Smart Home Area Networks Protocols within the Smart Grid Context

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Abstract —The Internet of things (IoT) applications are becoming one of the emerging smart grid enabling technologies. Smart home appliances are one the beneficiary of such applications. Machine-to-Machine and Man-to-Machine are the basic IoT communication platforms that enable home appliances to communicate with each other to be more efficiently operated. In a recent search for the IoT communication protocols that are utilized in smart home appliances, there was no inclusive reference that contains and describes the smart home area networks and guides the research and development (R&D) professionals to select the suitable protocol for an application. This paper presents a comprehensive review of the home area network (HAN) communication protocols that are used to enable bidirectional communication between the home owners, utilities and smart home appliances. The paper presents the most utilized HANs wired and wireless communication protocols and discusses their characteristics, advantages and disadvantages.

Index Terms—ZigBee, Wi-Fi, RFID, power line carrier, SPI, I^2C RS485

I. INTRODUCTION

One of the most important and rapidly evolving the technologies in electrical power system is the smart grid. The smart grid is a system of systems that integrates information and communication networks technologies with the traditional electrical power grid. This integration empowers utilities and consumers with bidirectional power flow and communication to better monitor, control and manage electrical power generation, transmission, distribution and consumption. From the communication point of view, the smart grid conceptual model consists of three major communication networks namely; wide area networks, local area networks and consumer area networks. Each one of these networks serves one of the electrical power domains namely; bulk generation and transmission domain, distribution domain and customers' domain respectively. Fig. 1 shows the smart grid communication networks that are mapped with the aforementioned electrical power grid domains [1]-[3].

The wide area network consists of the following sub communication networks:

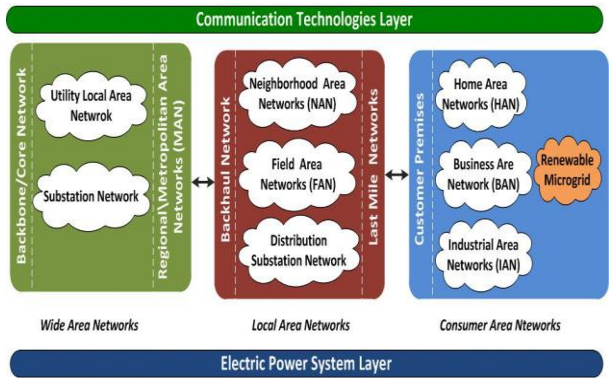

Fig. 1. Smart grid networks hierarchy

- Backbone/core network, utility local area network
- Substation area network,
- Regional/metropolitan area networks

The power distribution network consists of the following sub communication networks:

- Distribution substation network and
- Field area network, neighborhood area network
- Last mile area network

The consumer area network consists of the following sub communication networks:

- Home area network, Business area network
- Industrial area network

Several other papers have provided a general overview of the smart grid communication networks' specifications such as scalability, real-time capability, bandwidth, latency and the protocols used [1]-[4].

A recent paper presented an excellent in-depth and detailed survey on the power distribution communication sub networks structures, standards and topologies [5]. Such survey provides useful guidelines for smart grid professionals to design, operate and maintain the electrical power grid.

The paper presents a comprehensive review of the consumers' communication networks, in particular the home area network (HAN). The paper describes the HAN architecture and its communication protocols.

The rest of this paper is organized as follows: Section II presents the smart home area networks architecture, section III describes the home area networks communication protocols describes. The HANs wireless protocols is discussed in section IV, followed by the HANs wired network technologies which is discussed in section V. Section VI has the conclusion and finally the acknowledgment.

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II. Smart Home Area Networks Architecture

Smart homes nowadays are equipped with many devices such as smart meter, in-home displays, renewable energy sources and storage, and smart appliances such as washing machine, refrigerators, TV, oven, thermostat, HVAC, lights, and plugs for electrical cars. A HAN is considered the backbone communication network that connects these devices. It is a two-way communication that is utilized in the demand response, advance metering infrastructure, distributed energy generations and storage [6].

Devices can be accessed, monitored and controlled using different built-in wireless and wired communications protocols such as ZigBee, Wi-Fi, RFID, Bluetooth, general packet radio service (GPRS), Home-plug, RS485, I^2C, SPI and power liner carrier (PLC).

