Opportunities and Challenges of Wireless Communication Technologies for Smart Grid Applications

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Abstract—**Two-way seamless communication is the key aspect of realizing the vision of smart grid. There are several standardized wired and wireless communication technologies available for various smart grid applications. With the recent growth in wireless communication, it can offer standardized technologies for wide area, metropolitan area, local area, and personal area networks. Moreover, wireless technologies not only offer significant benefits over wired, such as including low installation cost, rapid deployment, mobility, etc., but also more suitable for remote end applications. Several activities are going on to explore specific applications of these technologies in smart grid environment. This paper presents various smart grid applications achieved through standardized wireless communication technologies, e.g. IEEE 802.11 based wireless LAN, IEEE 802.16 based WiMAX, 3G/4G cellular, ZigBee based on IEEE 802.15, IEEE 802.20 based MobileFi, etc. Moreover, challenges related to each wireless communication technologies have been discussed in brief.**

Index Terms— **Automatic Metering Infrastructure (AMI), Distribution Automation Systems (DAS), Distributed Energy Resources (DERs), smart grid, Substation Automation Systems (SAS), wireless communication technologies.**

I. Introduction

SEVERAL engineering efforts have already been initiated to modernized the power grid, variously known as 'Smart Grid', 'IntelliGrid', 'GridWise', 'Modern Grid', etc. [1], [2]. According to [3], the term "Smart Grid" refers to a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage transmission network and the distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices.

Smart grid will be characterized by two-way flow of power in electrical network, and information in communication network. In the recent report on National Institute of Standard and Technology (NIST) framework and roadmap for smart grid interoperability standards [3], several wired and wireless communication technologies are identified for smart grid. Advanced wireless systems offer the benefits of inexpensive products, rapid deployment, low cost installations, widespread access, and mobile communications which wired technologies and even the older wireless technologies often cannot provide [4], [5]. However, in the past, wireless technologies had comparatively slow acceptance in power industries due to low data rates, interference related issues, security concerns, limited product availability, etc. Several activities have already been initiated to address the wireless technical issues, and identify suitable wireless technologies especially for smart grid [6]. In the latest Electric Power Research Institute (EPRI) report to NIST on the smart grid interoperability standards roadmap [7], one of the suggested prioritized actions is to address the "Communications Interference in Unlicensed Radio Spectrum". The success of this action would alleviate many issues related to wireless communication in unlicensed radio spectrum by providing a dedicated communication channels for the mission-critical inter-operations of the smart grid.

With these motivations from recent developments and ongoing activities, the efforts have been carried out in this work to present the various smart applications using standardized wireless communication technologies, e.g. IEEE 802.11 based wireless LAN, IEEE 802.16 based WiMAX, 3G/4G cellular, ZigBee based on IEEE 802.15, IEEE 802.20 based MobileFi, etc. Different applications of these wireless technologies have been identified considering the latest available data rates, distance coverage, and other important technology features in smart grid environment. Moreover, the potential issues related to each communication technology have also been highlighted in the paper. Section-II discusses the framework of smart grid, as well as challenges related to smart grid communication system. Basic details of each potential wireless technology, its application in the smart grid environment, and the challenges have been presented in Section-III. Finally, Section-IV summarizes the smart grid applications of all potential wireless technologies.

II. Communication System for Smart Grid

This section describes the communication framework of smart grid and challenges associated with it.

A. Smart Grid Framework

Using the conceptual model of smart grid proposed in [3], the smart grid framework of information exchange among the communication domains (represented as clouds) has been illustrated in Fig. 1. The lower layer domains related to electric power system are generation domain; transmission domain presented as regional Control Center (CC) and

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Substation Automation System (SAS); distribution domain is consist of Distribution Control Center (DCC) and Distribution Automation System (DAS); customer domain includes DER plant automation, and residential or industrial customer automation system. Higher regulatory layer domains include regional system operator, energy service provider, and power market. The figure shows the two-way communication interfaces among these lower and higher layer domains.

