# Chapter - 3

# COMMUNICATION INFRASTRUCTURE OF SMART GRID TECHNOLOGY

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# COMMUNICATION INFRASTRUCTURE OF SMART GRID TECHNOLOGY

This chapter describes an introduction of Smart grid and Microgrid technologies. A comparison between existing passive grid and Smart grid is also presented to understand the features of Smart grid technology. A comparison between wired and wireless communication is also illustrated. Moreover, various hierarchical layers and a complete communication infrastructure of Smart grid are also included in this chapter. The further part of this chapter includes comparative analysis of various wireless communication standards for application in various network layers of Smart grid.

## 3.1. INTRODUCTION TO SMART GRID TECHNOLOGY

A grid carries an electricity from power generation unit to consumer premises. The grid can be termed as ''Smart'' if it is capable of taking decisions with its computational proficiencies. These proficiencies are essential for optimization and reliable operation of Smart grid. Energy efficiency, power quality, fault diagnosis, self-healing, economy, security, sustainability and reliability are the most crucial features of electrical energy. An existing power grid is going through a drastic and massive revolution through design and deployment of Smart grid technology. Smart grid is the most innovative, ingenious and radical technology of present era. An existing grid is passive in terms of information exchange, security, fault diagnosis and self-healing. Smart grid is an integration of communication infrastructure with existing power grid [7-10]. Smart grid can be characterized by full duplex communication, integration of renewable energy resources, advanced metering infrastructure, real time monitoring and control, distribution automation, active involvement of consumers, sensing and measurement of various parameters, reliable and consistent electricity etc. Transmission and distribution losses existing in primitive grid can be eliminated by deployment of Smart grid. Key benefits of Smart grid can be summarized as follows.

- Improved power quality
- Energy efficiency
- Reduced carbon emissions
- Elimination of energy theft and pilferages

- Dynamic pricing
- Real time management
- Less dependence on scarce primary energy sources
- Reliability and consistency of power
- Rapid disaster recovery
- Consumer friendly smart devices for active involvement
- Asset management
- Minimization of losses
- Waste heat management
- Cloud based operation and management
- Greater transparency in billing and elimination of errors

Smart grid can be defined in terms of its technical, beneficial and functional aspect as: ‘’A power grid with an integration of electrical and communication infrastructure to facilitate advanced metering, real time monitoring and control, distributed generation, consumer participation, renewable power generation and distribution, distribution automation, storage, fault diagnosis and healing, disaster recovery, device to device communication, IoT for grid management, reduced carbon emissions, EVs, PHEVs etc. in order to enhance reliability, security, safety and efficacy of generation, transmission, distribution and consumption of electric power supply.’’

From above definition, various technologies, characteristics, challenges and components are depicted in Fig.3.1.

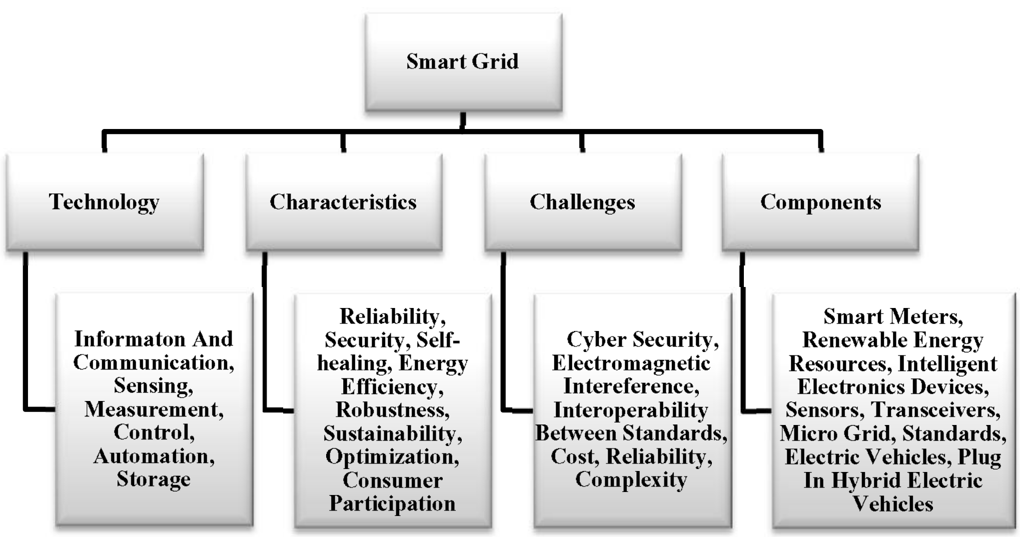


Fig.3.1. Technology, characteristics, components and challenges of Smart gird

A scalable, ubiquitous and persistent infrastructure is inevitable for operation and management of Smart grid technology [7]. Table 3.1 depicts the difference between present passive electrical grid and imminent Smart grid technology.

| **Existing Grid** | **Smart Grid** |
| --- | --- |
| Unidirectional communication | Bidirectional communication |
| Electromechanical | Digital |
| Restricted control | Scalable and Ubiquitous control |
| Centralized control | Distributed control |
| Very limited use of sensors and Intelligent Electronic Devices (IEDs) | Extensive use of wireless sensor network and Intelligent Electronic Devices (IEDs) |
| Physical monitoring, fault inspection and control | Self-healing, Remote management |
| Restricted use of renewable energy sources | Enormous use and assimilation of renewable energy sources |
| No consumer involvement in energy generation, usage and billing | Active involvement of consumers in energy generation, usage and billing cycles |
| Primitive metering | Advanced metering infrastructure |
| Failures and outages | Intelligent management of failures, outages and faults |
| Energy thefts and pilferages | Energy pilferages are not possible due to intelligent monitoring and close loop control |
| Less energy efficient | Exceedingly energy efficient |
| Vulnerable against failures and natural calamities | Robust, reliable and resilient to failures with self-healing and rapid restoration capabilities |
| Functionalities are limited up to energy generation, transmission, distribution and consumption | Facilitates various ingenious applications and advantages like IoT integration, Plug-in Hybrid Electric Vehicles (PHEVs), Vehicle to Grid technology, reduction of carbon foot print and Green House Gases (GHG) emissions |

Table 3.1. Comparison between existing passive power grid and Smart grid

The motive of Smart grid is an ''Always on'' information exchange between various components of power grid. Every stakeholder of Smart grid technology can actively participate in the decision making process. Electricity company is accountable for generation, transmission and distribution of power. Policy makers and researchers can contribute in technology upgradation and policy making process. Technology providers can be various Internet Service Providers (ISPs), telecom service providers, industries etc. Prosumers can decide the generation, usage and billing aspects. With the use of renewable energy resources, they can sell extra energy to grid [11]. Various stakeholders of Smart grid are depicted in Fig.3.2.

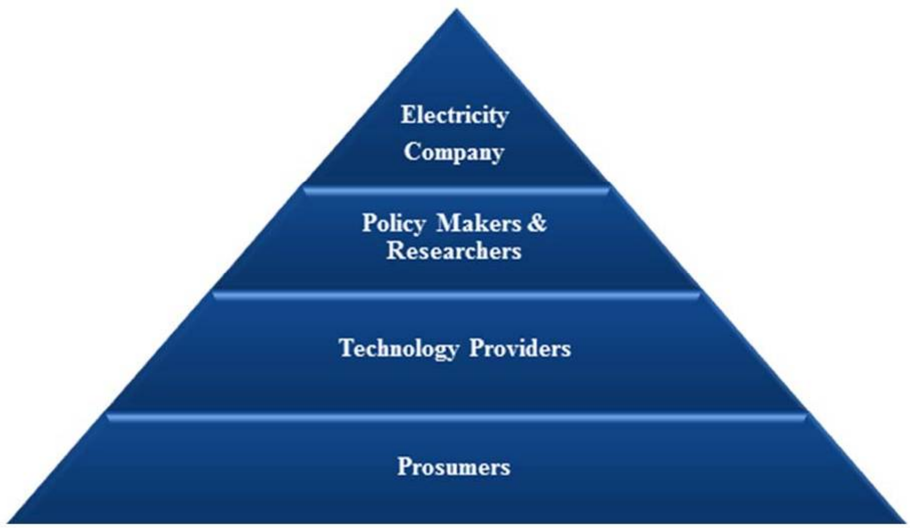


Fig.3.2. Various stakeholders of Smart grid technology

## 3.2. SMART MICROGRID

Smart grid technology is intelligent in terms of automation and control. Apart from these brainy features, clean and green energy generation is the most striking facet of Smart grid technology. Reduction of carbon emissions through distributed generation using renewable energy resources is the focal purpose of Microgrid [11]. Energy generation and distribution can be facilitated through local distribution companies or operators. Microgrid is the most promising component of Smart grid technology as it leads towards green energy system. It is a novel approach to overcome various challenges such as aging of power plants, GHG emissions, non dispatchable and unreliable nature of renewable energy resources and unelectrified villages.

Consumers can participate in the process of energy generation and also sell the extra power back to grid to earn a waiver in their energy utilization metering and billing. Thus

Smart microgrid is technically, environmentally and economically beneficial for all the stakeholders. A Microgrid can be categorized as AC Microgrid or DC microgrid. DC microgrid is considered in this thesis for prototype development. Power conversions can be avoided if DC load is used with renewable energy resources [11, 16]. Microgrid can be defined as a low voltage generation, transmission and distribution system comprising of various renewable and alternative energy resources such as solar, wind, hydro, fuel cell, geothermal etc. and storage devices such as capacitor, battery and flywheel with an ability to function in both grid connected and island mode. Combined Heat and Power generation and utilization is the most efficient feature of Microgrid as it prevents the wastage of heat generated during electricity generation. Micro power generation using renewable energy resources is the most promising solution against scarcity of primary energy sources. Smart microgrid is an assimilation of grid supply, renewable energy sources, storage and communication technologies for effective management of energy generation, transmission and distribution. Various wired as well as wireless communication standards can be applicable for real time management of distributed generation, transmission and energy distribution. Moreover, it is inevitable to exchange the information with central controller. Wired communication technologies provide robust infrastructure with interference avoidance. On the other hand, wireless technologies provide rapid deployment in remote location where there is no pre-existence of wired technologies [12]. Local power generators, electricity and heat loads, storage devices, EVs, PHEVs, Smart meters etc. are the various components of Smart microgrid [13].

Quality and reliability of power supply is a crucial aspect to be considered while switching between grid connected and island modes. In grid connected mode, microgrid is connected at the point of common coupling. Point of common is significant where multiple electrical loads are to be served. In island mode, microgrid functions independently of main grid and thus point of common coupling is not required. Microgrid can also function independently as isolated microgrid. This type of microgrid is called isolated microgrid which is generally located in remote area where integration with main grid is not feasible due to technical or economic issues. According to IEEE standard 519, point of common coupling is accessible to both utility and consumer for direct measurement purpose. Both AC and DC load can be served with Microgrid. Transmission of AC power is easier than DC supply.

Microgrid has unlocked the possibility of various renewable energy resources supplying DC power. AC power from the grid can be utilized for AC loads and DC power from renewable energy resources such as Solar PV can be used for DC load such as lightning for economical operation of Smart microgrid as DC to AC conversion is complicated, expensive and inefficient [14, 15]. DC to DC regulation and conversion is cost effective and efficient. Moreover, with an advancement in power electronics, various high efficiency power converters using solid state devices are also existing for conversion [15]. Fig.3.3. shows the various components of Smart microgrid system.

