Renewable and Sustainable Energy Reviews 19 (2013) 191–199

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

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

Evolution of Communication Technologies for Smart Grid applications

Ahmad Usman [a,*], Sajjad Haider Shami [b]

[a] Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA
[b] Department of Electrical Engineering, University of Management and Technology (UMT), Lahore, Pakistan

ARTICLE INFO

Article history:
Received 20 March 2012
Received in revised form
31 October 2012
Accepted 1 November 2012

Keywords:
Smart Grids
Power Line Communications (PLCs)
ZigBee
Wi-Fi
WiMAX
GSM/GPRS
DASH7

ABSTRACT

The idea of Smart Grid has started to evolve more rapidly with the enhancement in Communication Technologies. Two way communication is a key aspect in realizing Smart Grids and is easily possible with the help of modern day advancements in both wired and wireless communication technologies. This paper discusses some of the major communication technologies which include IEEE specified ZigBee, WiMAX and Wireless LAN (Wi-Fi) technologies, GSM 3G/4G Cellular, DASH 7 and PLC (Power Line Communications), with special focus on their applications in Smart Grids. The Smart Grid environments and domains such as Home Area Automation, Substation Automation, Automated Metering Infrastructure, Vehicle-to-Grid Communications, etc. are considered as priority areas for developing smarter grids. The advancements, challenges and the opportunities present in these priority areas are discussed in this paper.

Contents

1. Introduction

The infiltration of communication technologies in the Power Sector has helped the concept of Smart Power Grid to take quantum leaps towards a practically realizable stage. The idea of Smart Grid which surfaced long ago, started to take concrete shape when major breakthroughs were achieved in communication technologies and power electronic equipment. The definition of Smart Grid has variations but the common aspect is the bi-directional or two way communication along with power flow between the two concerned entities i.e. Consumer and Grid. The power flow was there long ago but the inclusion of communication technologies has enabled the aspect of bi-directional communication. The key features of Smart or Intelligent Grid involve monitoring, protection, automation, optimization, integration and security of the power flow from utility generators to the end user appliances. This eventually results in conservation of energy and its efficient utilization for both power and infrastructure applications.

A considerable credit goes to the communication technologies for the practical realization of the key features of the Smart Grid.

* Corresponding author. Tel.: +1 678 702 2360.
E-mail addresses: ahmadusman@gatech.edu, ahmad_usman86@hotmail.com, ahmadusman86@gmail.com (A. Usman), sajjad.shami@umt.edu.pk (S.H. Shami).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.11.002

The advancements in the wired and wireless communication and availability of low cost interoperable devices have resulted in development of many applications for the smart grids. Existing electrical utility systems are based on a hybrid combination of communication technologies to support a wide range of applications such as SCADA/EMS, distribution feeder automation, generating plant automation, and physical security.

The motivation behind this paper is to provide ample information regarding the integration, penetration and application of modern communication technologies with the existing Power Grid. Keeping in view the recent developments and research in this domain, this article gives a general overview of different support communication technologies and their applications in realizing Smart Grids. Some of these technologies included in this survey are IEEE 802.11 based wireless LAN, IEEE 802.15 based ZigBee, IEEE 802.16 based WiMAX, 3G/4G GSM, DASH 7 and Power Line Communication (PLC). These technologies are selected because of their penetration and ongoing research activities for the realization of Smart Power Grids.

The organization of this paper is as follows: Section 2 discusses the a conceptual architecture of a Smart Power Grid network. Section 3 discusses the above mentioned communication technologies and their potential applications in Smart Grid and Section 4 concludes the discussion.

2. Conceptual architecture for Smart Power Grids

Different conceptual models and architectures have been proposed for the Smart Grids' implementation. One such conceptual architectural model is proposed to National Institute of Standards and Technology (NIST) in the Smart Grid Interpretability Standards Roadmap [1]. The main purpose of this architecture is to be used as a guideline for describing, discussing, analyzing and developing smart grid architecture and standards. The top level abstraction of this architecture is shown in Fig. 1.

The key domains in developing a complete Smart Power Grid are shown. The interfacing and communication between these domains is also given in Fig. 1. These domains may contain multiple domains as well. Inter domain communication and Intra domain communication may or may not have similar requirements [1].

The Consumer Domain refers to the user of electricity (and other utilities). The consumer can generate, store and use the electricity. We have only considered domestic, industrial and commercial consumer aspects for this discussion. The "Market" domain refers to the operators and participants in the electricity market [1]. The "Operation" domain involves managing of electric supply. "Service Provider" refers to the organization providing services to the customers and other utilities. "Bulk Generation", "Transmission" and "Distribution" refer to the generation and storage of electricity, transmission of electricity to the distribution systems and distribution of electricity to the customers, storage and further generation, respectively [1]. This model gives the scope of the Smart Power Grid as it incorporates all the major aspects and domains involved in a power grid.

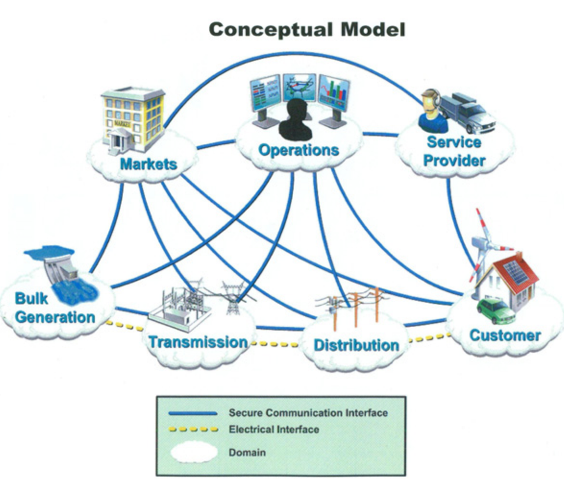

Fig. 1. Smart Grid architecture proposed to NIST [1].

These domains are already present in the conventional Power Grid. Interconnecting these domains is one of the key issues towards realization of a Smarter Grid. Communication Technologies are required for integrating these domains together. Interpretability among the Communication Technology Standards is again a key problem faced while integrating these domains. In order to move ahead in this regard, some priority areas are identified and work has commenced in these. These priority areas include "Awareness in the Masses", "Electrical Energy Storage", "Electric Transportation", "Advance Metering Infrastructure (AMI)", "Domestic Automation", "Distribution Grid Management", "Renewable Integrations" and "Cyber Security". These priority areas are considered in this discussion.