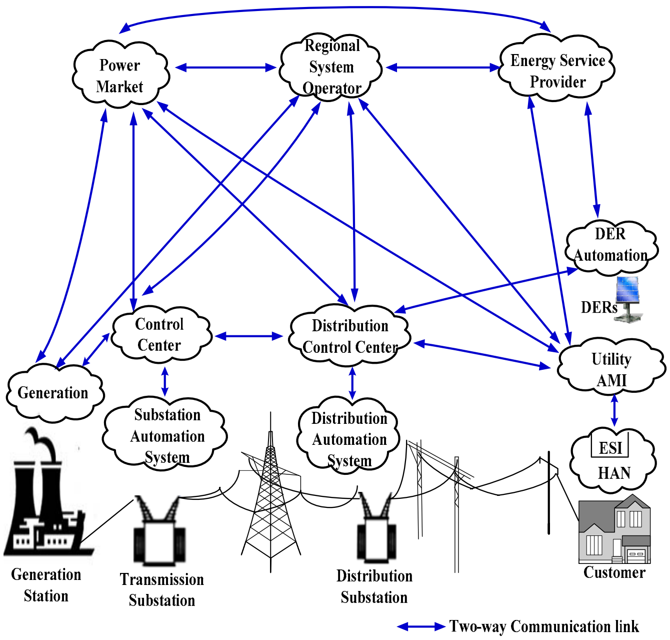

Fig. 1 Smart grid framework.

As shown in Fig.1, generation domain shares information with regional system operator, power market, and control center. In case of lack of generation or generator failure, immediate actions need to be taken by regional system operator and power market. Transmission domain is typically regulated by regional system operator with the help of information exchange with control center. Next generation transmission domain should be equipped with Wide Area Situation Awareness (WASA) system in conjunction with advanced Energy Management System (EMS) in the control center, and transmission substation automation system to maintain stability of the power grid. Future distribution domain should be set-up with Distribution Automation System (DAS); Voltage, Var, and Watt Control (VVWC) for DERs and PEVs; and Distribution Management System (DMS). Customer domain has Energy Services Interface (ESI) to interface with other domains via the AMI or another means, such as the Internet. ESI can be a local controller or customer's EMS [3]. The ESI communicates to devices and systems of customer's Home Area Network (HAN).

B. Major Challenges for Communication Systems in a Smart Grid

Communication systems refer to: 1) the communication media, and 2) the developing communication protocols. The smart grid communication systems must be robust enough to accommodate new media, as they emerge from the communication industries, while preserving interoperable and secured systems [3]. Major challenges related to smart grid communication systems are listed as follows:

1. Develop and/or identify interoperable communication protocols with standard semantic models for each domain of the smart grid, as well as, harmonize these communication protocols for inter-domain information exchange.
2. Identify suitable communication technologies for smart grid communication infrastructure.
3. Cyber security for intra-domain as well as inter-domain communication interfaces.

Several activities are going on to address this communication infrastructure related challenges [3]. The following section provides the identification of few specific smart grid applications using latest wireless communication technologies.

III. Wireless Communication Technologies for Smart Grid Applications

This section presents the opportunities and challenges with different wireless communication technologies for achieving various smart grid applications.

A. Wireless LAN

IEEE 802.11 based wireless LAN provides robust, high speed point-to-point and point-to-multipoint communication [8]. The spread spectrum technology was adopted in IEEE 802.11, because it allowed multiple users to occupy the same frequency band with a minimum interference to the other users [9]. IEEE 802.11 legacy standard proposes the standard for wireless Local Area Networks (LANs) covering three non-interoperable technologies: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and Infrared (IR) at 1 & 2 Mbps data rates. IEEE 802.11b, also known as Wi-Fi, offers a maximum data rate of 11mbps. It operates on 2.4GHz frequency band with DSSS modulation technique. Further, currently available technologies based on IEEE 802.11a and IEEE 802.11g can provide data rates up to 54 Mbps. IEEE 802.11a operated on 5.8GHz frequency band with Orthogonal Frequency Division Multiplexing (OFDM) modulation; whereas, 802.11g, also known as enhanced Wi-Fi, operates on 2.4 GHz frequency bands with DSSS modulation technique. IEEE 802.11n based on Multiple Input Multiple Output (MIMO) technology is intended to increase data rates further, up to 600 Mbps. IEEE 802.11i (known as WPA-2) enhances the cyber security in wireless LANs using Advanced Encryption Standard (AES) [10], [11]. Deployment of wireless LAN offers various benefits over wired LAN, as it is easy to install, provides mobility of devices, less expensive.