The HAN architecture consists of the following four main elements [7].

- The endpoints in HAN network such as smart meters, appliances, thermostats, oven and in-homedisplays
- The nodes inside a HAN network.
- A network operating system and network management software
- A gateway that connects the HAN network to communicate with home owners, the utility and third party service providers throughout the LANand/ or theWAN networks

The U.S Department of Energy presents two types of HAN network architectures namely; utility managed and utility and consumer managed [8]. The former is an existing architecture while the latter is a proposed architecture.

A. *The Utility Managed Architecture*

In this architecture, the utility monitors, controls and manages smart home appliances via its private network. As shown in Fig. 2, smart appliances are connected to the utility control server via its utility gateway and network. Home owners or other authorized users can access and view the status of home appliances from the utility server using an Internet gateway. The appliances send information to the smart meter using a suitable communication protocol. The smart meter then collects and stores the information and transfers it to the utility control server through the utility gateway. The communication between the utility and utility gateway is bidirectional, hence the utility is not only capable of monitoring the power consumption for billing purposes, but it is also able to control the appliances (ex: switching off the air conditioning units during peak demand).In this architecture, the user only has access to information that is provided by the utility. Therefore, the user has no control and can only monitor the performance of the appliances. It should also be noted that the user is connected to the utility through the Internet. Furthermore, the isolation of the two networks is mainly due to two major reasons: the difference in functionality of the two networks and cyber security [8].

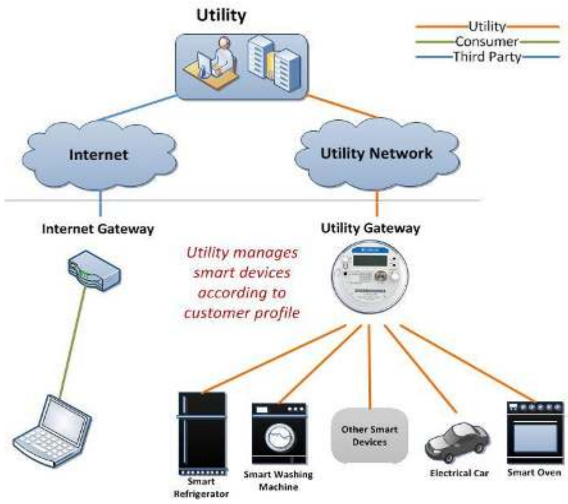

Fig. 2. Utility managed architecture [8]

B. *The Utility and Consumer Managed Architecture*

This architecture was proposed by the U.S. Department of Energy [8]; it addresses the shortcomings of the aforementioned architecture. As shown in Fig. 3, the Internet gateway within a home is connected to common gateway/hub. The common gateway/hub acts as an intermediate device between the utility, home owners, third party service providers and the home appliances. The users and the appliances can exchange data and control commands through this common gateway/hub. Home owners can access their home appliances' control system directly through Internet gateway as well as through the utility server. Furthermore, any relevant information about the appliances can also be delegated to a third party through the Internet. The isolation of the utility network from the Internet is for the same reasons as mentioned above.

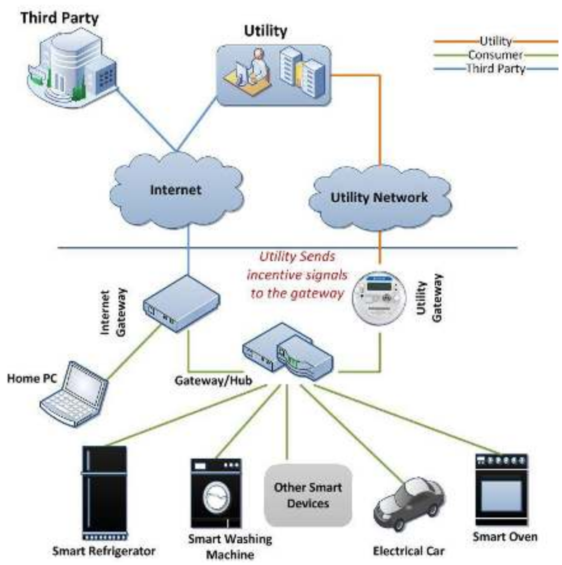

Fig. 3. Utility and consumer managed architecture [8].