3. Communication Technologies for Smart Grids

3.1. Power Line Communication (PLC)

One of the earliest initiatives for the automation of the electricity grid was taken using the Power Line Communication (PLC) Technology. The Power Line Communication technology involves introduction of a modulated carrier signal over the existing power line cable infrastructure for two way communication. PLC is classified into two major categories i.e. Narrowband PLC and Broadband PLC.

The Narrowband PLC has an operating range of 3–500 kHz. This operating range includes CENELEC, ARIB and FCC specified bands. Narrowband PLC is further classified as Low Data Rate Narrowband PLC and High Data Rate Narrowband PLC. The Low Date Rate Narrowband PLC is a single carrier based technology having data rate up to 10 kbps. It works on the recommendations and standards by IEC 14908-3 (Lon Works), IEC 14543-3-5 (KNX, BUS), CEA—600.31 (CEBus), IEC 61334-3-1 (DLMS), IEC 61334-5-1, etc. There are also standards and recommendations developed by Insteon, X10, SITRED and HomePlug for this [2]. The High Data Rate Narrowband PLC is a multi-carrier based technology having data rate less than 1 Mbps with standards and recommendations falling under the IEEE 1901.2, ITU-T G.henm, PRIME and G3-PLC.

The Broadband PLC technology has an operating range of 2–250 MHz with data rates up to several hundred Mbps. The standards developed for this includes IEEE 1901, TIA—1113 (HomePlug 1.0), ITU-T G.hn (G.9960/G.9961), HD-PLC, etc [2].

The Narrowband PLC technology is more suited to the sensing and communication purposes in Smart Grid environments while the broadband PLC is more inclined towards end user entertainment and Internet applications in addition to the Smart Grid Applications. Power Line Communication technology has found its applications in nearly all aspects of the Smart Grid Environment. From Generation to the End User, Power Line Communication can be considered as a viable solution.

Some of the key applications of Power Line Communication involve automation of the Medium Voltage (MV) grids and substations. These MV substations were the least equipped part as far as the communication technologies for automation and intelligent operation are concerned [3]. The main tasks involved here are location, isolation and fault restoration which involve low data rates for communication. This provides an ideal scenario for PLC based technology. PLC application in a MV/LV network is investigated by means of simulations and experimental tests in [4]. These tests are performed on a testbed of power network, which included a MV overhead power line and a MV/LV transformer. The communication channel is also characterized. The possibility to cross the power transformer is additionally investigated.

Distributed Generation especially with the introduction of Renewable Energy based Generation sources cause a problem of islanding in case of power failure. In order to avoid this problem PLC based narrowband systems are tested on MV power line for detection and isolation of islanding with considerable success [3]. PLC based smart meters are also one of the major applications of PLC technology.

The Automatic/Advanced Metering Infrastructure (AMI) is another application which does not require high data rates so Narrowband PLC applications are best suited for this purpose. The low frequency Narrowband PLC also has an advantage over the high frequency broadband. The low frequency signals pass easily through the MV/LV transformers as compared to the high frequency signals because of the inductive nature of the transformer. Couplers are used in order to bypass this attenuation at the MV/LV transformer but the cost becomes a major factor especially in the American continent where a single transformer is used to supply to 10–15 houses [2].

PLC based solutions have found success in Vehicle-to-Grid Communications. SAE J2931TM specifies the communication protocols for Vehicle Charging Applications [5]. SAE J2847TM and J2836TM specifications refer to the functional requirements and use case scenarios for Vehicle-to-Grid communications. The data rates required are not high and Narrowband PLC applications serve optimally for this purpose [5]. An ISO/IEC 15118 standard is pushing to standardize PLC as a technology that supports electric vehicle charging systems. An investigation into electric vehicle charging systems has been described in [6]. The works also explores the performance of a PLC modem used for communication for this purpose.

Another particular challenge, which is common to Vehicle-to-Grid PLC application scenarios is the temporal and spatial variation of the input impedance. The design of an adaptive impedance matching circuit for Vehicle-to-Grid PLC application has been shown in [7].

PLC for Home Area Networks (HAN) environment is still awaiting success. HAN is inherently a multi-vendor and multi-protocol environment [2]. The main reason for the lack of success is the unavailability of PLC standards which provides interoperability and compatibility with other communication technologies. Recommendations have been made to make these standards as a part of PLC standards for HAN applications by NIST [8].

The PLC technology is considered to be the most mature communication technology for Smart Grid applications. One of the main reasons behind this is the availability of the power line infrastructure and amount of the research conducted in this area. The development of software defined PLC modems has made the implementation and up-gradation cost of the overall solution quite low as compared to other viable and proposed solutions.

Interference and noise issues are inherently present in the PLC environment. The variation in the communication channel, which is highly frequency selective and is time invariant, is the key issue which still stands in the way of a complete PLC based solution. This is because the channel characteristics vary drastically from place to place. The channel modeling techniques for such harsh and noisy environments are still under development and some encouraging results have been put forward [9]. The application of multi-carrier OFDM technique with forward error correction and data interleaving, over the traditional signal carrier FSK and BPSK techniques in both narrowband and broadband PLC, has enabled low loss, low cost, high speed and high data rate communications over the power line channel. The primary advantage of OFDM technique is its robustness against noise and ability to deliver under harsh channel conditions [9]. Different noise modeling and reduction techniques have been proposed for PLC based communication in [10–14].

Another issue in Narrowband PLC in PLC systems is overcoming additive non-Gaussian noise. A cyclostationary model for the dominant component of additive non-Gaussian noise is proposed in [15]. The development of a cyclostationary noise generation model that fits measured data from the outdoor Narrowband PLC system has been presented in this work.

Channel congestion is considered a problem in communication. In case of channel congestion, wireless technologies fail to deliver when compared with PLC based technologies as suggested in [16]. A novel technique of using single frequency network with flooding based routing, converts the channel congestion into channel cooperation for a Narrowband PLC application [16]. This recently proposed technique in [16] is supposed to achieve better channel congestion performance in using PLC as compared to the available wireless communication techniques.

PLC also faces problems when the communication is lost with the devices installed on the open circuit ends of the power system. This issue severely reduces the application of PLC based communication in areas involving switches, sectionalizers and reclosers [17].

Security issues in PLC based solutions are addressed using flexible key management techniques and 128 bit Advanced Encryption Standards (AES) keys for authentication, data integrity and privacy. PRIME is currently using these techniques for its smart metering equipment. Both data and control messages are encrypted in the system [9].