Wireless LAN for Smart Grid Applications:

Wireless LAN can be considered for various smart grid applications, such as distribution substation automation and protection, and monitoring and control of distributed energy resources, especially for remotely located small substation and DERs, where data rate requirements and radio interferences are comparatively less. NIST has recognized IEC 61850 standard for substation automation and protection applications in smart grid environment [3]. IEC 61850 standard has proposed Ethernet based communication networks to achieve interoperable substation automation systems (SAS) [12]. Wireless LAN technologies are also known as wireless Ethernet; and therefore, it can be considered for these applications.

1) Enhanced transformer differential protection:

Fig. 2 shows the IEC 61850 based wireless LAN to enhance the distribution substation protection and automation. A technical report from IEEE PSRC [9] has presented protection and control applications using spread spectrum radio, some of the reported intra-substation application includes, enhanced transformer differential protection, breaker failure, fast bus over current trip. This report proposes that Load Tap Changer (LTC) sensor with wireless feature can enhance transformer differential protection by online monitoring LTC position, as shown in Fig. 2. Similarly, Wireless LAN can also be used for monitoring switchyard equipments using sensors and actuators with wireless interface.

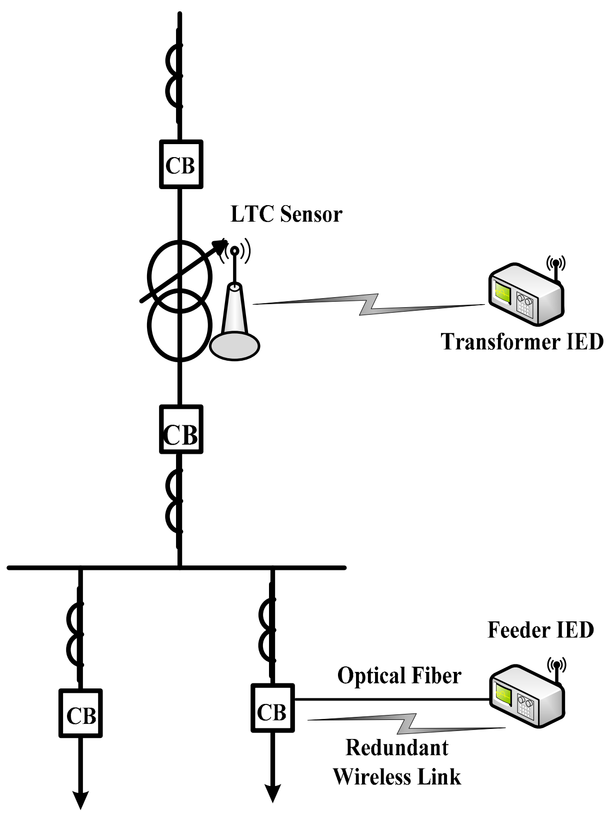

Fig. 2 Wireless LAN communication for distribution substation.

2) Redundant link for distribution automation system:

Wireless LAN can be used to provide redundant wireless link in parallel with optical fiber to enhance the reliability of critical operations, as show in Fig. 2. Reference [13] has presented wireless LAN applications for protection and control of IEC 61850 based medium-voltage substation by introducing e-breaker platform.

3) Communication aided line protection:

Fig. 3 shows the application of wireless LAN for inter-substation communication aided power line protection. In reference [14], authors have demonstrated the successful use of wireless LAN (Wi-Fi) for line differential protection applications in the laboratory environment. Using repeater between both the ends, the distance coverage can be enhanced; however, this would increase end-to-end delay.