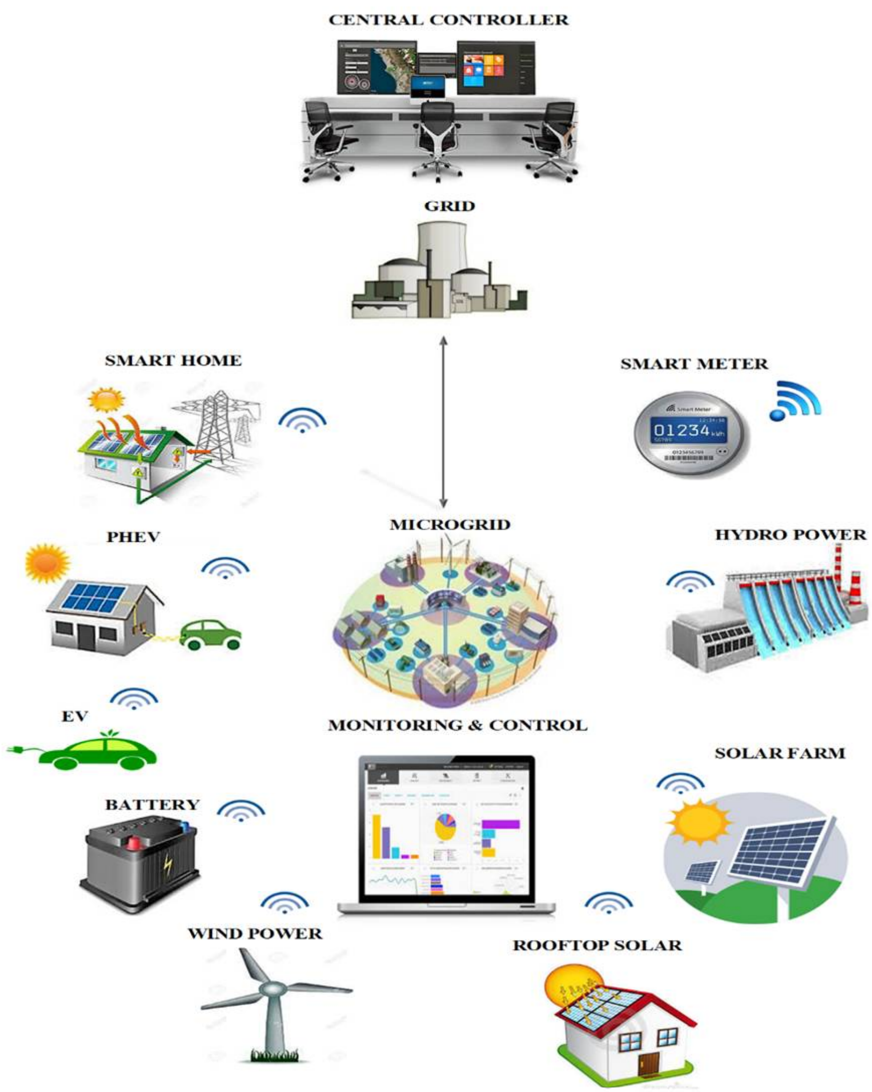


Fig.3.3. Various components of Smart Microgrid

Evolution of Smart grid technology has fostered the use of renewable energy resources. Rooftop solar systems and solar farm are the promising technologies for distributed energy generation. Integration of Smart grid technology with solar PV system is beneficial in terms of flexibility of generation and distribution, reduced complexity, reduced transmission loss and zero emissions. Solar rooftop system is advantageous in terms of active consumer participation as domestic and commercial consumers can take part in the process of generation. An extra energy can be sold back to grid to earn credits. Smart grid facilitates real time monitoring and management of energy usage statistics. Consumers can opt for energy usage depending upon dynamic prices. ICT integration will help overcoming the challenges related with intermittent nature of renewable energy resources. Moreover, Solar farm is also one of the prominent option for distributed generation in microgrid. Solar farm are used to generate the energy on larger scale. However, the technical challenges increases with the deployment of distributed energy resources but the communication infrastructure facilitates real time monitoring, diagnosis and control of faults and technical concerns. ICT makes the troubleshooting easier and faster with remote monitoring and management.

Integration of renewable energy resources with distributed generation necessitates a pervasive communication infrastructure for real time monitoring and control as well as reliable and secured operation.

A continuous monitoring of various energy resources facilitates switching of load on consistent energy source when output levels of other sources are below certain threshold. Furthermore, power dispatch strategy in microgrid is different from conventional power grid delivery as the renewable sources of power generation are distributed, inconsistent and unpredictable [16]. A close loop monitoring and control of Smart microgrid on the basis of real time information is a critical and challenging design aspect of Smart microgrid infrastructure.

## 3.3. SMART GRID COMMUNICATION INFRASTRUCTURE

The communication infrastructure of Smart grid is a complex network comprising of hierarchical and heterogeneous networks. Data acquisition for monitoring and control requires diverse set of communication standards based on various applications. Wired as well as wireless communication standards can be used for Smart grid communications [17].

Smart grid communication architecture can be designed and optimized on the basis of three network layers based on bandwidth requirement, coverage area and application. These three network layers can be categorized as HAN, NAN and WAN.

These layers are interconnected for real time monitoring, control, diagnosis and management of entire grid [18]. Each network requires an optimization of specific set of communication standards. Layered architecture supports various applications such as sensing, measurement, smart metering, home automation, SCADA, IoT etc.

HAN covers home area monitoring, regulation, control and management. HAN is designed to facilitate an active participation of consumers. NAN is applicable for distributed generation and distribution automation. It monitors and regulates various HANs. WAN shelters HAN and NAN for monitoring and control of entire communication network. WAN is a gigantic network covering management of generation, transmission, distribution and utilization of entire grid. Smart grid data communication is characterized by intra-network and inter-network communications for operation and management of various components of grid.

Fig.3.4. shows the layered communication infrastructure of Smart grid with different hierarchical networks and components.

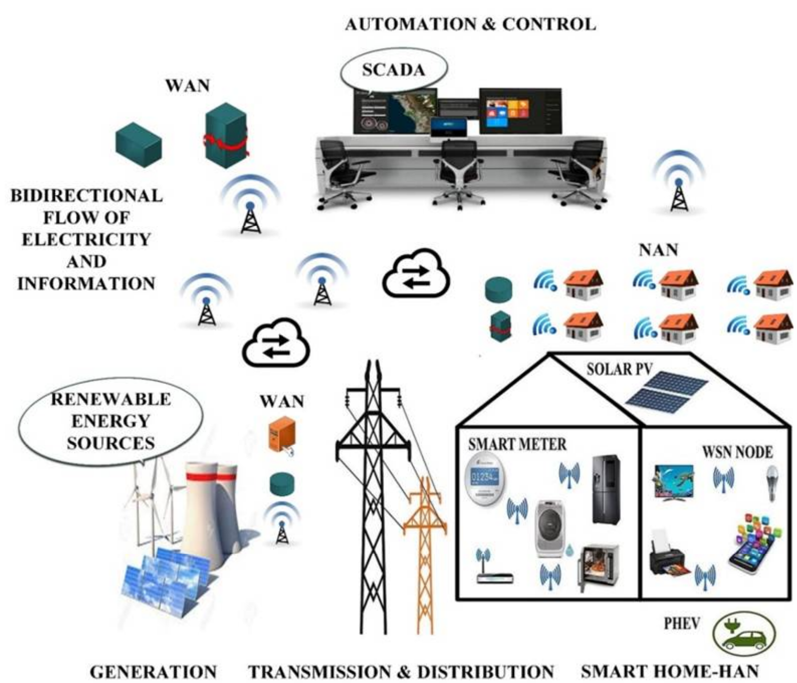


Fig.3.4. Layered Smart grid infrastructure

### 3.3.1. HAN

HAN is applicable for consumer premises. It contains various electronics appliances, Intelligent Electronics Devices (IEDs), sensors, smart meters, renewable energy sources, PHEVs etc. Consumers can actively participate in terms of generation, time of the day usage, billing and selling of extra power generated. Sensors and communication transceivers communicate the measured electricity parameters to smart meters for monitoring, billing and controlling purpose [19, 20]. Smart meters communicate these statistics to utility through intermediate central regulator, neighborhood area networks and wide area networks. WLAN, Zigbee, WirelessHART, 6LOWPAN, WiMAX, PLC etc. communication technologies are the suitable choices for HAN. The output of smart meter is connected to data aggregator. Data aggregator combines the outputs of HAN smart meters and communicates the data to WAN through meter data management system. Smart grid facilitates consumers to actively participate in the generation process by deployment of renewable energy sources. Consumer can sell an extra energy back to grid and earn credits. Fig.3.5. illustrates the connectivity as well as process of remote home area monitoring and control from central regulator.

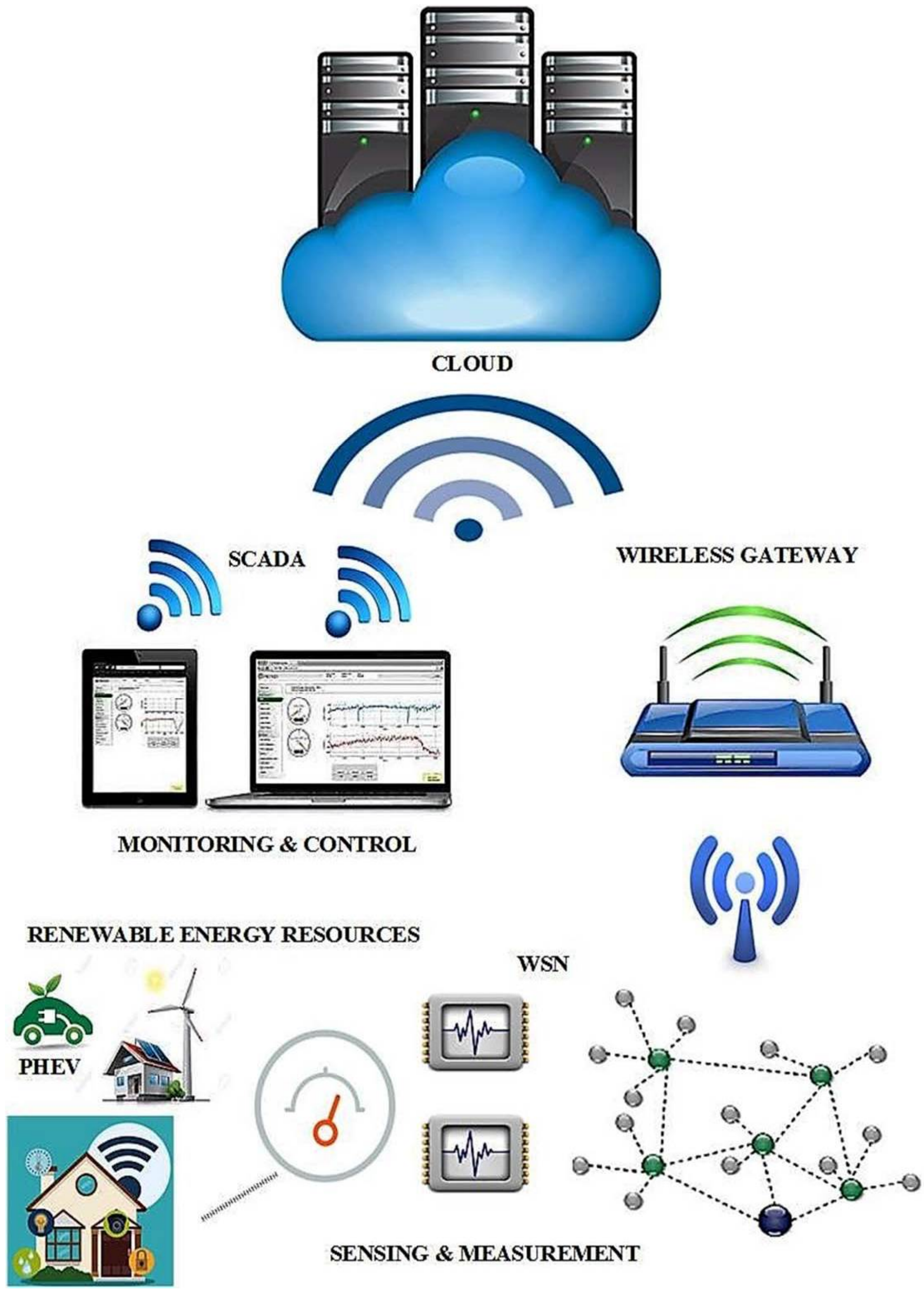


Fig.3.5. Home Area Network

Home area network gateways work as way in and way out terminal for NAN. Home area network facilitates demand side management through integration of appliances, sensors, transceivers, actuators, meter and renewable energy sources. HAN is also aimed to provide EV/PHEV charging facility to consumers. HAN is inevitable for active participation of consumers in energy consumption and usage. Advancement in IoT has facilitated cloud based management of HAN. Integration of renewable energy resources empowers consumers to generate an energy and sell an extra energy to grid to earn the credit. Consumers can also choose time of the day for energy usage based on dynamic energy price. HAN also supports utility to manage their peak energy demand. HAN facilitates energy saving and optimization. Potential blackouts can be avoided through energy optimization. Smart meters and central home regulator receive various commands from central grid for management of home appliances.

The requirement of data rates is around 100-250 Kbps for HAN applications. An area covered by HAN is in the range of few meters. IEEE 802.11, IEEE 802.15.1, IEEE 802.15.4, IEEE 802.16 etc. wireless standards can be used for HAN applications. As shown in the diagram, smart home contains various consumer electronics appliances and smart devices. Sensing and measurement of consumed energy is accomplished by sensor nodes. Transceivers communicate the collected data to Supervisory Control And Data Acquisition (SCADA) system through various wireless gateways. Wireless sensor network plays a pivotal role in HAN. A wireless sensor node mainly contains power supply, transceivers, memory, processor, actuator and sensors such as current, temperature, humidity etc. Wireless sensor network sends the collected data to central regulator. Central regulator is connected through IoT based network which facilitates remote operation, monitoring, fault diagnosis, dynamic energy prices and billing cycle, consumer participation etc.

**Smart meter and AMI**

Smart meter is a measurement module which conveys real time energy usage statistics to both consumer as well as utility with full duplex communication. Smart meter is a core module of Advanced Metering Infrastructure (AMI). AMI is an integration of sensors, smart meters, communication transceivers, network devices etc. to facilitate full duplex communication between consumer premises and utilities. AMI is meant for communicating an overall statistics of energy utilization of HAN [19].