The PLC technologies both narrowband and broadband find fitting applications in the Smart Grid Environment. The selection between the narrowband and broadband technologies is also dependent upon the regulations present in the country. The US allows both the narrowband and broadband solutions for outdoor deployments. The EU has stricter limits over the power transmitted and radiated over the power line cables thus restricting the broadband PLC solutions. The Japanese only allow narrowband communication solutions for deployment [2]. These scenarios give quite an edge to narrowband PLC based solutions over the broadband solutions.

Narrowband PLC has some further key advantages over the Broadband PLC when it comes specifically to the Smart Grid applications. Broadband PLC technologies such as IEEE 1901 and ITU-T G.hn were initially developed for Internet applications and home user entertainment purposes. These were not optimized for the Smart Grid applications on the whole as compared to the high data rate narrowband applications developed on the G.hnem and IEEE 1901.2 standards which are specifically optimized for numerous Smart Grid applications [2]. The ease of implementation using DSP and availability of soft-modems for Narrowband PLC has made it easier to upgrade as compared to broadband solution, thus making it more useful for the Smart Grid application purposes.

3.2. IEEE 802.15.4 (ZigBee)

IEEE 802.15.4 is a standard which specifies the physical layer and media access control for low-rate wireless personal area networks. ZigBee is a popular, low power wireless communication technology developed by the ZigBee Alliance based on the

Physical Layer and Media Access Control Layer of the IEEE 802.15.4 standard. Operating on the ISM bands of 868 MHz, 915 MHz and 2.4 GHz adopting direct sequence spread spectrum (DSSS), with low data rates up to 300 kbps, it is very much popular in home automation applications [18].

The IEEE 802.15.4 standards adopt beacon and non-beacon mode for communication. In beacon mode communication, the device searches for the network beacon for data transmitting interval, while in non-beacon mode the device simply sends the data to the network coordinator node [18,19].

The ZigBee enabled devices use the same functionality in a slightly different way. They have two types of devices. One is the Full Function Device (FFD) and the other is the Reduced Function Device (RFD). The network formed on the basis of ZigBee devices consists of both these devices. The establishment and management of the network, along with routing of the data lies with the FFD. The RFDs are there to support the functions of the FFDs [18,19].

The network consists of three types of nodes: Coordinator, Router and End Device. The FFDs can be either of these while the RFDs can only be the end devices. FFD, having the ability of being an end device is normally not used as one. The task of establishment and management of the network goes to the Coordinator. The Router routes the traffic between the end devices and the Coordinator. Routers and Coordinators are capable of communicating with all network devices and are battery powered devices. They are not allowed to go to sleep mode in most cases. The End Devices are only allowed to communicate with the Coordinator or Router. These are not allowed to communicate with each other. These are usually in sleep mode, tend to wake up periodically, check for their tasks from the parent node, send the required data and go to sleep mode. The presence of sleep mode mechanism among the ZigBee network nodes, gives the ability of being low power and energy efficient as compared to the other communication networking technologies [18].

Electrical power networks are required to be scalable in order to support the new and the future set of functions characterized by the Smart Grid requirements. These are also required to be highly pervasive in order to support the deployment of last-mile communications (i.e. from a backbone node to the customer location) [20,21]. ZigBee can serve as a right technology enabling wireless networking between the different devices connected in the Power Grids. The robust nature of ZigBee networks also makes these ideal for hostile environments where node failures may be common [18,22]. ZigBee's spread spectrum modulation scheme and channel change features also help mitigate the effect of interference. Their mesh networking topology, self-healing and route repair features enable routing around failed nodes, facilitating robust network architecture [18,22].

The installation of AMI is viewed as a bridge to the construction of smart grids. Therefore, ZigBee based Smart Meters for the purpose of AMI has also been deployed at various places. Many ZigBee based AMI systems have been proposed in [23–26]. One such proposed system is given in [24]. The proposed system also enables outage recording and automatic reliability calculation apart from enabling the metering purpose. A system enabling tiered pricing mechanism is proposed in [27,28]. The integration and installation of ZigBee capable meters with different installation approaches have been reported in [29]. The performance evaluation using the field data obtained is also shown in [29].

The integration of ZigBee based smart devices with light switches, occupancy sensors, temperature sensors, smoke detectors, and ventilation actuators, facilitates fine-grained measurement and has resulted in significant energy savings, greater comfort, safety and security for the building occupants [18]. One such example is the Perfect Power System demonstration carried out at Illinois Institute of Technology where ZigBee is the wireless communication technology selected for data collection and communication throughout the campus [30]. An intelligent self adjusting sensor for smart home services has been proposed in [31].

A ZigBee based load monitoring system has been proposed in [32]. This proposed system is designed to effectively solve the insufficiency problem of power supply when such a problem occurs in the electricity utility side. The system restrains the peak loading of the system (in time) to prevent the transformer from overloading and decreases peak power generation simultaneously, to achieve the goal of energy conservation and carbon reduction [32].

ZigBee has found some of its applications in monitoring and control of substation equipment as well. An online monitoring and control of a high voltage circuit breaker is proposed in [33]. A substation temperature monitoring system has been proposed in [34] and a substation perimeter protection system based on ZigBee is given in [35]. A ZigBee based online insulation monitoring system for high-voltage capacitive substation equipment is given in [36]. A number of ZigBee subnets are installed in the substation, working in accordance with the voltage levels to measure the leakage current of the capacitive equipment.

Security is a key issue in Smart Grids. The metering and monitoring devices must have secure communications between the end user and the utility. ZigBee uses strong authentication process between the communicating devices based on 128 bit AES encryption. The security issues and threats in ZigBee based Smart Grid HAN environment are discussed along with a proposed solution in [37].

ZigBee has been developed for wireless devices requiring low data rate communications in conjunction with ultra low power consumption. The potential markets for ZigBee includes Home Automation, Building Automation, Energy Management and Efficiency, Industrial Control, Personal Health Care, Consumer Electronics and Telecom Services. An increased trend towards energy efficiency, monitoring and control has allowed the ZigBee alliance to develop ZigBee Smart Energy (ZSE) application. ZigBee appears to be the first choice when it comes to developing Home Area Networks (HANs) for monitoring and smart utilization of the energy available at the domestic consumer level. The ZSE profile includes the many Smart Grid features including Metering, Load Control, Pricing, Demand Response, User Alerts, GUI based Monitoring and Control, Enhanced Security and compatibility for Gas and Water Monitoring and Control as well.