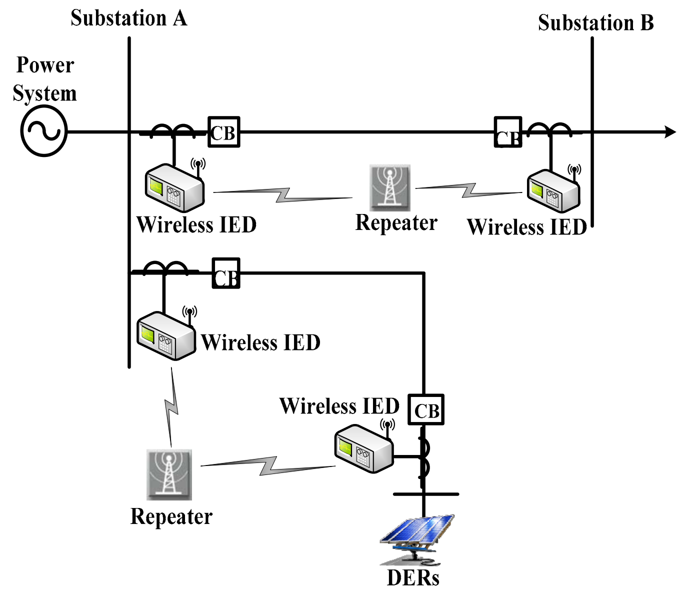

Fig. 3 Wireless LAN communication for inter-substation and DERs.

4) Control and monitoring of remote DERs:

Wireless LAN point-to-point link can be used between distribution automation system and distributed energy resources, as shown in Fig. 3. For rural area distribution system with more dispersed DERs, it is not economical to deploy fiber-optic communication. Hence, wireless communication technologies are more feasible. The protection, control, monitoring, and metering between DAS and DERs have been studied in reference [15].

Challenges and solutions of wireless LAN technology:

The challenges with wireless Ethernet technologies are: 1) reliability and availability of wireless signal is less comparatively; 2) Electro-magnetic interference in high voltage environment can slow down data transmissions; 3) Radio frequency interference from wireless equipment can affect the equipments functioning; 4) limited availability of industrial-hardened wireless LAN equipment.

High reliability and availability (>99.9% of time) of wireless communication can be achieved by applying proper path engineering and system design techniques [9]. Moreover, the proper implementation of message acknowledgement, error correction algorithms, data buffering enhances the reliability of message transmission over wireless medium. Recent developments in smart antenna, other techniques, e.g. waveguide, it is possible to develop wireless LAN equipment immune to EMI and RFI [13], [14]. With huge investment for smart grid applications, it is expected that more industry-strength wireless LAN equipment for high voltage environment will be proliferated in the market.

B. WiMAX

Worldwide inter-operability for Microwave Access (WiMAX) technology is a part of 802.16 series standards for Wireless Metropolitan Area Network (WMAN) [16]. Main objective of WiMAX is to achieve worldwide interoperability for microwave access. In 2001, when the first draft of IEEE 802.16 standard was released, it defined the wide operating range of 10-66GHz for communication infrastructure. WiMAX forum has published a subset of the range for interoperability. For fixed communication 3.5 and 5.8GHz bands have been dedicated, while for mobile communication frequency bands 2.3, 2.5 and 3.5 GHz have been assigned. The spectrums 2.3, 2.5, 3.5GHz are licensed; whereas 5.8GHz is unlicensed spectrum. It provides data rate up to 70Mbps and distance up to 48km [11]. However, distance and network speed are inversely proportional to each other. Licensed spectrums allow higher power and longer distance transmission, which is more suitable for long distance communication. The bandwidth and the range of WiMAX provide the alternative of cable, DSL and T1 communication channel for last-mile access.

WiMAX for smart grid applications:

1) Wireless Automatic Meter Reading (WMAR)

Large distance coverage and sufficiently high data rates make WiMAX technology more suitable for Wireless Automatic Meter Reading (WMAR) as a part of utility Automatic Metering Infrastructure (AMI). Fig. 4 shows the WAMR system based on WiMAX. Implementation of WAMR for revenue metering offers several advantages to electric utilities and/or service provider in the smart grid environment by reducing the need for human meter readers.