AMI facilitates consumers and utility with energy usage statistics, time of the day prices, grid health conditions, operation, planning, dispatch, metering, maintenance, analysis, purchasing and selling of power, billing, demand side management etc. This information is beneficial to maintain power quality and for cost optimization.

AMI reduces the operational and financial burden on utilities through better energy management and theft prevention. Consumers can have a control on their energy usage pattern and billing. Thus, AMI has entirely changed the dynamics of energy consumption [20]. Various metering data like gas, water, temperature, electricity etc. can be communicated by means of Smart meter. AMI keeps consumers well informed about their energy usage and dynamic pricing.

Smart meters collects readings of energy, water and gas consumption and communicates this data to utility through intermediate NAN. Various real time information such as time of the day prices and usage statistics are conveyed to consumer by utility through smart meters.

Fig.3.6. shows the various components of AMI based on EPRI guidelines.


Fig.3.6. Components of AMI

Communication network includes various transceivers working on heterogeneous communication standards for different hierarchical network layers. Meter data acquisition

It consists of data concentrator units and firmware. Meter data management system is meant for analysis and storage of congregated data.

### 3.3.2. NAN

NAN facilitates the connectivity between HAN and WAN. The data collected by smart meters is communicated to utilities for monitoring, control and billing purposes through NAN. It is a group of various HANs. Thus, NAN contains several smart meters and gateways to route the information to control center belong to WAN. The bandwidth requirement and coverage area of NAN is higher than HAN [21]. The requirement of data throughput is in terms of Mbps. Neighborhood area network covers an area of few Kilometers. Various standards like IEEE 802.11, IEEE 802.3, IEEE 802.16, GSM, CDMA, 4G, 5G, PRIME PLC, G3 PLC etc. can be used for an implementation of NAN.

### 3.3.3. WAN

WAN is the largest and ubiquitous network layer of Smart grid communication network. WAN consists of several integrated neighborhood area networks. Data collected by NANs is to be forwarded to central controller through WAN.

Various information collection points are located at NAN gateways to forward the collected data to central grid monitoring and control center. The area covered by WAN is in terms of thousands of kilometers to facilitate a pervasive network coverage. The requirement of data throughput is in terms of Gbps. Cellular communication technologies such as LTE, 4G and 5G, IEEE 802.16, and fiber optics communication can be optimum adoptions for WAN [22]. WAN is implemented by Internet of Things as it connects different devices, meters and networks.

## 3.4. COMMUNICATION STANDARDS FOR SMART GRID APPLICATIONS

Smart grid is an assimilation of electrical and ICT infrastructure for real time data acquisition, monitoring, analysis, diagnosis and control. Smart grid communication infrastructure is a heterogeneous, hierarchical, multi-layered and multifaceted network comprising of diverse set of communication standards for innumerable applications [23-25]. Moreover, interoperability between varied set of standards is the most critical aspect of Smart grid design and deployment [24, 25]. Various wireless communication standards are required to cover an extensive span of Smart grid communication architecture [22-

26]. Powerline communication can also be used for various Smart grid applications [26]. Various communication standards are required for Smart metering, AMI, SCADA, home automation, data logging, disaster management, fault management, distribution automation, management of renewable energy resources etc. [24-26]. Fossil fuels are dominant in the transportation sector but environmental problems and fuel crisis have encouraged the design and development of electrical vehicles as an alternative transportation option. Development of Smart grid has accelerated the research, design and development of Electric Vehicles (EVs) and Plug in Hybrid electric vehicles (PHEVs). EVs completely depend on battery power while PHEVs are the combination of internal combustion engine running on gasoline or diesel as well as battery.

Moreover, PHEVs can be plugged in and charged through power outlets to cover an extended distance entirely on battery. Vehicle to grid technology is one of the prominent feature of Smart grid technology which facilitates communication between plug in electric vehicles and Smart grid communication infrastructure. Smart grid technology has paved the way for design of vehicle to grid technology which facilitates bidirectional exchange of energy between power grid and electrical vehicle. This exchange of energy is beneficial in terms of various applications such as spinning reserve, peak load shaving, regulation and reactive power compensation. A charging infrastructure will be provided to electric vehicles and the grid can also acquire energy from electric vehicle. An electric or hybrid electric vehicle can be informed regarding charging location through Smart grid communication infrastructure [23]. EVs and PHEVs are prominent features of Smart grid technology which require communication technology for transmission of statistics and receptions of commands [23, 25]. Various cellular wireless communication standards such as 5G, WiMAX, LTE, GSM etc. can be explored for design and implementation of vehicle to grid technology.

Different features of wired as well as wireless communication standards and technologies influence the choice of a specific standard for different applications of Smart grid.

Communication standards can be selected on the basis of various requirements such as data throughput, bandwidth requirement, coverage area, deployment cost and especially the category of application in Smart grid communication infrastructure. Table 3.2. depicts the comparison between wired and wireless communication.

| Characteristics | Wired Communication | Wireless Communication |
|---|---|---|
| Characteristics of medium | Various characteristics of wired channel such coaxial cable, fiber optics cable, copper cable remains consistent with respect to time. | Propagation characteristics of channel is time variant due to multipath fading and mobility of users. |
| Increasing channel capacity | Channel capacity can be increased by multiplexing techniques or adding resources. | Channel capacity can be increased by various modulation and multiplexing techniques or reduction in cell size in cellular concept as the spectrum space is limited. Cognitive radio technique can also be used for effective spectrum utilization. |
| Limiting factor in coverage area of communication | Interference, noise, attenuation, distortion etc. brings out a limitation on the range over which information can be communicated without repeater. | The range over which an information can be communicated is limited by fading, attenuation, signal distortion, absorption etc. |
| Bit Error Rate (BER) | If SNR is increased, BER decreases almost exponentially. i.e. An increase in transmitted power can reduce BER significantly. | Increment in transmitted power cannot reduce BER significantly. Signal processing is a better solution. |

| | | |
|---|---|---|
| Transmission quality | Quality of transmission is decent due to wired medium. | Enhanced quality of transmission requires special measures due to characteristics of wireless medium. |
| Power consumption | Power consumption is not a major issue for wired communication devices. | Power consumption and energy efficiency are major concerns for wireless equipment and devices. |
| Transmission delay | Transmission delay is time-invariant and determined by cable length and group delay of repeater amplifiers. | Transmission delay is time-variant and depends on distance between transmitter and receiver. |
| Interception and jamming | Interception and jamming are not possible in wired medium. | Interception and jamming may occur. |

Table 3.2. Comparison of wired and wireless communication

### 3.4.1. WIRELESS COMMUNICATION STANDARDS FOR SMART GRID APPLICATIONS

Smart power grid is a hierarchical network comprising of heterogeneous communication standards [27-33]. Interoperability between various standards is the most critical issue for realization of Smart grid communications [27-31].

Most of the standards used for short distance communications are based on ISM band. This section includes an illustration of various short distance and long distance wireless communication technologies.

#### 3.4.1.1. BLUETOOTH

Bluetooth is designed on the basis of IEEE 802.15.1 standard. It is a WPAN for short distance communication between various electronics devices. Bluetooth was primarily industrialized by Ericsson in 1994.

It supports point to point and point to multipoint communications [32]. Bluetooth functions in ISM band of 2.4 GHz. It is used for device to device communication.

Table 3.3. shows various technical specifications of Bluetooth. Advanced versions of Bluetooth such as 2.0 and 2.1 provides data throughput of 2.1 Mbps [32].

| **Bluetooth features/ characteristics** | **Technical specifications** |
|---|---|
| Frequency band | 2400 MHz to 2483.5 MHz, Industrial, Scientific and Medical band (ISM) |
| FHSS | 79 channels of 1 MHz each from 2402 to 2480 MHz |
| Modulation technique | Gaussian Frequency Shift Keying (GFSK) |
| Channel bandwidth | 1 MHz |
| Hops per second | 1600 |
| Frequency spectrum management | Dynamic |
| Symbol rate /Maximum transmission rate | 1 Mbps |
| Wired backbone network | IEEE 802.3-Ethernet or PPP |
| Authentication and encryption | 128 bit key |
| Maximum data throughput | 700 Kbps |
| Receiver sensitivity | -70 dBm for BER 0.1% |
| Power classes<br>1<br>2<br>3 | Range<br>100 mW-100 m<br>2.5 mW-10 m<br>1 mW- 1 m |

Table 3.3. Technical specifications of Bluetooth

Bluetooth is a very low power technology for short distance communication between various devices. Bluetooth protocol stack is shown in Fig.3.7. The functions of protocol stack are information exchange, device location and connection. Logically, it is divided in three main groups namely transport, middleware and application.

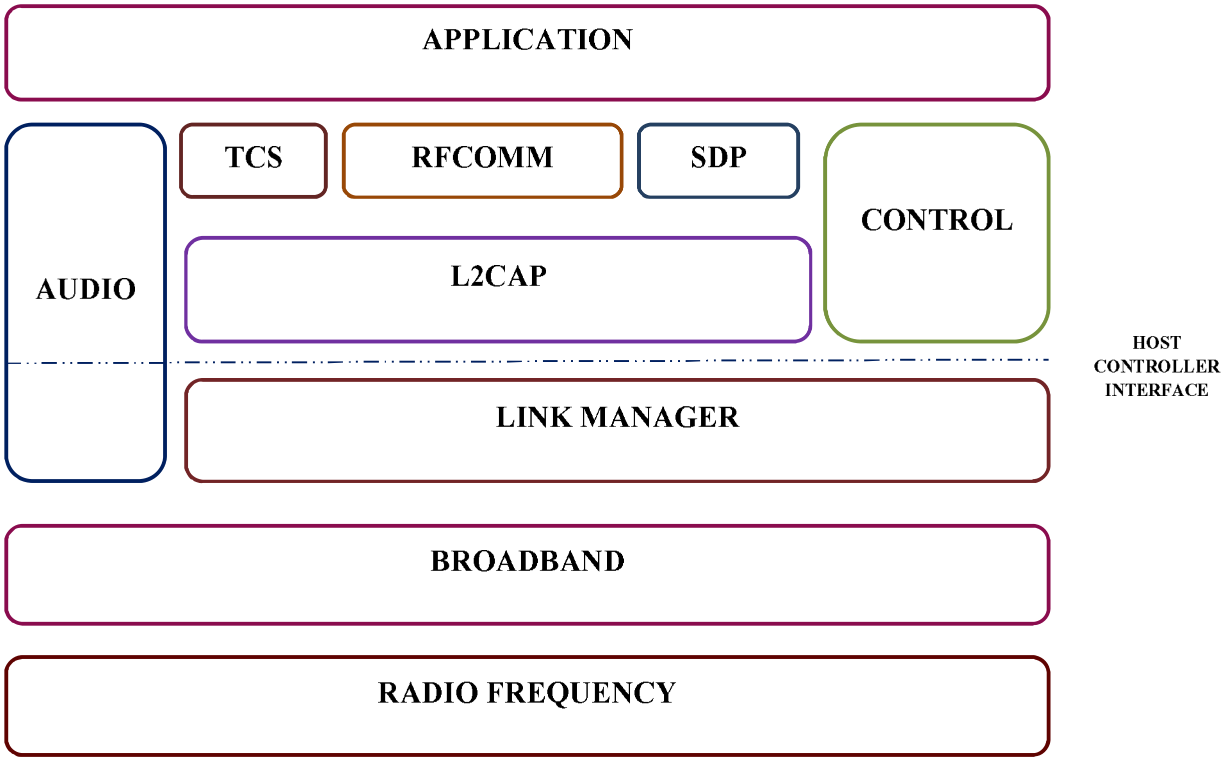


Fig.3.7. Bluetooth protocol stack

Various layers of protocol stack are described below.

**Transport Protocol Group**

This group includes various protocol divisions such as physical or radio, baseband, link manager, LLC and adaptation. This group facilitates various Bluetooth devices to locate each other, connect, configure and mange the wireless connections. The QoS of Bluetooth link is governed by LMP. L2CAP divids large packets into smaller packets and also governs QoS parameters such as latency, bandwidth, delay etc. Host controller interface provides an interface between higher and lower layers [32].

The connection is formed in terms of Piconet. Cluster of Piconets is termed as Scatternet. The device which initiates the comminication process is called master and the rest are called slaves. Group of piconet is called scatternet. Fig.3.8. shows the architecture of Piconet and Scatternet. The physical layer defines transciver design charateristics. The baseband layer deals with creation of frequency hops, medium access control and connection establishment.