The upcoming trends for ZigBee are seen in exploiting the benefits from the hybrid integrations with both wired and wireless technologies. The development of IETF based IP stack for IEEE 802.15.4 based platforms based on OpenHAN SRS and IEEE 1901 compliant power line carrier solutions such as Home Plug AV is under way, eventually moving towards integration of the ZigBee IP stack with the Power Line Communication (PLC). ZigBee based solutions for PHEVs, Distributed Generation and Sub-Station Control and Protection are also under development with ZigBee working closely with the recognized standards developing organizations such as IEC, EPRI, ESMIG, etc.

3.3. IEEE 802.11 (Wireless LAN (WLAN) or Wi-Fi)

Wireless LAN (WLAN) or Wi-Fi is the most popular among the wireless standards developed by Wi-Fi Alliance under the IEEE 802.11 standards. The Physical Layer and the MAC layer of the Wi-Fi Technology are governed by the IEEE 802.11 standards. The IEEE 802.11 is a family of standards. The most popular among these versions are IEEE 802.11b and IEEE 802.11g. The latest release is the IEEE 802.11n.

IEEE 802.11b allows working in the ISM band at 2.4 GHz. It employs Direct Sequence Spread Spectrum (DSSS) modulation technique with data rates reaching up to 11 Mbps for indoor environment and up to 1 Mbps for outdoor environments. The indoor range is around 30–40 m while the outdoor range is around 90–100 m [38–40]. IEEE 802.11g allows working at the same ISM band frequency of 2.4 GHz. It uses orthogonal frequency division multiplexing technique (OFDM) with data rates up to 54 Mbps. It is also compatible with IEEE 802.11b standard devices. IEEE 802.11b is most commonly used between the two [38–40].

Wi-Fi provides robust performance in shared spectrum and noisy RF channel environments. It supports all IP based protocols and numerous applications including Smart Energy Profile 2.0. A wide range of data rates is supported along with point-to-point and point-to-multipoint communications. Security features for secure and authentic data communication are also implemented, making it a strong contender for communication technologies for Smart Grids [41].

Home Area Network (HAN) for a Smart Grid involves communications and collection of data from smart appliances within a home. The data collected is stored at a central location in HAN environment. Smart Meters proves to be an ideal candidate for this. Wi-Fi allows a variety of devices to communicate in this manner with the meter installed at the customer premises and also allows the user to view the energy profile over the internet. Interference in Wi-Fi remains a key issue as it is operated in the unlicensed ISM band whose spectrum is very crowded. Security is also a concern but the latest Wi-Fi enabled devices seem to overcome this.

The Automatic Metering Infrastructure (AMI) involves relaying information from the energy meters back to the utility central database. This involves a Neighborhood Area Network (NAN) scenario where different meters in the locality relay information to the nearest collector station (access points-APs) in their region. This involves municipality level deployment of Wi-Fi mesh network. The performance and range of Wi-Fi degrades in dense mesh environment and research is going on is this area. A Wi-Fi based remote meter reading application has been presented in [42].

Implementation of backhaul communication between the APs in multiple NANs to the central back-end database can also be done using Wi-Fi technology. These point-to-point and point-to-multipoint links can be used for monitoring, control and protection and metering of the dispersed distributed energy resources [43]. The constraints are the availability of high bandwidth Wi-Fi links supporting a considerable range. Wi-Fi devices are available for such purposes but the competition with other technologies like WiMAX, GSM and Optical Fiber is tough in this regard.

NIST has approved IEC 61850 standards for Substation Automation applications [1]. IEC 61850 supports Ethernet (LAN) based communication network for intelligence purposes on a Substation Environment [44–46]. Wi-Fi technologies which are inherently Wireless LAN Technologies are equally applicable for deploying substation automation schemes [43].

Security is implemented for Wi-Fi using WPA2 protocol. WPA2 is functionally supported for all the Wi-Fi enabled devices. WPA2 is based on 128 bit AES encryption technique and IEEE 802.11i security protocol for network access and authentication. A secure and privacy-preserving communication scheme for a Wi-Fi based AMI has been proposed in [47]. Paillier cryptosystem is utilized to ensure strong device authentication, data confidentiality and message integrity in the proposed scheme.

WLAN/Wi-Fi technology has found numerous applications in Smart Grid Environment while taking all the aspects into account. It is the most dominant wireless technology for the high speed Internet in indoor and outdoor environments and for entertainment purposes. It has the potential to play a strong role in enabling a complete HAN environment. The devices are cost effective and mostly plug and play in nature. Wi-Fi—Alliance has shown commitment towards the Smart Grid applications and devices like Wi-Fi enable thermostats, refrigerators and washing machines will soon be available for commercial purposes. Interference, reliability and availability of industrial grade WLAN/Wi-Fi equipment still remain some issues for WLAN or Wi-Fi technology.

3.4. IEEE-802.16 (WiMAX)

WiMAX, Worldwide Interoperability for Microwave Access is a communication technology developed under the IEEE 802.16 standards for Wireless Broadband. Among the family of IEEE 802.16 standards, the most used standard is the IEEE 802.16e 2005. The IEEE 802.16 specifies the Physical and MAC layer for the WiMAX technology. The Physical layer involves OFDMA with other features including MIMO based antenna systems used in order to provide the Non-Line of Sight capability. WiMAX technology uses two frequency bands, one for line-of-sight (11–66 GHz) and other for the non-line-of-sight operation (2–11 GHz). WiMAX involves Data Encryption Standard (DES) and AES encryption techniques for secure and reliable data communication [38,48,49]. These security mechanisms are implemented at the MAC layer. MAC layer also incorporates power saving techniques such as sleep mode, idle mode, etc. WiMAX is specifically designed for point-to-multipoint communications for both fixed and mobile applications; with data rates up to 70 Mbps over a distance of 50 km [50].

WiMAX is more seen as a backbone solution in Smart Grid environments. Its long communication range, inherent interoperable nature and ability to support high data rates and point-to-multipoint capability make it much likely to be used as a reliable back-end communication link. It can be further considered as a viable option for communication between the distributed energy resources at remote locations. Other than these options it can also serve as a redundant high data rate link at the backbone of the utilities.

WiMAX technology provides reliable, high data rate and automatic network connectivity along with low overall installation costs and large coverage area for the Smart Grid Applications. Optimization, Mobility Support, Harsh Monitoring Environments and Security are some areas in this technology which still need some attention [17].