2) Real-time pricing

WiMAX network for AMI can be used to provide real-time pricing models based on real-time energy consumption of the customers. Real-time pricing capability of WAMR systems can also be beneficial to the customers by shifting their loads during off-peak times [17].

3) Outage Detection and Restoration:

Currently, distribution network has almost negligible outage detection mechanism especially for residential customers, which result into low reliability of power supply. With the help of two-way communication using WiMAX, fast outage detection and restoration can be implemented.

Challenges and solutions of WiMAX technology:

Radio frequency hardware for WiMAX tower is comparatively expensive, and therefore, the placement of WiMAX tower should be done optimally to reduce infrastructure costs and meet Quality of Service (QoS) requirements.

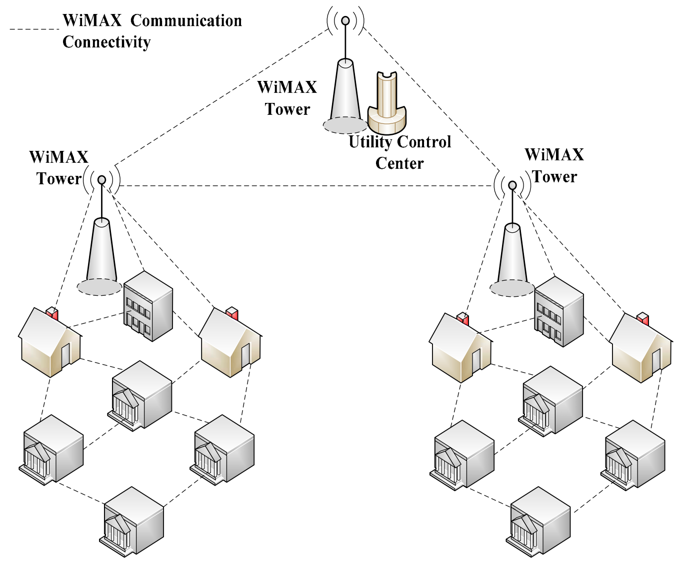

Fig. 4 WiMAX communication for WAMR.

Moreover, WiMAX frequency above 10 GHz cannot penetrate through obstacles; therefore, lower frequencies are the most practical for AMI applications especially in urban area. However, the lower frequency bands are already licensed, and hence, the most likely way of utilizing WiMAX is by leasing it from the third party.

C. Cellular

The 3G (3rd Generation) / 4G (4th Generation) cellular technology operates on the spectrum range of 824-894MHz/1900MHz [18]. These are the licensed frequency bands. Data transmission rate of this technology is 60-240Kbps, and distance converge is depend upon the availability of cellular service [11]. This cellular network topology consists of cells, which are formed by many low power wireless transmitters. With the moment of mobile devices having cellular modem, transmission of data is also exchanged between cell to cell, which facilitates non interrupted data flow. This way it forms a point to point architecture. It can also receives data from serial or Ethernet interface and transmit data on a second interface over cellular network, to enable normally wired components to become wireless. This technology offers extensive data coverage, no maintains costs and network fully maintained by carrier [19].

Cellular technology for smart grid applications:

The advantage with cellular technology is that the existing infrastructure can be used at some extent. Also, with the recent growth in 3G / 4G cellular technology, the data rate and Quality of Service (QoS) are improving very fast.

1) SCADA interface for remote distribution substation

Due to mobile phone users, cellular coverage is available even in very remote locations. Reference [20] has demonstrated use of Code Division Multiple Access (CDMA) technology for power system Supervisory Control And Data

Acquisition (SCADA), by providing cellular communication between substation Remote Terminal Unit (RTU) and SCADA server. Fig. 5 shows the application of cellular technology for SCADA interface of remote distribution substation site.