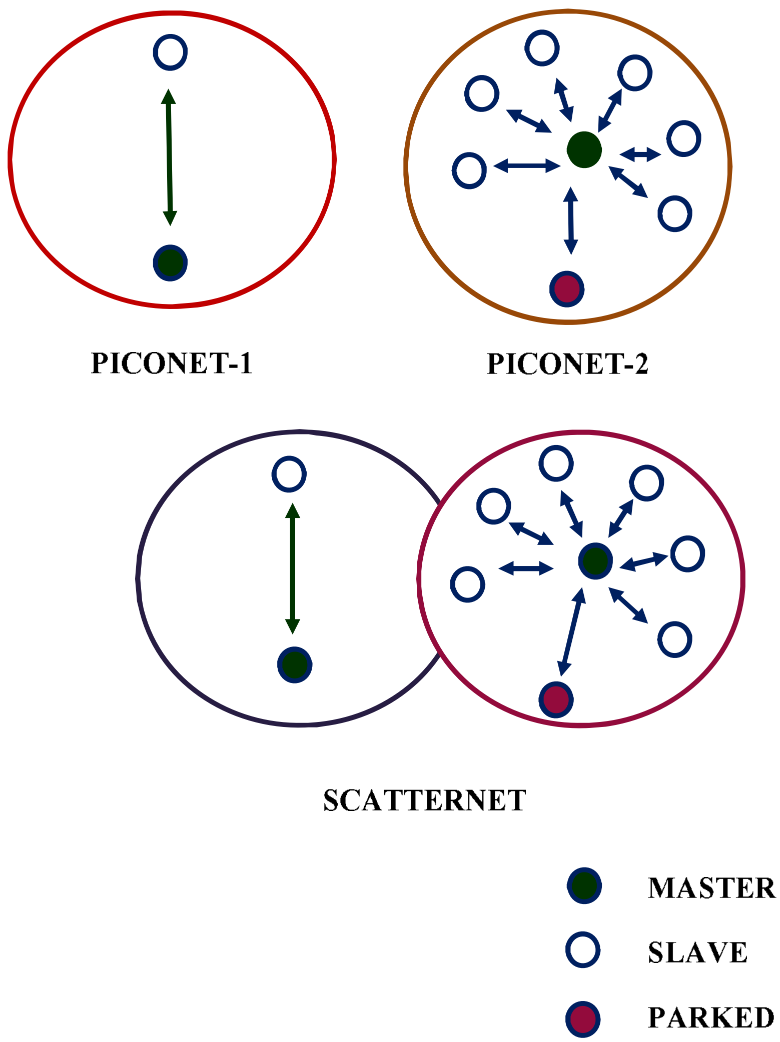


Fig.3.8. Piconet and Scatternet

**Middleware protocol group**

This protocol layer provides a standard interface for communication between transport and application layer. It consists of following layers.

- RFCOMM layer

  This layer facilitates virtual serial port to the applications which use serial connection.

- SDP

  Service Discovery Protocol facilitates the self-configured and automatic device discovery.

- IrDA

  It facilitates existing IrDA (Infrared) devices to work on Bluetooth.

- TCS

  Telephony Control Specification manages and controls calls which carry data and voice.

### 3.4.1.2. WIRELESSHART

WirelessHART technology is designed on the basis of IEEE 802.15.4 standard published in 2006 [34]. It supports various devices like mobile devices, routers, sensors, actuators, gateway devices etc. This protocol can be used for automation and control applications. Table.3.4 shows the various technical specifications of WirelessHART standard.

| **WirelessHART features/ characteristics** | **Technical features** |
| --- | --- |
| Frequency band | 2.4 GHz-ISM |
| Spread Spectrum technology | DSSS |
| Modulation scheme | O-QPSK |
| Transmitter Power | 10 dBm |
| Multiple access scheme | TDMA |
| Wired backbone network | Wired HART, IEEE 802.3-Ethernet |
| Authentication and encryption | AES 128 bit key |
| Data throughput | 250 Kbps |
| Coverage area | Approximately 200 meters |

Table 3.4. Technical specifications of WirelessHART standard

In WirelessHART protocol, communication takes place in time slots using TDMA. In TDMA, devices communicate by taking turns in time domain. Communication requirements and routing information are essential for scheduling.

Network manager governs the scheduling of communications. Network manager provides slots to each device for communication depending upon the requirement [35].

The function of network manager is to continuously adapt the graph and scheduling information based on various network topologies and communication necessities. Fig.3.9. shows the communication stack of WirelessHART standard.

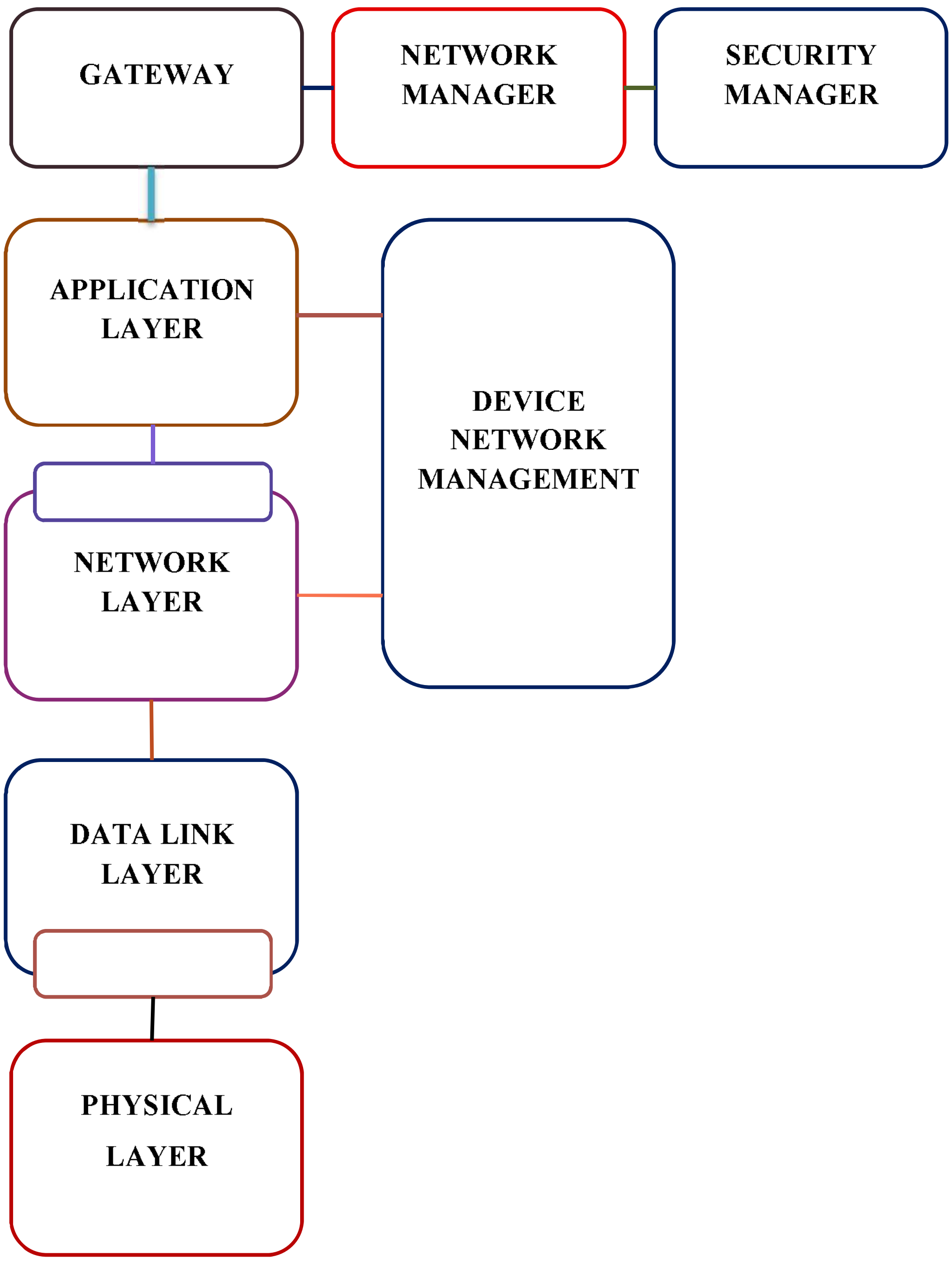


Fig.3.9. Communication stack of WirelessHART standard

Protocol stack of WirelessHART standard consist of various layers based on OSI reference architecture as described below.

**Physical layer**

This layer defines various transmission and reception characteristics such as antenna specifications, receiver sensitivity, power levels, data throughput, distances, signaling information etc.

The physical layer of WirelessHART is created on the basis of IEEE 802.15.4 standard. This technology functions on 2.4. GHz ISM band. The data rate is 250 Kbps and the modulation scheme used is DSSS.

**Data link layer**

This network layer is accountable for framing, establishment of data structure, time synchronization and packet formation. Data link layer facilitates the data transfer between various network nodes with error correction. TDMA is used with time slot of 10 ms.

This layer facilitates collision free trustworthy and secured communication. There are two sublayers of data link layer namely MAC and Logical Link Control LLC. MAC is accountable for the way in which communication channel is accessed by nodes and LLC deals with network layer service.

**Network layer**

In WirelessHART standard, network layer contains all three layers (Network, transport, session). Network layer is responsible for addressing, routing and data transmission. WirelessHART network includes,

- Field devices pertaining to plant progression
- WirelessHART enabled hand-held/portable devices for calibration, diagnosis and configuration of devices
- Network gateway for connecting host and field devices
- Network manager for network configuration, management and scheduling

**Transport layer**

The reliable data transmission is ensured by transport layer through segmentation, de-segmentation, error control and flow control.

**Session layer**

Session layer manages connections, communications and sessions between various WirelessHART nodes.

**Application layer**

In WirelessHART standard, commands and responses are inevitable for communication between gateway and devices. Commands, responses, data types etc. are defined by application layer. Commands are extracted and executed for response generation. Presentation layer is spun in application layer in this standard. Fig.3.10. shows the WirelessHART protocol stack.

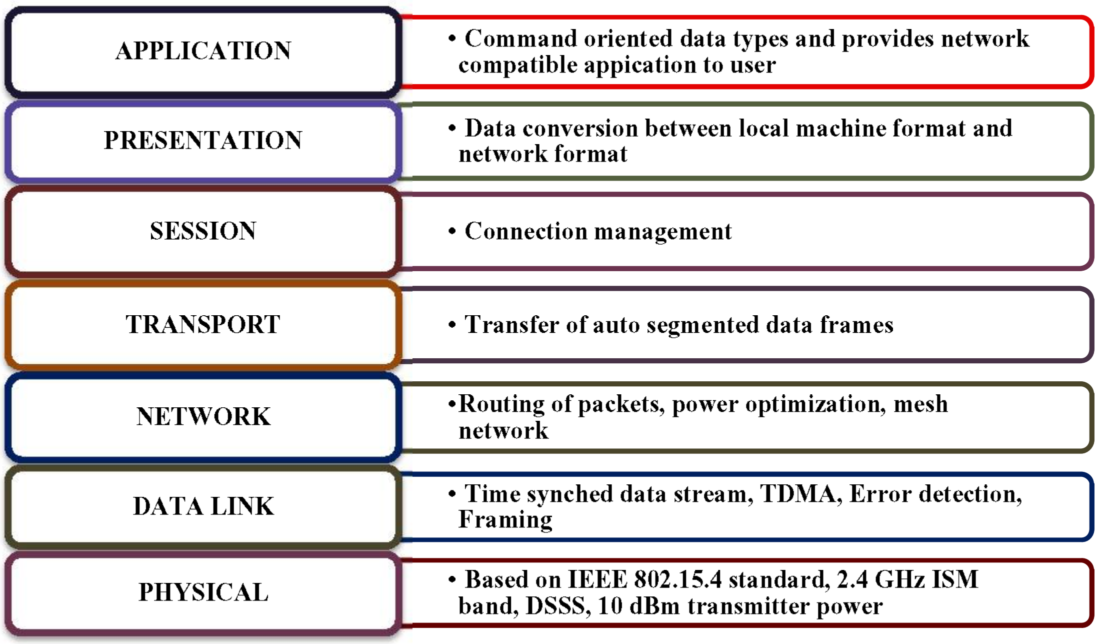


Fig.3.10. WirelessHART protocol stack

WirelessHART standard has evolved two novel network devices termed as an adapter and handheld device. In Wired HART network, adapter functions as a master and facilitates wireless communication in wired devices.

Handheld devices are used for maintenance, configuration and troubleshooting. WirelessHART is safeguarded, reliable, centralized and mesh network protocol for personal area communications [34, 35].

### 3.4.1.3. ZIGBEE

Zigbee technology is designed on the basis of IEEE 802.15.4. standard. It is a WPAN with low data rates. It operates on unlicensed band [27, 31]. This standard was developed by Zigbee alliance. The physical and media access layers are adopted from IEEE 802.15.4 standard and the other layers are demarcated by Zigbee alliance.

Zigbee is the most widely used personal area network [36]. Various technical specifications of Zigbee are listed in Table 3.5.

| Zigbee features/ characteristics | Technical specifications |
|---|---|
| Frequency band | 2.4 GHz, 868 MHz, 915 MHz |
| Spread Spectrum technology | DSSS |
| Modulation technique | BPSK, O-QPSK |
| Transmitter Power | -25 to 0 dBm |
| Multiple access scheme | DSSS |
| Wired backbone network | Ethernet |
| Authentication and encryption | CBC-MAC, AES |
| Data throughput | 20 to 250 Kbps |
| Coverage area | 10 to 100 meters |

Table 3.5. Technical specifications of Zigbee standard

Zigbee physical devices are categorized as RFDs and FFDs. FFDs can perform various functions such as sensing, PAN coordination and routing. RFDs are allied with FFDs and they do not possess routing capabilities [36].