A hybrid wireless communication system for power line monitoring in Smart Grid is proposed in [51]. The solution integrates the Wi-Fi and WiMAX technologies to support dual directional broadband communications. The WiMAX system modification for spectrum sensing and sharing with other systems is also proposed in this scheme.

Performance Analysis of WiMAX polling service for Smart Grid Meter Reading Applications has been shown in [52]. The analysis of different variables in WiMAX network designed to serve Smart Grid Applications is shown. It was revealed by the results that the polling services are able to support and fulfill the needs of metering application [52]. The size of the network affects the used capacity and the number of admitted smart meters that could be connected to the network. Further work is still required in this domain to improve the QoS related issue when using WiMAX form Smart Grid Applications.

The performance of Distribution Area Network (DAN) was monitored using WiMAX with uplink traffic in [53]. The smart metering capacity and the Quality of Service (QoS) of DAN using WiMAX technology is reported. From the obtained results, the authors suggest that the 4G technologies such as WiMAX and LTE are potential candidates for implementing the DAN in smart grids [53].

Unless deployed by the utilities themselves, which is a very expensive solution, WiMAX setup will be a third party communication link between the utilities and the consumers. The general development of WiMAX worldwide is to provide entertainment and communication links for the residential customers. With its high speed, high data rate communications it can easily support video, audio and internet services for the domestic users. On the other hand the deployment scenarios of the Smart Grid environment are totally different. This gives utilities less control over the communication infrastructure, for which they have many concerns.

3.5. GSM and GPRS

Global System for Mobile (GSM) is the most popular cellular network deployed all over the world. It is a circuit switched network and operates at 900 MHz and 1800 MHz. It uses Gaussian Minimum Shift keying (GMSK) as a modulation technique with data rates up to 270 kbps. Its architecture consists of four basic components i.e. Mobile handset, Base Station Subsystem, Network Switching Substation and Operation Support Substation. GSM is considered among the most secure communication networks.

General Packet Radio Service (GPRS) employs packet based transfer of data over the circuit switched GSM network. This allows it to run IP based network applications over the GSM network. The data rate is much larger as compared to the GSM. In Smart Grid applications mostly it is used for remote monitoring purposes. A remote monitoring of a substation via GPRS technology is proposed in [54] and GPRS based online power quality monitoring in [55,56].

GSM/GPRS has found numerous applications in HAN environment. Home Monitoring and Load Control can be easily done via GSM–GPRS technology. Load Control and Automation of devices is implemented in various areas. The domestic user always stays in touch with his home via his mobile phone. Apart from GSM–GPRS, SMS (Short Message Service) based alerts and control of devices can be done using this GSM technology.

GSM based smart meters have also found their way in the AMI infrastructure. Subscriber Identity Module (SIM) cards are embedded in the meters and the recorded data is relayed to the backend database via GPRS or SMS. Other than metering purposes, GSM based devices can also be used for Substation Automation and Protection purposes. These can be used to monitor distributed energy resources as well.

GSM has the advantage of being the worlds' most deployed communication technology after the fixed line telephone network. It is present in the remotest of locations which makes it a very strong competitor in Smart Grid applications. Some major issues are the amount of traffic and reliability of the SMS service in case of network congestion. It is always seen that the network performance degrades at peak traffic hours. Quality of Service (QoS) is a serious problem especially in cases where absolute reliability of communication is required such as Substation Protection, Remote Monitoring, etc. The utilities do not have direct control over the communication network as the network provider companies are in charge of the services.

3.6. DASH7

DASH7 is a new wireless sensor network technology using the ISO/IEC 18000-7 standard. It is named after a non-profit consortium promoting this technology known as DASH7 Alliance. It is developed for active Radio Frequency Identification Devices (RFIDs) operating at 433 MHz band. DASH7 enabled devices or sensor nodes are said to have typical range about 250 m which is extendable to 5 km with nominal and maximum data rates of 28 kbps and 200 kbps. These are considered to be low power devices with small sensor stacks resulting in long battery lives extending up to years [57].

DASH7 uses a wake up signal with very small amount of computation overhead to achieve low power and low latency. The average power consumption is around 30–60 μW and latency is around 2.5–5 s [57]. The communication signals are said to penetrate water and concrete, enabling the devices to be useful in numerous applications.

DASH7 has developed a concept of BLAST as a methodology for data transfer. The data is transferred in bursts of small packets in asynchronous manner [57]. DASH7 is transitional in nature, which makes DASH7 enabled devices easy to manage and the requirement of a central fixed base station is not there in a strict sense. DASH7 enabled devices also provide cost effective solution for long term deployment of sensor nodes [57]. The long battery life plays a key role in the cost effectiveness. The use of a single global frequency by the DASH7 enabled devices has simplified the deployment and maintenance issue thus allowing better interoperability opportunities [57].

DASH7 has found numerous applications in different sectors. Initially this technology was under US military and NATO use but recently, seeing its potential, it was made open for commercial applications like other communication technologies. The applications include Mobile Advertisement, Location based Services, Ticketing, Logistics, Building Automation, Access Control and Smart Energy.

Specifically for Smart Grid and Smart Energy applications, DASH7 seems to be a good alternative to ZigBee based solutions. Wider range for more coverage eliminates the multi-hoping technique for the DASH7 enabled devices for communication. In a Home Area Network (HAN) environment, one master node will suffice for proper coordination with the other devises as compared to ZigBee technology which uses multi-hoping techniques in the same environment. Less number of nodes and less time for communication will be a considerable advantage over ZigBee for HANs.

Taking the automated metering perspective, DASH7 can eliminate the mesh and in many cases makes it unnecessary because of its longer range as compared to the other wireless technologies which employee mesh networks for complete coverage. Plug-in Hybrid Electric Vehicles (PHEVs) are one of the latest introductions into the Smart Grid environment. Monitoring of PHEVs' parameters like tyre pressure, energy consumption and location of energy stations are some of the areas where DASH7 is currently under use. DASH7 is an acceptable ISO standard. ISO standards have more recognition as standards as compared to the IEEE based standards. This gives an added advantage to DASH7 enabled devices. DASH7 has rapidly moved its focus towards interoperability and compatibility with the existing standards, something of a low priority for the other communication technologies. Texas Instruments (TIs) devices working under the DASH7 specifications are recently available in the market with implementations and results are yet to arrive from an academic research environment.

