable communication architecture is needed to create a roadmap for a progressive realization of the smart grid. In this paper, we have presented an architecture for the next-generation grid based on the IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications and Loads, and National Institute of Standards and Technology framework. Finally, we highlighted the growing consensus amongst the stakeholders on the use of IP technology for end-to-end communication of smart grid network elements.

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