Zigbee logical devices can be categorized as follows.

- **Coordinator**

Only FFD can work as a coordinator. The task of coordinator is to initiate the personal area network by selecting network parameters.

It is also responsible for storage of security keys and other network information. 16 bit PAN ID is assigned by the coordinator as soon as the network is initiated.

- **Router**

  An intermediate node in PAN is termed as router. It relays the information. It can accept the connections from network devices. Network expansion can be performed using routers.

- **End devices**

  End devices are low power battery operated devices. These devices receive sensor readings and communicate to either router or coordinator. They can be in sleep mode. Each end device can possess maximum 240 nodes sharing similar radio.

Fig.3.11. shows the protocol stack of Zigbee. The various layers are described as below.

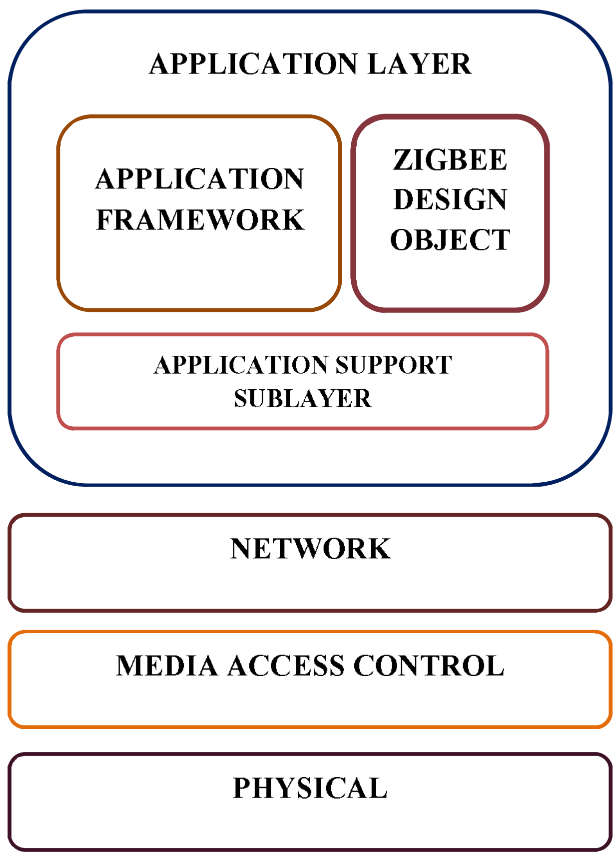


Fig.3.11. Zigbee protocol stack

**Physical Layer**

This layer is accountable for the transmission and reception of information. It performs various tasks such as link quality management, channel assignment, initialization of devices and power management. It provides 20 Kbps data rate in 868

MHz band, 40 Kbps data rate in 915 MHz band as well as 250 Kbps data rate in 2.4 GHz band.

**MAC Layer**

MAC layer is accountable for routing and scheduling of frames. Frame structures of acknowledgement, beacon, data and command frames are determined by MAC layer.

Association and dissociation functions are also performed by MAC layer. Implementation of CSMA-CA is done by MAC layer. Guaranteed time slot mechanism is governed by this layer.

**Network Layer**

An interface between MAC and application layer is provided by network layer. Network layer facilitates formation of network as well as routing of information. There are three topologies in Zigbee network namely tree, star and mesh. At this layer, the networks are discovered, initiated, connected and left.

**Application Layer**

Application layer is the uppermost layer of Zigbee protocol stack. It contains various sub layers.

- **Zigbee device object**

It is responsible for defining device functions such as coordinator, router or end device. It is also accountable for security, device discovery and binding.

- **Application object**

It is accountable for management of various protocol layers of Zigbee. A Zigbee device can support maximum 240 application objects. Application object is termed as a software meant to control the hardware.

- **Application support sub-layer**

This layer facilitates interfacing between network and application layer. This layer processes an entering and leaving frames for secured management of cryptographic keys.

In Zigbee network, star, mesh and tree topologies are supported. In star topologies, PAN coordinator functions as a master and the rest of the devices work as slaves. Slaves can be FFD or RFD. In mesh topology, all the devices communicate with each other. Mesh topology is complicated but fault tolerant. In tree topology, an expansion of the network takes place by more RFDs and FFDs connected together even if the FFD is not the PAN coordinator. Fig.3.12. shows the Zigbee network architecture.

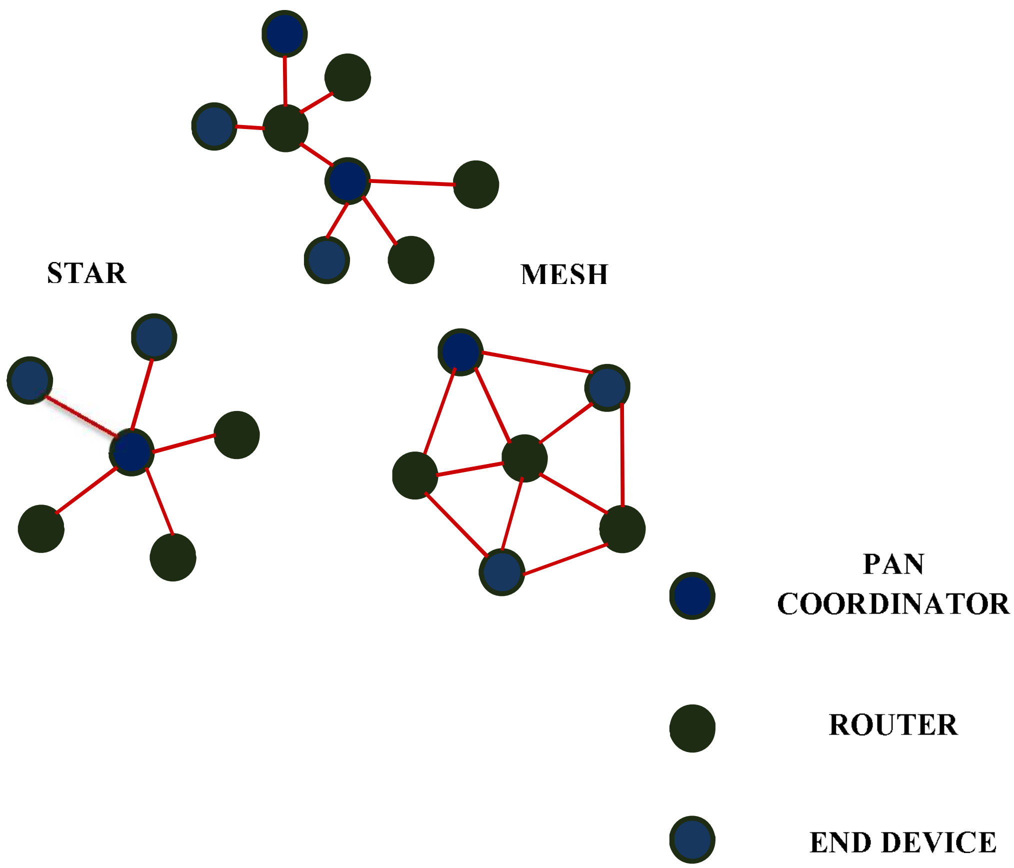


Fig.3.12. Zigbee network architecture

### 3.4.1.4. WAVENIS

Wavenis is a short distance optimized wireless communication technology for device to device and machine to machine communications. Wavenis was developed and designed by Coronis in the year 2000 [27]. This technology spans up to 200 meters to 1 Km.

Wavenis is mostly used for indoor applications. It is apt for WSN communications to convey readings of various sensor data and IoT applications. Table 3.6. shows the various technical specifications of Wavenis technology.

| Features/ characteristics of Wavenis | Technical specifications |
|---|---|
| Frequency band | 868 MHz, 915 MHz, and 433 MHz. |
| Spread Spectrum technology | FHSS |
| Coverage Area | 200 meters, 1 Km indoor |
| Modulation technique | GFSK |
| Channel bandwidth | 25 KHz and 50 KHz |
| Output power | For 25 KHz channel bandwidth-25mW, For 50 KHz channel bandwidth-10mW or 25mW |
| Wired backbone network | IEEE 802.3-Ethernet |
| Authentication and encryption | AES 128 bit key |
| Data throughput | For 25 KHz channel bandwidth - 4.8 kbps, For 50 KHz channel bandwidth-9.6 kbps, For 433 MHz and 868 MHz channel bandwidth-19.2 kbps |

Table 3.6. Technical specifications of Wavenis standard

Wavenis supports point to point as well as point to multipoint communication. It can work using tree, mesh and star topologies. Wavenis is best suited for building automation and AMI applications of Smart grid for its very low power and long coverage operation. Wavenis supports Ethernet and cellular network interface which is a salient feature for IoT applications.

### 3.4.1.5. 6LOWPAN

6LOWPAN is an abbreviation of IPv6 over Low Power WPAN. It is meant for inclusion of small devices over IPv6. 6LOWPAN is designed on the basis of IEEE 802.15.4 standard [27, 31].

IoT is the core feature of Smart grid communication network. WSN is one of the key module of IoT. Personal Area Network is apt for communication between various WSN devices. IoT is a network of IP enabled intelligent devices. IP based communication is very complex in terms of processing and management.

It is critical to integrate low power tiny devices with limited processing capabilities for IoT applications. The IETF 6LOWPAN group has developed the simple solution for IoT.

Nodes are given a common 64 bit IPv6 prefix so that irrespective of the location of a node, its IPv6 prefix remains same. This standard facilitates an integration of IPv6 with embedded devices having low power, low data throughput and limited processing power through adaptation and optimization. Table 3.7. shows the technical specifications of 6LOWPAN standard.

| Features/ characteristics of 6LOWPAN | Technical specifications |
|---|---|
| Frequency band | 2.4 GHz, 915 MHz, 868 MHz |
| Modulation technique | O-QPSK |
| IP support | IPv6 |
| Coverage Area | 200 meters |
| Multiple access technique | TDMA |
| Wired backbone network | Ethernet |
| Authentication and encryption | AES 128 bit |
| Data throughput | 20 to 250 Kbps<br>20 kbps for 868 MHz<br>40 kbps for 915 MHz<br>250 Kbps for 2.4 GHz |

Table 3.7. Technical specifications of 6LOWPAN standard

6LOWPAN can be categorized in three basic configurations.

- **Simple 6LOWPAN**

  A simple 6LOWPAN is connected to cloud through edge router.

- **Extended 6LOWPAN**

  An extended 6LOWPAN contains sets of 6LOWPANs and connected to cloud through backbone network such as Ethernet. It contains more than one edge routers.

- **Adhoc 6LOWPAN**

  This type of 6LOWPAN functions as a basic personal area network without Internet connectivity.

  An architecture of 6LOWPAN is shown in Fig.3.13.