4. Conclusion

The global trend is towards conservation of energy and discovering new energy resources. The depleting oil, coal and natural gas reserves have led the way towards developing smarter

Communication Technologies	Generation		Transmission			Distribution			Consumer			
	Conventional Generation	Distributed Renewable Energy based Generation	Transmission Line Monitoring and Protection	Insulator Monitoring	FACTs Monitoring and Control	Substation Automation and Protection	Distribution Line Monitoring and Protection	Equipment Monitoring and Protection	Home Automation and Control	Industrial Automation and Control	Automatic Metering Reading	PHEVs
Power Line Communication (PLC)	∞	∞	√	√	√	√	√	√	√	√	√	Δ
ZigBee	Δ	Δ	∞	∞	∞	Δ	Δ	Δ	√	√	√	Δ
WiFi	Δ	∞	Δ	∞	Δ	√	∞	√	√	√	√	Δ
WiMAX	Δ	Δ	Δ	∞	∞	Δ	∞	∞	∞	∞	Δ	∞
GSM and GPRS	√	√	√	Δ	√	√	√	√	√	√	√	√
DASH 7	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ

√ = In use, some mature solutions available
∞ = Not in currently in use, solutions can be developed
Δ = On-going Research, some solution available but under testing

Fig. 2. Penetration of Communication Technologies in Smart Grids.

equipment and sustainable technologies. Smart Energy Grid plays an important role in this effort and Communication Technologies are considered the backbone for its realization.

We have discussed some of the emerging technologies for Smart Energy Grid communications in this work. Some of the technologies are in their early stages with respect to Smart Grid applications and extensive work is going on in making reliable and sustainable solutions based on these technologies. The hybrid nature of the Smart Grid is given more preference in order to extract maximum benefits from all of the communication technologies.

The table shown in Fig. 2 summarizes the overall penetration of the communication technologies in the Smart Grid environment. It reveals the current status of these technologies for different smart grid applications. Moreover, it also indicates the available communication solutions and the ongoing research in these areas. The scenarios/applications which are considered for evaluation are from the four main components of a Power System/Network i.e. Power Generation, Power Transmission, Power Distribution and Consumer.

The conventional and non-conventional generation finds the penetration of GSM/GRPS technology for smart communications. Other technologies are finding it hard to penetrate this sector. It is mainly because of the robust nature of the solutions available using the GSM/GPRS communication technology. Although the standardization and interoperatibility issue are still prevailing, the smart information sharing from this end is mostly done using the GSM/GPRS. Technologies and standards like IEEE 802.11 (Wi-Fi) and IEEE 802.16 (WiMAX) have good potential and efforts are going on towards developing and maturing these standards for this domain.

Power Transmission Network along with the Power Distribution Network have more penetration of Power Line Communication (PLC) as a technology for smart information sharing. The solutions based on PLC are quite mature and considered among the oldest available. GSM/GPRS is the other most commonly used technology in this domain and poses a tough competition to the PLC based solution. In the ongoing deployments, GSM/GPRS has the edge especially in the power distribution sector over the PLC based solutions. IEEE 802.15.4 (ZigBee) based solutions are posing a serious challenge to the PLC and the GSM/GPRS based solutions as a lot of ongoing research for ZigBee based solutions is under way. IEEE 802.11 (WiFi) also finds its applications in this sector but the performance of ZigBee based devices as elaborated in [33–36] has shown the promising potential of IEEE 802.15.4 based solutions.

Most of the ongoing activity in the smart grid communication is currently in the Consumer domain. It would not be wrong to say that the focus is more towards the consumer applications since the last two decades. Power Line Communication, IEEE 802.11 (Wi-Fi), IEEE 802.15.4 (ZigBee) and GSM/GPRS based solutions are easily available for Home Automation and Automatic Metering Reading (AMR) purposes. The hot issue nowadays is to develop solutions for PHEVs which will soon be a major consumer of electricity. GSM/GPRS based solutions are currently available and research is underway for other technologies. IEEE 802.16 (WiMAX) is not very popular among researchers and therefore only AMR based activities are seen till now. IEEE 802.15.4 (ZigBee) finds the most positive response towards the home automation and the trend is changing from PLC and Wi-Fi based automation solutions to ZigBee base solutions. There are also interoperable ZigBee based nodes available which support Wi-Fi or GSM/GRPS along with ZigBee.

DASH7 is an upcoming technology and is considered to have a lot of benefits. This technology is under development for the commercial purposes but the earlier use in military communications was considered quite successful. It is therefore considered to be among the ideal technologies for Smart Grid communications on the consumer scale.

The standardization and interoperability issues are still there and international regulatory authorities (IEEE, The IET, NIST, ISO, etc.), people in academia and power utility companies such as EPRI, Siemens, ABB, BPL Global, General Electric, IBM, Iberdrola, etc. are making their best effort towards developing realizable, sustainable and acceptable standards and solutions worldwide. Smart devices have started to reach the consumer market but the interoperability and complete solution for Smart Grid Environment is still far away.

5. Glossary

- PLC: Power Line Communication
- CENELEC: European Committee for Electrotechnical Standardization
- ARIB: Association of Radio Industries and Businesses
- FCC: Fedral Communication Commission
- NIST: National Institute of Standards and Technology
- HAN: Home Area Networks
- AES: Advanced Encryption Standards
- PRIME: PoweRline Intelligent Metering Evolution
- DSSS: Direct Sequence Spread Spectrum
- AMI: Automatic Metering Infrastructure
- ISM Bands: Industrial Scientific and Medical (Radio) Bands
- ZSE Profile: ZigBee Smart Energy Profile
- WiMAX: Worldwide Interoperability for Microwave Access
- GSM: Global System for Mobile
- GPRS: General Packet Radio Service
- GMSK: Gaussian Minimum Shift Keying
- PHEVs: Plug-in Hybrid Electric Vehicles