III. The Home Area Networks Communication Protocols

Smart home appliances nowadays are equipped with a built-in communication module. Homeowners, utility and third party service providers utilize wireless and wired communication technologies to monitor, control and operate home appliances. Within the smart grid context, both technologies can be used to form a communication network which then forms a home area network (HAN). Depending on the home appliances, manufacturers use the following wireless technologies such as ZigBee, Wi-Fi, Z-Wave, and RFID and wired technologies such as RS485, PLC, I2C and SPI to develop HANs. Fig. 4 shows the most common home area network technologies.

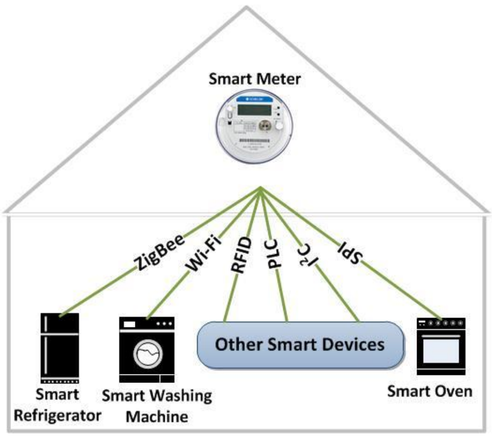

Fig. 4. Home area networks communication protocols

IV. HAN Wireless Network Technologies

Wireless protocols are used in HANs to provide remote access to the homeowners, utilities and third party service providers. ZigBee, Wi-Fi, RFID, Bluetooth and Z-Wave are the most widely used wireless communication protocols in home area network.

A. ZigBee Technology

ZigBee is a bidirectional radio frequency (RF) wireless network standard which conforms to IEEE 802.15.4.It has a low data rate, long life battery and operates in the license-free frequency for short range [9]. ZigBee is the most suitable and most implemented protocol in HANs. It is used in most home appliances such as lighting, air conditioning and security systems [10], [11]. The ZigBee architecture is built based on a master-slave model where appliances act as slaves and the coordinator acts as the master.

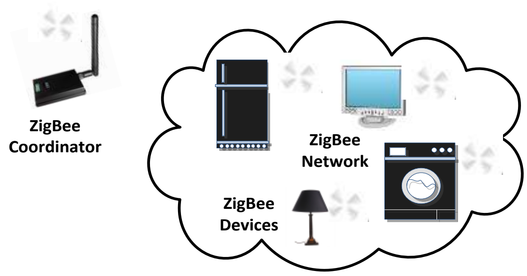

Fig. 5. Typical ZigBee master-slave architecture

Fig. 5 illustrates a typical ZigBee based HAN [10]. The master coordinates and manages bidirectional communication between the slaves (home appliances). The master also communicates directly with each slave (home appliance) since it is responsible for creating and maintaining the network.

The benefits and drawbacks of using ZigBee in HANs are listed below:

Advantages of using ZigBee in HANs include:

- Highly secured connection which utilizes 128-bit AES encryption [12], [13].
- Low power consumption allows for batteries for longer lifetime (100-1000 days) and reduced energy consumption [12]-[15].
- ZigBee network is reliable since it avoids collision, conflict and competition between nodes [13].
- ZigBee has a short delay latency from 15ms to 30ms
- Capacity ZigBee allows controlling a large network from a specific ‘coordinator’ [15].
- ZigBee protocol has self-organizing networking capabilities [6].

Some major disadvantages of ZigBee are as follows:

- Setting up a ZigBee network requires additional devices which increases cost.
- Appliances running ZigBee areincompatible with other network protocols such as Wi-Fi.
- ZigBee has low data transmission rates and lacks Internet Protocol support [6].

Examples of ZigBee applications in smart homes are security and alarm system, remote control, environmental monitoring thermostat, door control, motion detector, lighting control and smart metering system [10].

Table I shows the main characteristics of the ZigBee protocol.

B. Wi-Fi Technology

Wi-Fi is a bidirectional radio frequency (RF) wireless network standard which conforms to IEEE 802.11. It coexists with ZigBee in smart home as illustrated in Fig. 6 [16]. Wi-Fi is utilized in HANs for high-rate, information-related devices such as computers, printers, fax machines, TV, digital camera, surveillance cameras outside homes , video playback and smart terminals as well as data download [16], [17].