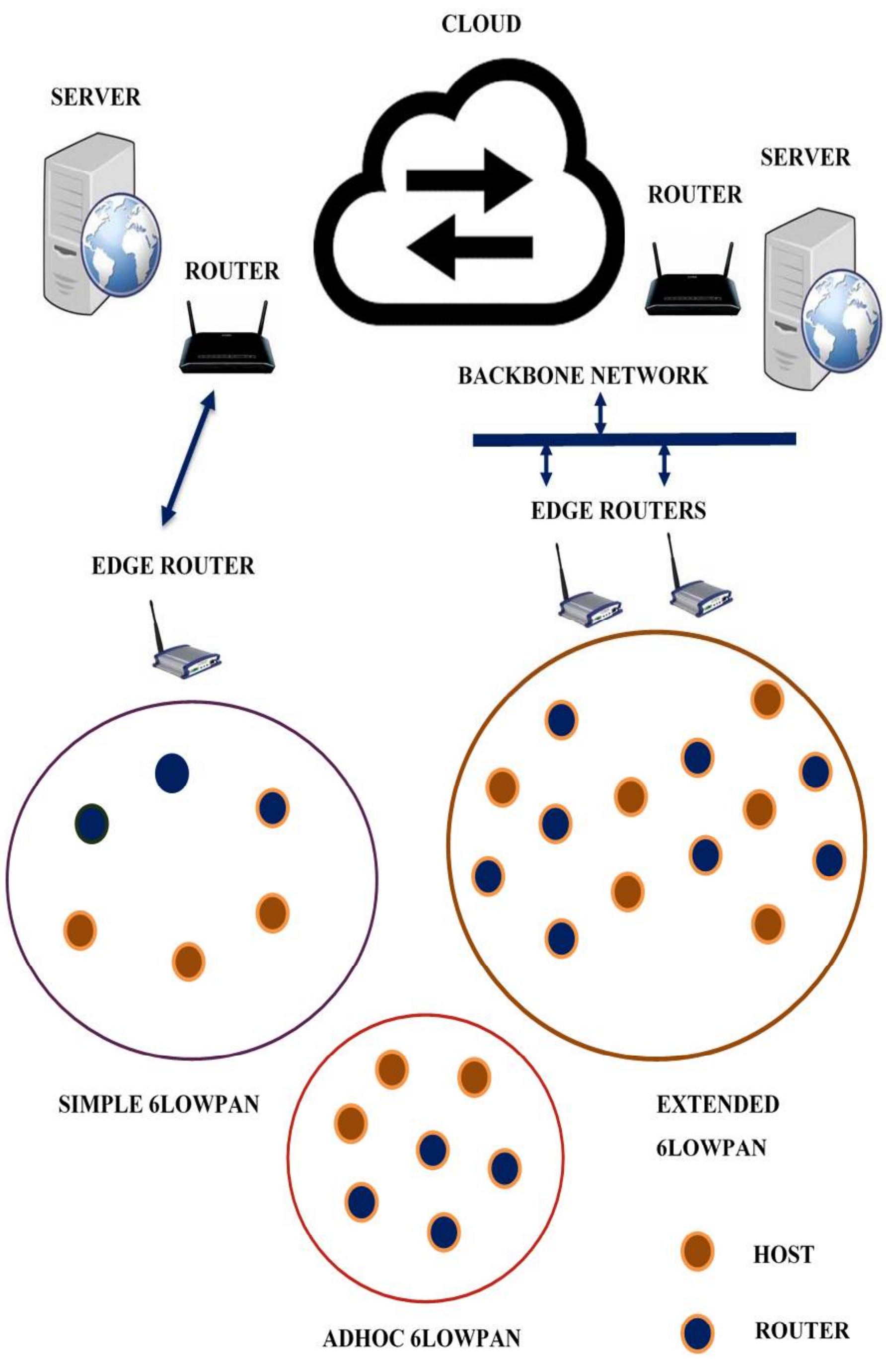


Fig.3.13. 6LOWPAN network architecture

Fig.3.14. shows the protocol stack of 6LOWPAN standard. Physical and media access layers are identical to IEEE 802.15.4 standard. 6LOWPAN supports only IPv6. So, an adaptation layer is inevitable for optimization of IPv6 for IEEE 802.15.4 standard.

TCP is replaced by UDP for simplicity and efficiency. An ICMP is used for message control. Application protocols are meant for communication between various processes over IPv6.

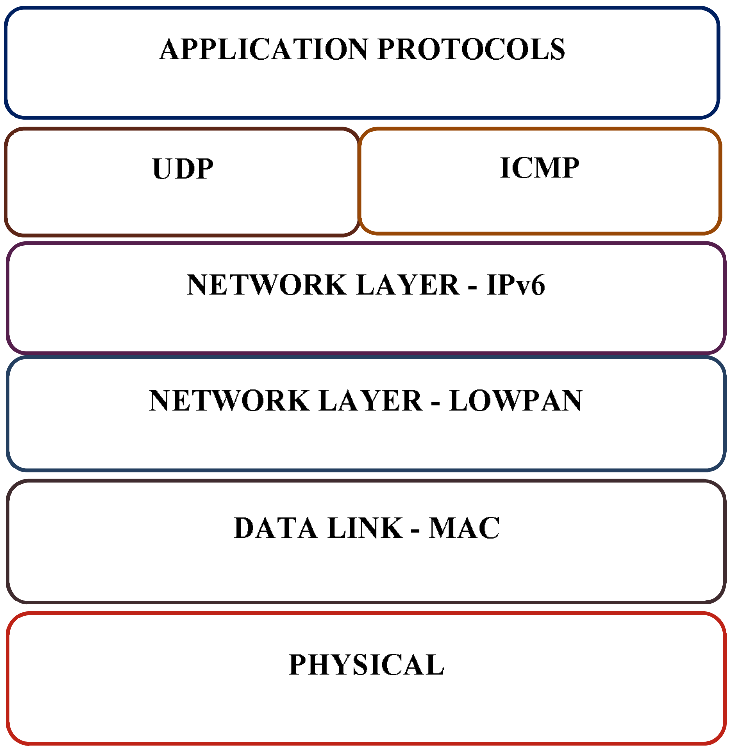


Fig.3.14. 6LOWPAN protocol stack

### 3.4.1.6. Wireless Fidelity/WLAN

Wireless fidelity is based on IEEE 802.11 standard which was commercialized in 1997. IEEE 802.11 outlines physical and media access layers [27, 37]. Various versions of this standards such as IEEE 802.11a, IEEE 802.11b and IEEE 802.11g were also developed with different technical specifications [38].

Wireless local area networks are suitable for home automation, smart metering and IoT applications in Smart grid technology [37-40].

Technical specifications of various versions of WLAN are listed in Table 3.8.

| **Features/Characteristics of WLAN** | **Technical Specifications** | | | |
|---|---|---|---|---|
| | **IEEE 802.11** | **IEEE 802.11 a** | **IEEE 802.11 b** | **IEEE 802.11 g** |
| Frequency band | 2.4 GHz | 5 GHz | 2.4 GHz | 2.4 GHz |
| Physical layer specifications | DSSS, FHSS | OFDM | DSSS | OFDM |
| Maximum rate of transmission | 2 Mbps | 54 Mbps | 11 Mbps | 54 Mbps |
| Maximum data throughput | 1.2 Mbps | 32 Mbps | 5.5 Mbps | 24 Mbps |
| MAC specification | CSMA-CA | CSMA-CA | CSMA-CA | CSMA-CA |
| Wired backbone network | Ethernet | Ethernet | Ethernet | Ethernet |
| Encryption/coding method | 40 bit RC4 | 40 bit RC4 | 40 bit RC4 | 40 bit RC4 |

Table 3.8. Technical specifications of WLAN standard

The protocol stack of WLAN is shown in Fig.3.15.

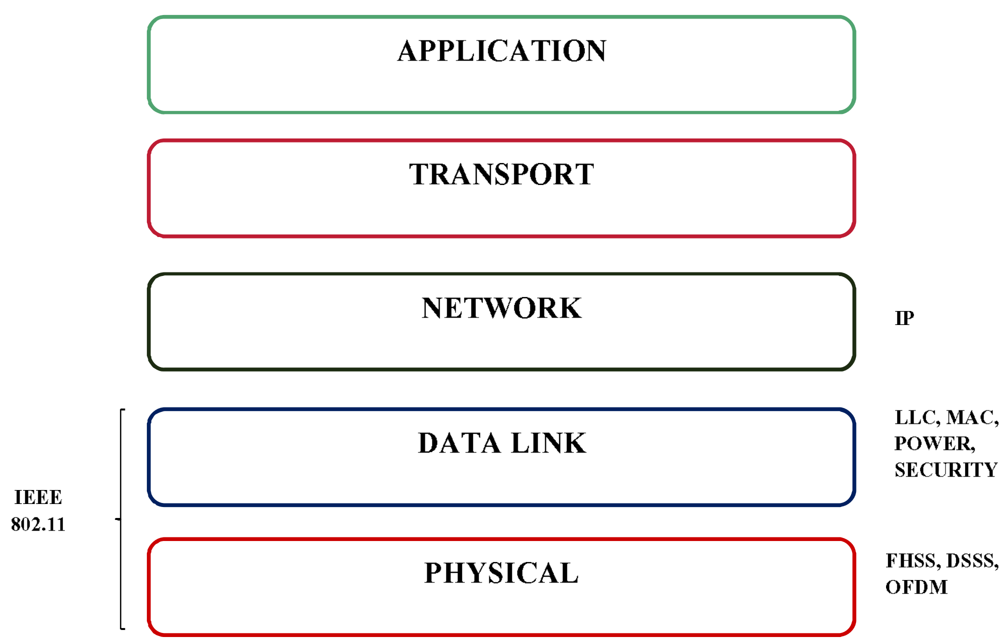


Fig.3.15. WLAN protocol stack

The functions of various layers are described below.

**Physical Layer**

Physical layer is associated with transmission and reception characteristics. It is also accountable for preamble generation, encryption, decryption, transmission medium characteristics etc.

**Data link layer**

This layer is separated into two sublayers namely MAC and LLC. MAC performs various functions such as framing and error detection. LLC is associated with error control and flow control between transmitter and receiver as well as interfacing with upper layers. Data link layer also deals with physical addressing.

**Network layer**

This layer is accountable for delivery of packet from transmitter to receiver. The key functions of network layer are routing and logical addressing.

**Transport layer**

This layer is accountable for port address and connection management. The process to process delivery of data frames is governed by transport layer.

**Application layer**

Application layer is accountable for providing user interface, network access, file transfer and access etc.

WLAN can operate in Adhoc or Infrastructure mode. In Adhoc mode, wireless devices interconnect with each other without access point. While in Infrastructure mode, access point facilitates communication between wireless devices.

BSS and ESS are the two basic components of WLAN infrastructure mode. BSS is a combination of wireless devices sharing a network. ESS is a combination of more than one basic service sets. Fig.3.16. shows the various modes of WLAN.

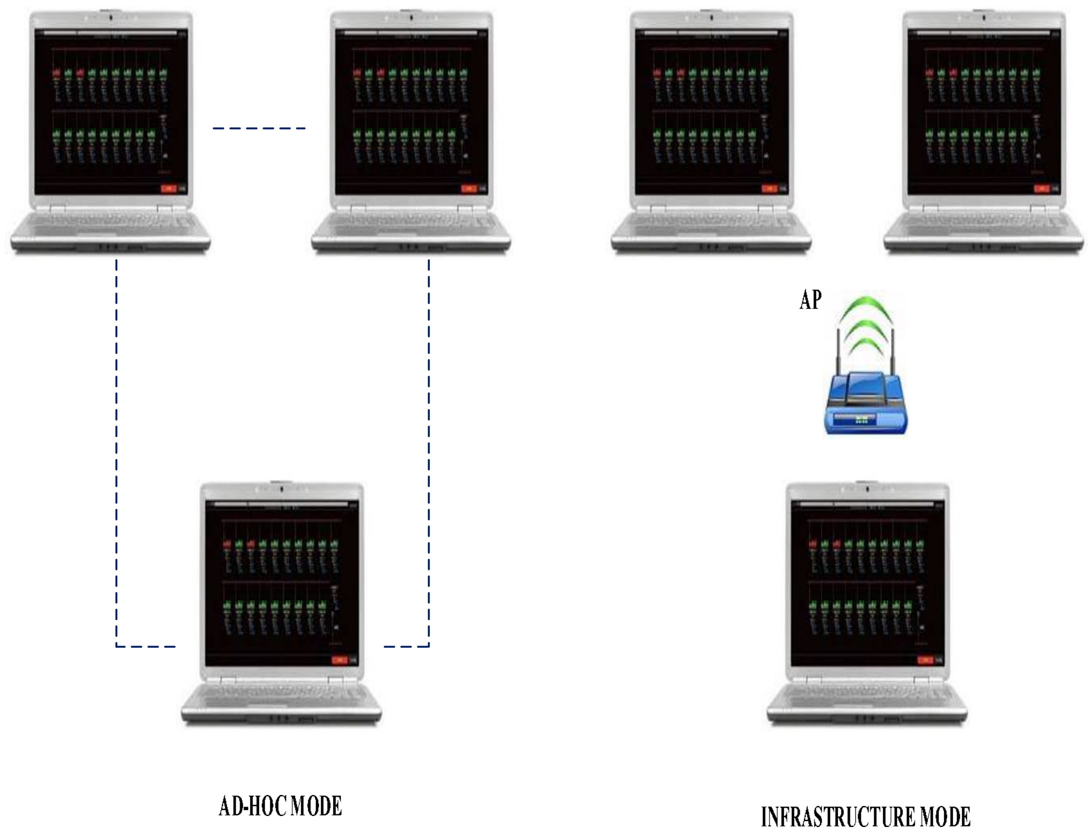


Fig.3.16. WLAN architecture

### 3.4.1.7. Z WAVE

Z Wave can be used for home automation in Smart grid HAN [27, 40]. It was initially developed by Zen-Sys. It provides data rates from 9.6 Kbps to 40 Kbps. It operates in 868.42 MHz and 908.42 MHz band. The radio distance between two Z wave nodes is 30 meters. The physical layer and MAC layer is defined in ITU-T-G9959 standard. Z wave functions by using source routed mesh technology.

If node A needs to communicate with node B which is outside the coverage area of node A then node A can communicate through Node C. Z wave provide 30 meters indoor and 100 meters outdoor coverage.

Maximum 232 devices can be connected in Master-Slave topology. The significant advantage of Z wave is it does not interfere with the standards working on 2.4 GHz frequency.