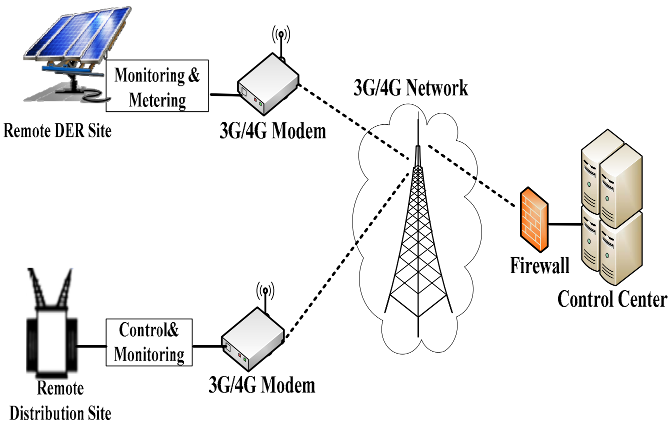

Fig. 5 Cellular technology for SCADA and power grid monitoring.

2) Monitoring and metering of remote DERs

As shown in Fig.5, the cellular technology can be used for monitoring and metering of remotely installed DERs. Non-critical information exchange can be carried out in the form of SMS, which is cheap solution comparatively. The monitoring application of remote substation using General Packet Radio Service (GPRS) technology is explained in [19], [21].

Challenges and solutions of cellular technology:

Call establishment takes indefinite time delay, and moreover, call dropout can affect the large data exchange. Due to high monthly fees for individual connection and expensive call costs, cellular technology may not be economical for larger group of remote sites or regular data transfer [11].

D. ZigBee

ZigBee is reliable, cost effective, and low power home area wireless network developed by ZigBee Alliance based on an open global standard. It provides compatibilities with IEEE 802.15.4 standard. ZigBee operates on the unlicensed frequency range of 868MHz, 915MHz and 2.4GHz with DSSS modulation technique. It offers a data rate of 20-250 Kbps. It provides coverage of 10-100m. ZigBee supports the star, tree and Mesh topologies. Transmission reach and battery life of the ZigBee devices vary depending upon the topology adopted. ZigBee employs 128-bit AES encryption for security [22].

ZigBee is widely used for building automation, security systems, remote control, remote meter reading and computer peripheral applications.

ZigBee technology for smart grid applications:

1) Control of home appliances

ZigBee is very suitable for Wireless Sensor Networks (WSN), due to low power consumption, low cost, and low data rate. Smart Home Area Network (HAN) can be formed using advanced ZigBee network consist of Full Function Node (FFN) and Reduced Function Node (RFN). Only the FFN has the full ZigBee functionality and hence, one of the FFN becomes a network coordinator. The RFN has limited resources and does not allow some advanced functions, e.g. routing, as it is a low cost end device solution. Fig. 6 shows the star configured ZigBee HAN for home appliances control.

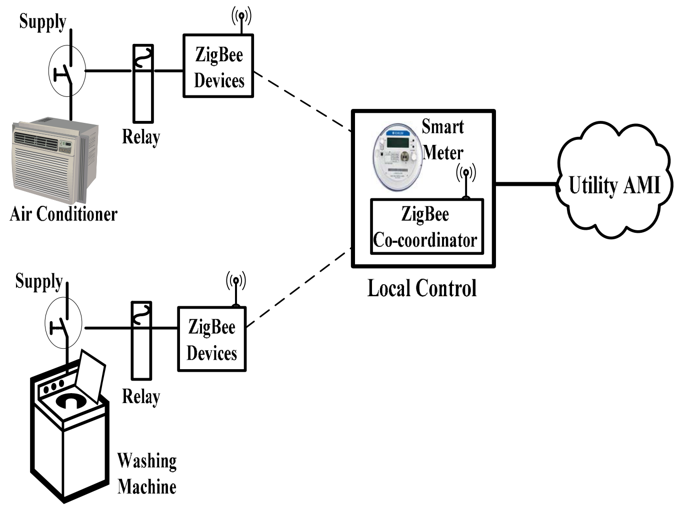

Fig. 6 ZigBee technology for smart home area network.

As illustrated in Fig. 6, ZigBee end devices are connected with relay which can control the power supply switch of home appliances. ZigBee coordinator manages the ZigBee network configuration, as well as, exchanges the information between each home appliances and local HAN control.

2) Direct load control

The local HAN can be automatically controlled locally with the help of controller or remotely using utility AMI infrastructure. References [23], [24] present implementation of direct load control for home appliances.