- FFD: Full Function Device
- RFD: Reduced Function Device
- BLAST: Its a networking scheme/technology stands for Bursty Light ASynchronous Transitive
- IEC: International Electrotechnical Commission
- IEC 14908-3: Information technology – Control network protocol – Part 3: Power line channel specification
- IEC 14543-3-5: Information technology – Home electronic system (HES) architecture – Part 3–5: Media and media dependent layers – Powerline for network based control of HES Class 1
- IEC 61334-3-1: Distribution automation using distribution line carrier systems – Part 3-1: Mains signalling requirements – Frequency bands and output levels
- IEC 61334-5-4: Distribution automation using distribution line carrier systems – Part 5-4: Lower layer profiles – Multi-carrier modulation (MCM) profile
- CEA 600.31: Power Line Physical Layer and Medium Specification
- KNX: A standardized (EN 50090, ISO/IEC 14543), OSI-based network communications protocol for intelligent buildings
- DLMS: Device Language Message Specification (originally Distribution Line Message Specification
- LonWorks: LonWorks (local operation network) is a networking platform built on a protocol created by Echelon Corporation for networking devices over media such as twisted pair, powerlines, fiber optics, and RF.
- Insteon: Dual-band mesh home area networking topology employing AC-power lines and a radio-frequency (RF) protocol to communicate with devices designed by SmartLabs Inc.
- X10: International and open industry standard for communication among electronic devices used for home automation, also known as domotics. Uses power line wiring for signaling and control. Developed in 1975 by Pico Electronics
- HomePlug: Family name of various power line communication specifications which support networking over existing home electrical wiring
- IEEE 1901.2: Standard for Low Frequency (less than 500 kHz) Narrow Band Power Line Communications for Smart Grid Applications
- ITU-T: International Telecommunication Union (ITU)—Telecommunications (T)
- G.henm: G.hn is the common name for a home network technology family of standards developed under the International Telecommunication Union's Standardization arm (ITU) and promoted by the HomeGrid Forum and several other organizations. The G.hn specification defines networking over power lines, phone lines and coaxial cables with data rates up to 1 Gbit/s
- G3-PLC: Standard based on powerline communications specification promoting interoperability in smart grid implementations worldwide
- HD PLC: High Definition Power Line Communication
- SAE J2931TM: Protocol specifying vehicle to grid communication using PLC technique
- SAE J2847TM: Protocol specifying vehicle to grid communication using PLC technique
- SAE J2836TM: Protocol specifying vehicle to grid communication using PLC technique

References

[1] Von Dollen D. Report to NIST on the smart grid interoperability standards roadmap. EPRI, Contract No. SB1341-09-CN-0031 Deliverable 7; 2009.

[2] Galli S, Scaglione A, Wang Z. Power line communications and the smart grid. In: First IEEE international conference on smart grid communications (SmartGridComm). IEEE; 2010. p. 303–8.

[3] Benato R, Caldon R, Cesena F. Application of distribution line carrier-based protection to prevent DG islanding: an investigating procedure. In: IEEE Bologna power technology conference proceedings, vol. 3. IEEE; 2003. p. 7.

[4] Cataliotti A, Cosentino V, Di Cara D, Russotto P, Tine G. On the use of narrow band power line as communication technology for medium and low voltage smart grids. In: IEEE international instrumentation and measurement technology conference (I2MTC); 2012. p. 619–23.

[5] Shaver D. Narrowband PLC solutions for AMI achieve long distance communications and flexibility with immediate market impact. In: IEEE international conference on consumer electronics (ICCE). IEEE; 2011. p. 601–602.19.

[6] Park C-U, Lee J-J, Oh S-K, Bae J-M, Seo J-K. Study and field test of power line communication for an electric-vehicle charging system. In: Sixteenth IEEE international symposium on power line communications and its applications (ISPLC); 2012. p. 344–9.

[7] Pine N, Choe S. Modified multipath model for broadband mimo power line communications. In: Sixteenth IEEE international symposium on power line communications and its applications (ISPLC); 2012. p. 292–7.

[8] Plan P. Harmonize power line carrier standards for appliance communications in the home; 2010.

[9] Berganza I, Sendin A, Arriola J. Prime: powerline intelligent metering evolution. In: SmartGrids for distribution; 2008. IET-CIRED. CIRED Seminar, IET. p. 1–3.

[10] Lonfei Z, Zhai M. Modeling the noise in power line communications. In: 2010 international conference on multimedia technology (ICMT). IEEE. p. 1–3.

[11] Zimmermann M, Dostert K. Analysis and modeling of impulsive noise in broad-band powerline communications. IEEE Transactions on Electromagnetic Compatibility 2002;44:249–58.

[12] Meng H, Guan Y, Chen S. Modeling and analysis of noise effects on broadband power-line communications. IEEE Transactions on Power Delivery 2005;20:630–7.

[13] Guillet V, Lamarque G. Unified background noise model for power line communication. In: IEEE international symposium on power line communications (ISPLC) and its applications, 2010. IEEE. p. 131–6.

[14] Torio P, Sanchez M. Method to cancel impulsive noise from power line communication systems by processing the information in the idle carriers. IEEE Transactions on Power Delivery 2012;27:2421–2.

[15] Nassar M, Dabak A, Kim IH, Pande T, Evans B. Cyclostationary noise modeling in narrowband powerline communication for smart grid applications. In: IEEE international conference on acoustics, speech and signal processing (ICASSP); 2012. p. 3089–92.

[16] Bumiller G, Lampe L, Hrasnica H. Power line communication networks for large-scale control and automation systems. IEEE Communications Magazine 2010;48:106–13.

[17] Gungor V, Lambert F. A survey on communication networks for electric system automation. Computer Networks 2006;50:877–97.

[18] Alliance Z. ZigBee specification (document 053474r17). Luettu 2008;21:2010 Wwwdokumentti. Saatavissa: 〈http://www.zigbee.org/ZigBeeSpecificationDownloadRequest/tabid/311/Default.aspx〉.

[19] Yi P, Iwayemi A, Zhou C. Developing ZigBee deployment guideline under WiFi interference for smart grid applications. IEEE Transactions on Smart Grid 2011;2:110–20.

[20] Ullo S, Vaccaro A, Velotto G. The role of pervasive and cooperative sensor networks in smart grids communication. In: Fifteenth IEEE mediterranean electrotechnical conference on MELECON 2010–2010. IEEE. p. 443–7.

[21] Madani V, Vaccaro A, Villacci D, King R. Satellite based communication network for large scale power system applications. In: Bulk power system dynamics and control—VII. Revitalizing operational reliability, 2007 iREP symposium. p. 1–7.

[22] Egan D. The emergence of ZigBee in building automation and industrial control. Computing Control Engineering Journal 2005;16:14–9.

[23] Chen B, Wu M, Yao S, Binbin N. ZigBee technology and its application on wireless meter-reading system. In: IEEE international conference on industrial informatics. IEEE; 2006. p. 1257–60.

[24] Luan S, Teng J, Chan S, Hwang L. Development of an automatic reliability calculation system for advanced metering infrastructure. In: Eighth IEEE international conference on Industrial informatics (INDIN). IEEE; 2010. p. 342–7.