Table 3.9. shows the various technical specifications of Z WAVE.

| Features/ characteristics of Z WAVE | Technical specifications |
|---|---|
| Frequency band | 868 MHz, 908 MHz |
| Standard | ITU-T-G9959 |
| Modulation technique | GFSK |
| IP support | Z/IP gateway |
| MAC | CSMA/CA |
| Coverage Area | 30 meters indoor and 100 meters outdoor |
| Wired backbone network | Ethernet |
| Encryption | Manchester, NRZ |
| Data throughput | 9.6 Kbps, 40 Kbps, 100 Kbps |

Table 3.9. Technical specifications of Z wave standard

Z wave contains primary controller, secondary controllers and slaves. The controller which initiates the Z wave network becomes primary controller. Primary controller is authorized to include and exclude the nodes. Primary controller manages the routing and secondary controller has a copy of routing table availed from primary controller. The slaves execute the command if they have a valid 32 bit Home ID. Fig.3.17. shows the Z wave network architecture.

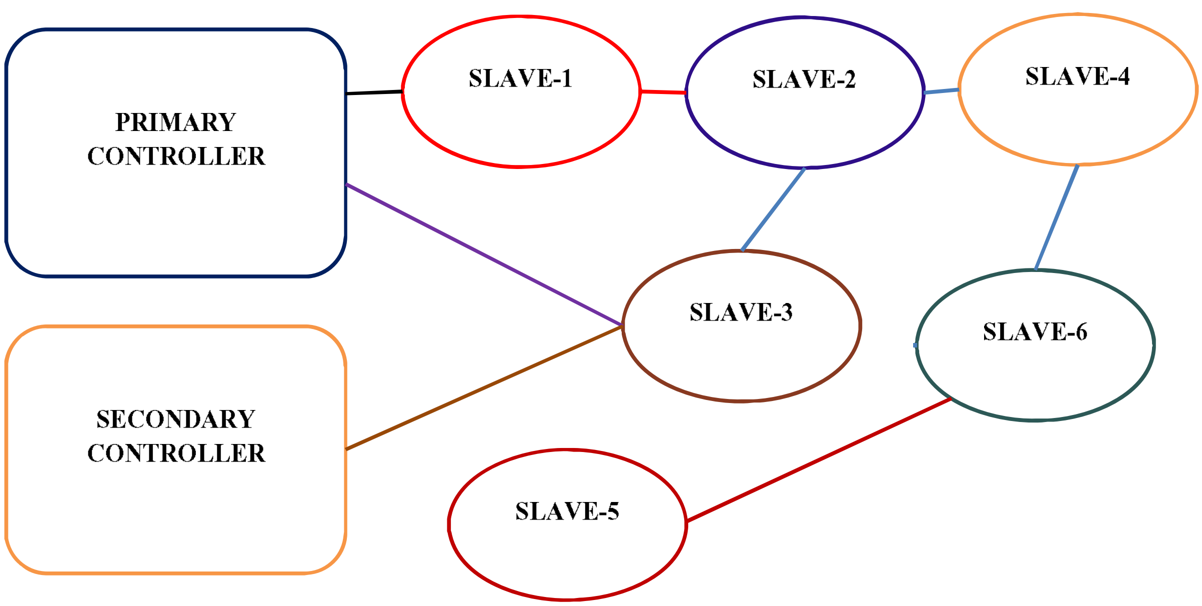


Fig.3.17. Z wave network architecture

#### 3.4.1.8. WiMAX

WiMAX technology is designed on the basis of IEEE 802.16 standard. This standard is meant for WMAN. It is a broadband wireless standard with scalability. WiMAX operates in 2 GHz to 66 GHz range [40-42]. WiMAX has the capability to replace entire wired infrastructure and to provide last mile connectivity from service provider to consumer. WiMAX can be categorized into either fixed WiMAX or Mobile WiMAX. Fixed WiMAX (IEEE802.16d) can provide point to multipoint connectivity up to 50 Km. Mobile WiMAX (IEEE802.16e) is designed for mobile wireless consumers with the coverage area up to 15 Km. WiMAX technology uses Multiple Input Multiple Output technology as well as smart antennas for higher data rates [41, 42]. Technical specifications of various versions of WiMAX standard are listed in Table 3.10.

| **Features/ Characteristics of WiMAX** | **Technical Specifications** | | |
|---|---|---|---|
| | **IEEE 802.16** | **IEEE 802.16a/d** | **IEEE 802.16e** |
| Frequency spectrum | 10-66 GHz | 2-11 GHz | < 6 GHz |
| Transmission | Line of Sight (LOS) | Non Line of Sight (NLOS) | Non Line of Sight (NLOS) |
| Modulation technique | 16 QAM, 64 QAM, QPSK | 16 QAM, 64 QAM, 256 QAM, OFDM-QPSK | 16 QAM, 64 QAM, 256 QAM, OFDM-QPSK |
| Data rates | 32 to 134 Mbps | 70 to 100 Mbps | 15 Mbps |
| Mobile/Fixed | Fixed | Fixed | Mobile |
| Radius of cell | 1-3 Miles | 3-5 Miles | 1-3 Miles |
| Channel bandwidth | 20 MHz, 25 MHz, 28 MHz | 1.25 MHz to 20 MHz | 5 MHz |

Table 3.10. Technical specifications of WiMAX standard

The protocol stack of WiMAX is shown in Fig.3.18. It follows OSI model. IEEE 802.16 standard specifies physical layer, air interface, data link layer and point to multipoint broadband wireless access.

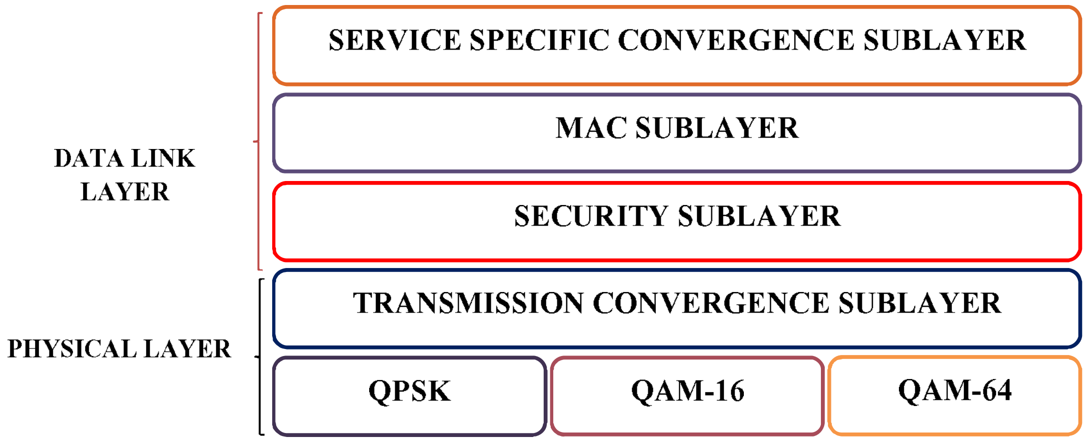


Fig.3.18. WiMAX protocol stack

**Physical layer**

Physical layer is accountable for various transmission and reception characteristics. It includes convergence layer to hide the transmission features from data link layer. It uses QAM and QPSK modulation techniques. IEEE 802.16a operates in the band of 2-11 GHz and IEEE802.16b operates in 5 GHz band. Multiple specifications of physical layer are supported by data link layer.

**Data link layer**

WiMAX is a broadband wireless technology. So, data link layer is designed to support very high uplink and downlink data rates. The data link layer of WiMAX is alienated into three sublayers. The security sublayer is responsible for security and privacy. It deals with key management, encryption and decryption. MAC is responsible for allocation of slots and channel management. Service specific convergence sublayer governs an interfacing with network layers.

### 3.4.1.9. CELLULAR COMMUNICATION STANDARDS

Existing cellular communication infrastructure can be optimized for Smart power grid applications such as AMI, distribution automation, real time monitoring and control etc. [27, 44]. Long Term Evolution and 4G wireless communication standards can be suitable choices for bandwidth hungry Smart grid applications.

LTE and 4G provide wide coverage with high speed bi-directional communication. LTE technology is progression of 3G mobile communication technology. LTE is 3.9 G technology. An uplink and downlink data throughputs of LTE are 50 Mbps and 100 Mbps respectively. LTE-Advanced is an industry standard for 4G technology. It attains an uplink and downlink data rates up to 500 Mbps and 1 Gbps respectively. The rates are 10 times higher than the current GPRS system. 4G technology is a combination of PAN, WLAN, Cellular network and Satellite network. The data throughput of 3G is 384 Kbps to 2 Mbps which is very low for wide area applications. 4G achieves data throughput up to 100 Mbps. 4G has numerous innovative features such as OFDM, MIMO, smart antenna systems, software defined radio, high data rates and greater anti-jamming capacity. 4G can facilitate efficient resource utilization through adaptability in bandwidth. 5G technology is the successor of 4G cellular standard with advance functionalities. 5G is apt for IoT, machine to machine communication, sensing etc. The expected data throughput of 5G is 10 to 50 Gbps and bandwidth is 60 GHz. 5G provides World Wide Wireless Web (WWWW) for integrated network connectivity. BDMA and FBMC technologies are key features of 5G. It provides Software defined radio based reconfigurable infrastructure for global connectivity [43]. BDMA enhances the capacity of cellular system by division of beam according to geographical location of user. 5G is a heterogeneous cellular network. 5G is developed for pervasive and universal networks and services [44]. Table 3.11. shows the various technical features of 4G and 5G technologies.

| **Features/ Characteristics of Cellular technology** | **Technical Specifications** | |
|---|---|---|
| | **4G** | **5G** |
| Technology | OFDM | BDMA, FBMC |
| Data throughput | LTE- Downlink-3 Gbps, Uplink-1.5 Gbps | 10 to 50 Gbps |
| Frequency spectrum occupancy | LTE- 1.8 GHz, 2.6 GHz | 1.8 GHz, 2.6 GHz, 30 GHz to 300 GHz |
| Channel bandwidth | LTE-1.4 to 20 MHz | 60 GHz |
| Type of switching | Packet switching | Packet switching |
| Error correction | Turbo codes for FEC | Parity check codes for FEC |
| Application support | HDTV | Ultra-high video, virtual applications |

Table 3.11. Technical specifications of Cellular communication technologies

Physical layer of 5G technology defines open wireless architecture. Fig.3.19. and Fig.3.20. shows the protocol stack and technical components of 5G technology respectively.