Challenges and solutions of ZigBee technology:

Due to limited physical size, ZigBee devices have limited battery energy supply, internal memory and processing capacity. The use of ZigBee in industrial environments is not well document [11], and hence this technology may be limited for residential automation system.

E. Other Potential Wireless Technologies

1) Mobile Broadband Wireless Access (MBWA):

IEEE 802.20 standard for MBWA provides high bandwidth, high mobility and low latency in the licensed frequency bands below 3.5 GHz, by utilizing the positive features of both IEEE 802.11 WLANs and IEEE 802.16 WMANs. It is also known as MobileFi. It offers real time peak data rate of 1Mbps to high speed data rate of 20Mbps. This standard is optimized for full mobility up to vehicular speed of 250km/h [25].

IEEE 802.20 may be used for smart grid applications, such as broadband communication for plug-in electric vehicles, wireless backhaul for electric grid monitoring and SCADA systems.

IEEE 802.20 (MBWA) is new emerging technology, and hence, communication infrastructures for this technology are not readily available. Currently, use of this technology may be costly solution compare to cellular technology.

2) Digital Microwave Technology:

Digital microwave operates on licensed frequency band of 2-40GHz, and provides the data rate up to 155Mbps. Microwave technology provides very long distance coverage up to 60 kilometers. It accepts data from Ethernet or ATM port and transmits it to the other as microwave radio.

Digital microwave can support point to point communication for smart grid applications, e.g. transfer trip between DER and distribution substation feeder protection relay.

Microwave radio is susceptible to two types of signal fading, precipitation and multi-path interference. Encryption for security may result in to additional latency as it takes larger message sizes [11].

3) Bluetooth

Bluetooth is part of wireless personal area network standard, IEEE 802.15.1. It is low power, short range radio frequency communication standard. It operates on 2.4–2.4835GHz unlicensed ISM band. It offers a data rate of 721Kbps [22]. Devices with Bluetooth configuration consist of complete OSI 7 layer communication stack. It can facilitate both point to point, and point to multipoint communication configuration. Depending upon the communication configuration it offers distance coverage between 1m – 100m.

Bluetooth technology can be used for local online monitoring applications as a part of substation automation systems [26].

These devices are highly influenced by surrounding communication link and may interfere with IEEE 802.11 based wireless LAN network. The Bluetooth offers weak security compare to other standards.

VI. Conclusion

In the first part of the paper, framework of smart grid and challenges related to wireless communication infrastructure of the smart gird have been presented. The potential smart grid applications for wireless LAN, WiMAX, ZigBee, 3G/4G cellular, MobileFi, digital microwave, Bluetooth discussed in this paper, have been tabulated as follows.

Wireless Technology	Data Rate	Approx. Coverage	Potential Smart Grid Applications
Wireless LAN	1-54Mbps	100m	distribution protection and automation
WiMAX	70Mbps	48Km	Wireless Automatic Meter Reading (WMAR)
Cellular	60-240Kbps	10-50km	SCADA and monitoring for remote distribution
ZigBee	20-250Kbps	10-100m	Direct load control of home appliances
MobileFi	20Mbps	Vehicular Std.	communication for PEVs and remote monitoring
Digital Microwave	155Mbps	60 km	transfer trip (point-to-point)
Bluetooth	721Kbps	1-100m	local online monitoring applications

Implementation of wireless technology offers many advantages over wired, e.g. low installation cost, mobility, remote location coverage, rapid installation, etc. However, each technology has certain challenges, as discussed in the paper, which need to be address for its future use in smart grid environment. Few common concerns for wireless technologies are: 1) wireless technologies operating in unlicensed frequency spectrum are more susceptible to interference/noise effects; 2) wireless technologies with licensed spectrum has less interference, but they are costly solution comparatively; 3) security of wireless media is less inherently. Several activities to address these major challenges have already been initiated. If FCC will provide an unlicensed wireless frequency band dedicated for smart grid, issues related to interference and cost of licensed frequency band will be alleviated. Moreover, developments in wireless security standard may allow realization of many mission-critical smart grid applications using wireless communication technologies.

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V. BIOGRAPHIES

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