[25] Cao L, Tian J, Liu Y, Remote wireless automatic meter reading system based on wireless mesh networks and embedded technology. In: Fifth IEEE International Symposium on embedded computing, 2008. SEC'08. IEEE. p. 192–7.

[26] Kulatunga N, Navaratne S, Dole J, Liyanagedera C, Martin T. Hardware development for smart meter based innovations. In: Innovative smart grid technologies—Asia (ISGT Asia). IEEE; 2012. p. 1–5.

[27] Junhua X, Tingling W, Chao Y. The design of tiered pricing meter based on ZigBee wireless meter reading system. In: Third international conference on measuring technology and mechatronics automation (ICMTMA), vol. 3; 2011. p. 761–4.

[28] Xiong J, Wang T, Xu S. Design of intelligent tiered pricing meter based on ZigBee. In: International conference on advanced intelligence and awareness internet (AIAI 2010); 2010. p. 291–4.

[29] Batista N, Melicio R, Matias J, Catalao J. ZigBee standard in the creation of wireless networks for advanced metering infrastructures. In: Sixteenth IEEE mediterranean electrotechnical conference (MELECON); 2012. p. 220–3.

[30] Iwayemi A, Yi P, Liu P, Zhou C. A perfect power demonstration system. In: Innovative smart grid technologies (ISGT); 2010. p. 1–7.
[31] Byun J, Jeon B, Noh J, Kim Y, Park S. An intelligent self-adjusting sensor for smart home services based on zigbee communications. IEEE Transactions on Consumer Electronics 2012;58:794–802.
[32] Kang M-S, Ke Y-L, Li J-S. Implementation of smart loading monitoring and control system with zigbee wireless network. In: Sixth IEEE conference on industrial electronics and applications (ICIEA); 2011. p. 907–12.
[33] Hu Z, Geng X, Xiao J, Hu X. Research and realization of on-line monitoring system for high voltage circuit breaker based on ZigBee technology. In: IEEE international conference on control and automation, ICCA, 2009; 2009. p. 190–5.
[34] Long H, Zhang L, Pang J, Li C, Song T. Design of substation temperature monitoring system based on wireless sensor networks. In: Second international conference on advanced computer control (ICACC), vol. 1; 2010. p. 127–30.
[35] Wei C, Yang J, Zhu W, Lv J. A design of alarm system for substation perimeter based on laser fence and wireless communication. In: International conference on computer application and system modeling (ICCASM), vol. 3; 2010. p. 543–6.
[36] Juan L, Shaohua J, Yirong W, Hui W. Online insulation monitoring system of high-voltage capacitive substation equipment based on WSN. In: China international conference on electricity distribution (CICED); 2010. p. 1–6.
[37] Fouda M, Fadlullah Z, Kato N. Assessing attack threat against ZigBee based home area network for smart grid communications. In: International conference on computer engineering and systems (ICCES); 2010. p. 245–50.
[38] Akyildiz I, Wang X. A survey on wireless mesh networks. IEEE Communications Magazine 2005;43:S23–30.
[39] Yick J, Mukherjee B, Ghosal D. Wireless sensor network survey. Computer Networks 2008;52:2292–330.
[40] Ferro E, Potorti F. Bluetooth and Wi-Fi wireless protocols: a survey and a comparison. IEEE Wireless Communications 2005;12:12–26.
[41] Alliance W. Wi-Fi for the smart grid: mature, interoperable, secure technology for advanced smart energy management communications. Online: 〈http://www.wifi.org/knowledge〉 center overview.php?docid=4686; 2010.
[42] Li L, Xiaoguang H, Jian H, Ketai H. Design of new architecture of AMR system in smart grid. In: Sixth IEEE conference on industrial electronics and applications (ICIEA). IEEE; 2011. p. 2025–9.
[43] Parikh P, Kanabar M, Sidhu T. Opportunities and challenges of wireless communication technologies for smart grid applications. In: IEEE power and energy society general meeting. IEEE; 2010. p. 1–7.
[44] Andersson L, Brand K. The benefits of the coming standard IEC 61850 for communication in substations. In: Proceedings of southern African conference power system protection. p. 8–9.
[45] Baigent D, Adamiak M, Mackiewicz R, SISCO G. IEC 61850 communication networks and systems in substations: an overview for users. In: Proceedings of the VIII simposio iberoamericano sobre proteccion de sistemas electricos de potencia, Monterey, Mexico, Citeseer.
[46] Mackiewicz R. Overview of IEC 61850 and benefits. In: Power systems conference and exposition. PSCE'06. 2006 IEEE PES. IEEE; 2006. p. 623–30.
[47] Deng P, Yang L. A secure and privacy-preserving communication scheme for advanced metering infrastructure. In: Innovative smart grid technologies (ISGT), 2012 IEEE PES. p. 1–5.
[48] Akyildiz I, Wang X, Wang W. Wireless mesh networks: a survey. Computer Networks 2005;47:445–87.
[49] So-In C, Jain R, Tamimi A. Scheduling in IEEE 802.16e mobile WiMAX networks: key issues and a survey. IEEE Journal on Selected Areas in Communications 2009;27:156–71.
[50] WiMAX-Part M. I: A technical overview and performance evaluation. In: WiMAX forum.
[51] Wang Q, Lin Y, Zhan H. A hybrid wireless system for power line monitoring. In: Innovative smart grid technologies—Asia (ISGT Asia). IEEE; 2012. p. 1–6.
[52] Castellanos G, Khan J. Performance analysis of WiMAX polling service for smart grid meter reading applications. In: IEEE Colombian communications conference (COLCOM); 2012. p. 1–6.
[53] Rengaraju P, Lung C-H, Srinivasan A. Communication requirements and analysis of distribution networks using WiMAX technology for smart grids. In: Eighth international wireless communications and mobile computing conference (IWCMC); 2012. p. 666–70.
[54] Kong L, Jin J, Cheng J. Introducing GPRS technology into remote monitoring system for prefabricated substations in china. In: Second international conference on mobile technology, applications and systems. IEEE; 2005. p. 6.
[55] Lee P, Lai L. A practical approach to wireless GPRS on-line power quality monitoring system. In: Power engineering society general meeting. IEEE; 2007. p. 1–7.
[56] Lee P, Lai L. A practical approach to wireless power quality, energy and facilities monitoring system. In: Power and energy society general meeting-conversion and delivery of electrical energy in the 21st century. IEEE; 2008. p. 1–3.
[57] Norair J. Introduction to dash7 technologies. Dash7 Alliance Low Power RF Technical Overview; 2009.