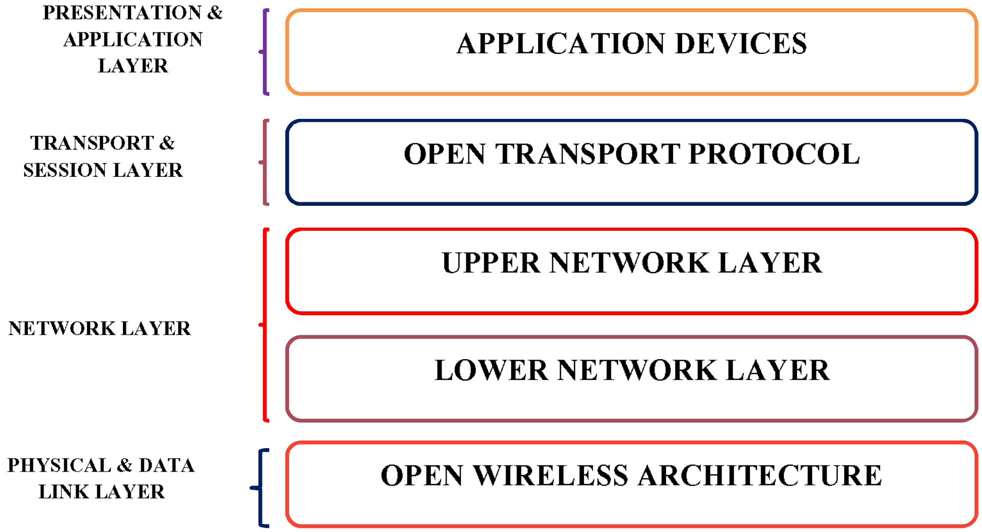


Fig.3.19. 5G protocol stack

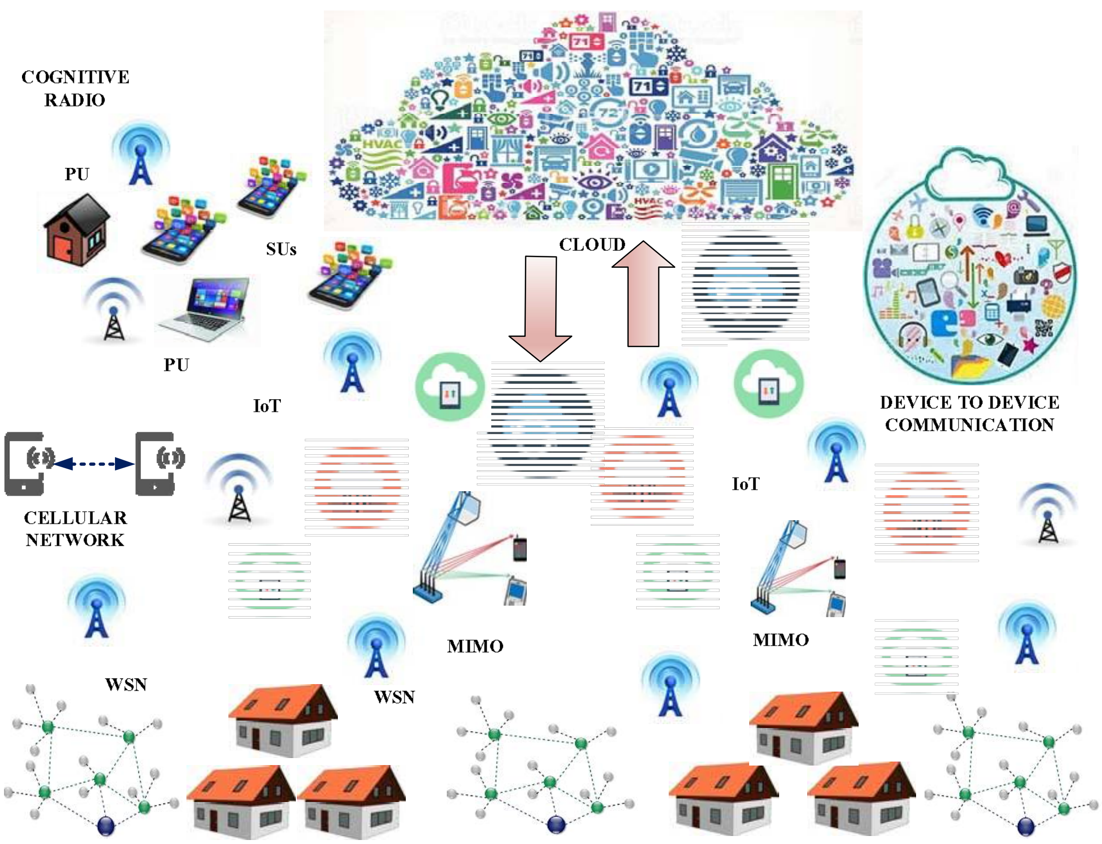


Fig.3.20. Various components of 5G

Open wireless architecture facilitates an integrated wireless platform in which an application layer is independent to physical layer characteristics. This concept will support multiple wireless standards with open interface. Network layer is an IP enabled layer for machine to machine communication and IoT application support. Upper layer is designed for mobile wireless terminal and lower layer is meant for interfacing [44]. 5G mobile terminals are designed such that any transport protocol pertaining to a specific wireless standard can be installed. 5G mobile terminal will be able to optimize and select the best wireless connectivity by using intelligent algorithms pertaining to QoS parameters.

### 3.4.1.10. COGNITIVE RADIO-IEEE 802.22

Smart grid communication infrastructure is a gigantic network of heterogeneous networks. Huge spectrum space is required for various intelligent applications of Smart grid such as WSN, IoT, AMI, SCADA, distribution automation etc. Spectrum is a scarce resource [45-47]. Each frequency band in electromagnetic spectrum has its own area of application. Realization of Smart grid is only possible with well-organized and effectual use of frequency spectrum. An efficient use of spectrum is a huge challenge due to scarcity of bandwidth and complexity of heterogeneous Smart grid network. Moreover, the available licensed spectrum is sporadically used and thus some portion of the spectrum remains unused for intermittent intervals. The most prominent solution to enhance the consistent and efficient use of spectrum space which is not occupied by primary consumers is cognitive radio technology [48-50]. Cognitive radio enables and facilitates the resourceful usage of spectrum space by assigning an unoccupied spectrum spaces of primary users to secondary users. Primers users have precedency and legacy to use the available spectrum. They are authorized to use the available spectrum. Secondary users are given the specific fragment of spectrum only if it is not engaged by primary users as well as it does not result into disparaging interference to the frequency band being used by primary users having legitimate privileges [51]. IEEE 802.22 standard is designed for cognitive radio applications. It defines the spectrum sensing technique to sense the unoccupied licensed spectrum allocated to primary users at a specific period of time in a precise geographical place. With the use of spectrum sensing technique, an equitable distribution of available spectrum among secondary users can be accomplished [47-53].

It can also be used to enhance the data throughput. Based on transmission methodologies and spectrum access, cognitive radio can be categorized as below.

- **Interweave cognitive radio**
  In this type of cognitive radio network, an unused portion of spectrum space occupied by primary user is sensed as well as opportunistically and resourcefully used by secondary users.

- **Overlay cognitive radio**
  In this type of cognitive radio network, secondary users use the unoccupied spectrum space on the basis of spectrum occupation details available to them.

- **Underlay cognitive radio**
  In this approach, primary and secondary users use the available spectrum simultaneously by adjusting the parameters to avoid interference.

The communication infrastructure of Smart grid is an amalgamation of HAN, NAN and WAN. These networks contain cognitive gateways for efficient utilization of spectrum space. Moreover communication between these hierarchical gateways is also inevitable. HAN cognitive gateway manages an effective use of spectrum among various devices in home area network. It also communicates with NAN cognitive gateway. NAN cognitive getaway unites HAN gateways and assigns spectrum spaces to primary as well as secondary users. WAN cognitive gateways manage NAN gateways. As defined in IEEE 802.22 WRAN standard, secondary users can be allocated television white space. The channel bandwidth in cognitive radio is 6 MHz. Various bands for cognitive radio are 54 MHz-72 MHz, 76 MHz-88 MHz, 174 MHz-216 MHz and 470 MHz-806 MHz [52-54]. Fig.3.21. shows the cognitive radio gateways.


Fig.3.21. Cognitive radio gateways

IEEE 802.22 standard accentuates on availability of wireless broadband communication technology in remote areas. Moreover its coverage is better than existing wireless broadband standard such as IEEE 802.16 based WiMAX. Cognitive radio technology can significantly contribute in the realization of complex and heterogeneous Smart grid communication infrastructure.

### 3.4.2. WIRED COMMUNICATION STANDARDS FOR SMART GRID APPLICATIONS

Wired technology can be used as a backbone for Smart grid communication infrastructure. Broadband or narrowband powerline communication network can be combined with IP based devices or they can be used as redundant connections [55-58]. Powerline communication can be used in both low voltage and medium voltage systems. Transmission line is very sensitive to interference, noise, propagation loss etc. at low frequency [55]. Orthogonal Frequency Division Multiplexing can be used for effective spectrum utilization. Power line communication technology can be categorized as narrowband and broadband powerline technologies. Broadband over power line technology can be used for real time management of Smart grid applications. IEEE 1901 standard depicts high speed BPL with data throughput of 500 Mbps. As BPL does not require the deployment of new infrastructure, it can be a prominent solution for Smart grid communication network. Home plug power line technology can be used for Smart grid HAN. Various variants of HOME Plug powerline such as Home Plug AV, Home Plug AV2 and Home Plug green PHY can be used for AMI and Smart metering. Narrowband powerline communication can be used for home automation. The committee for Narrowband PLC has proposed two standards namely G3-PLC and PRIME-PLC [56, 57]. These narrowband powerline technologies are defined in IEEE 1901.2 standard. These technologies operate in CENELEC A band. They use cyclic prefix OFDM and DPSK. The standards are described below.

#### 3.4.2.1. PRIME

PRIME stands for PoweRline Intelligent Metering Evolution. It is apt for AMI applications [56]. PRIME uses DQPSK, 8PSK and BPSK for modulation. It also uses OFDM for efficient bandwidth utilization and interference avoidance. It uses 42 KHz to 89 KHz spectrum in CENELEC A band. Prime devices can be categorized as Base nodes or Service Nodes.

The function of base nodes is to manage the connections and resources. Service nodes are registered with base nodes and they are the part of sub-network [57]. A tree topology is used by sub-networks where base node is a trunk.

Service specific convergence sub-layer and common part convergence sub-layer are the two sub-layers of convergence layer. PRIME standard defines SSCS for IPv4, IPv6, IEC 61334 and null SSCS for node management.

#### 3.4.2.2. G3

G3 PLC technology can facilitate communication between various intelligent electronics devices, actuators and sensors over IPv6. G3 is developed by G3 alliance. G3 uses orthogonal frequency division multiplexing to overcome attenuation and interference. It has a capability to provide reliable communication over medium and low voltage transformers. P1901.2 is the universal version of G3 developed by IEEE [56-58]. Coherent modulation is used to achieve high data rates. G3 can be used to provide robust communication links for Smart grid infrastructure.

Various technical features of PRIME and G3 are listed in Table 3.12.

| **Features/ Characteristics** | **Technical specifications** | |
|---|---|---|
| | **PRIME** | **PLC G3** |
| Frequency band | 42 KHz to 89 KHz | 35 KHz to 91 KHz |
| Value of sampling frequency | 250 KHz | 400 KHz |
| Data throughput | 128.6 Kbps | 33.4 Kbps |
| FEC | Convolutional code | Convolutional code, Reed Solomon code, Repetition code |
| Interleaving | Per symbol of OFDM | Per packet of data |
| Modulation technique | DBPSK, DQPSK, D8PSK | DBPSK, DQPSK |

Table 3.12. Technical specifications of PRIME and G3 PLC

Table 3.13. shows a comparative study of various communication standards on the basis of various features and applications.

| Standard | Type of Spectrum | Spectrum | Maximum Data Throughput | Coverage area | Advantages | Disadvantages | Respective network layer | Regions of Application in SG | Market Espousal |
|---|---|---|---|---|---|---|---|---|---|
| **Bluetooth** | Unlicensed | 2.4 GHz | 700 Kbps | Up to 100m | Low power usage | Low data throughput, Short coverage range, Security issues, Interference with other technologies operating on ISM band | HAN | Data logging, Home automation, Device control | Very High |
| **Zigbee** | Unlicensed | 868 MHz, 915 MHz, 2.4 MHz | 250 Kbps | Up to 100 m | Less expensive, Low power usage, Less complicated | Low data throughput, Short coverage range, Interference with other standards working on ISM band | HAN | Home automation, Smart lightning, Energy management, Metering [59] | Very High |
| **Wi-Fi/ Wireless LAN** | Unlicensed | 2.4 GHz, 5.8 GHz | 2 Mbps to 54 Mbps | Up to 250 m | High data throughput, Robust in terms of reliability and security,<br><br>Point to point and point to multipoint communication, Less expensive | Complicated design, Susceptible to interference, Low data rates due to interference | HAN, NAN | Monitoring and control of devices and RES/DER, Home automation, Protection,<br><br>Distribution & substation automation, PHEV | Very High |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **6LoWPAN** | Unlicensed | 868 MHz, 915 MHz, 2.4 MHz | 250 Kbps | Up to 100 m | Low power usage | Low data throughput, Short coverage range | HAN | Home automation, metering | Medium |
| **Z-Wave** | Unlicensed | 868 MHz, 908 MHz | 9.6 Kbps to 40 Kbps | Up to 30 m | Low power usage | Very Low data throughput, Short coverage range | HAN | Home automation, metering | Medium |
| **Cellular Communication** | Licensed | Various licensed bands | 4G-Up to 1 Gbps<br><br>5G- Up to 50 Gbps | Several Kms | Highest range and data throughput, Exceptional QoS | Costly, High propagation delays due to broad coverage | HAN, NAN, WAN | SCADA, metering, monitoring and control in HAN and management of DERs, Substation automation, home automation and energy management [59], PHEV [60] | Very High |
| **Wireless RAN-IEEE 802.22** | Licensed as well as Unlicensed | 54 MHz to 862 MHz | 4.54 to 22.69 Mbps | Up to 100 Km | Adaptive energy levels, High data throughput,<br><br>High coverage area, energy/power efficiency,<br><br>Effective spectrum | Disruptions due to high priorities to PUs<br>Interoperability and security issues | HAN, NAN, WAN | SCADA, Substation automation, AMI, protection,<br><br>Wide area management, Spectrum management, Data communication in HAN, NAN, | Medium |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | management and utilization, Resistance to interference | | | WAN | |
| **Power line communication** | Licensed | 9 KHz to 95 KHz- Prime PLC<br><br>10-490 KHz-G3 PLC | 21 kbps to 128 kbps- Prime PLC<br><br>4 Mbps- G3 PLC<br><br>10 Mbps- Home Plug | In Kms | Less expensive, High data throughput, Low latency | Signal quality is affected by number of apparatus connected in network, distance between transmitter and receiver may degrade the quality | HAN, NAN | Meter reading, low voltage distribution, data communication, PHEV | Very High |

Table 3.13. Comparison of various communication standards

## CHAPTER SUMMARY

Smart grid is the most ingenious technology of present era. It is a complex grid consisting of various hierarchical and heterogeneous communication network layers along with electrical infrastructure. The hierarchical network layers of Smart grid can be classified as HAN, NAN and WAN. Diverse set of communication standards is required for realization of complete Smart grid infrastructure. A detailed review and comparative analysis of different communication standards is illustrated in this chapter for communication network optimization. Choice of a specific communication standard for application in Smart grid hierarchical network layers depends upon various factors such as coverage area, data throughput, interoperability, bandwidth requirement, cost, quality of service etc. This chapter serves as a base for design and implementation of prototype developed for validation of theoretical research framework.