The benefits and drawbacks of using Wi-Fi in HANs are listed below:

Advantages of Wi-Fi in HANs:

- Highly secured connection which utilizes 128-bit AES encryption [12].
- Wi-Fi supports networking over power lines, coaxial cables and phone lines [12].
- Wi-Fi does not require a special gateway because it inherits the Internet protocol support capability and features [6].
- Wi-Fi has a short delay latency which is less than 3ms [14].

TABLE I: MAJOR HANS COMMUNICATION PROTOCOLS CHARACTERISTICS

Feature	ZigBee/ IEEE 802.15.4	Bluetooth/ IEEE 802.15.1	Wi-Fi/ IEEE 802.11	RFID	I2C	SPI	HomePlug 1.0 (PLC)
Based data rate	250 kbps	1Mbps	11,000+kbps		100kbps-3.4 Mbps	20Mbpts	14Mbps
Frequency	2.45GHz	2.45GHz	2.45GHz	120kHz - 10 GHz	limited to either 100 KHz , 400 KHz or 3.4 MHz	Free (n MHz to 10n MHz) : where n is an integer from 1 to 9	5000kHz-1MHz
Range	10-100 m	10 m	1-100 m	10cm - 200m	few meters	100 m	1-3 km
Latency	30msec	18-21usec	0.3usec	25-300usec	Depends on the master clock	depends on the master clock	x
Nodes/Masters	65540	7	32		1024	2-3.	x
Battery life	years	days	hours	battery-less	low power requirement	low power requirement	low
Complexity	simple	complex	very complex	simple	simple hardware	simple hardware	simple
Security	128 bit	128 bit	WPA/WPA2	AES 128-bit	X	X	x

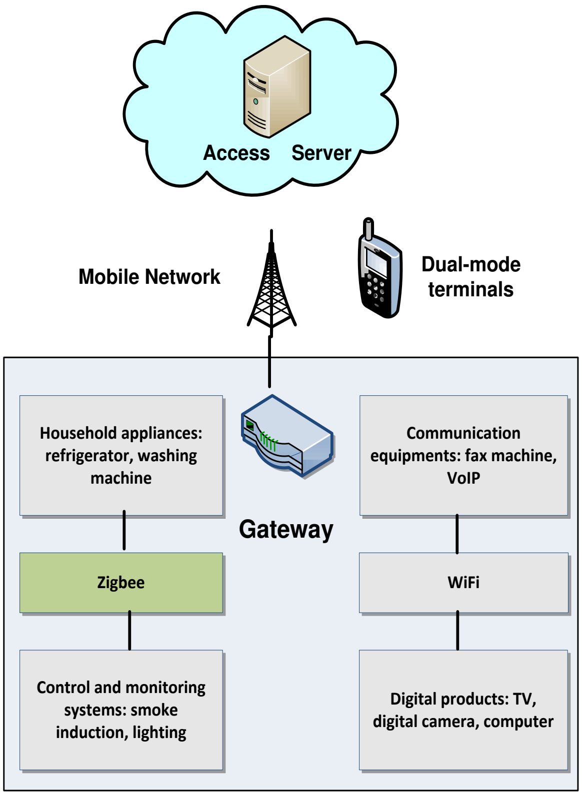

Fig. 6. ZigBee and Wi-Fi coexistence HAN network [16].

Disadvantages of Wi-Fi in HANs:

- Wi-Fi consumes significant power when compared to ZigBee. The battery lifetime extends from 0.5-5 days without charging [14].
- Wi-Fi gets affected by electromagnetic radiation emitted from household appliances which in turn affects the speed of transmission [18].
- Wi-Fi is prone to interference with certain HAN network protocols such ZigBee and Bluetooth since these protocols operate under the same frequency range [16].

Table I shows the main characteristics of the Wi-Fi protocol.

C. Radio Frequency Identification (RFID) Technology

RFID is a bi-directional radio frequency identification system which consists of tags and readers that can be interfaced to handheld computing devices or personal computers. It follows the electronic product code (EPC) protocol [19]. It can coexist with other technologies such as ZigBee and Wi-Fi. RFID operates under a wide range of frequency which varies from 120 kHz - 10 GHz and the detection distance can vary from10 cm - 200 m [19].

RFID is used in home area network applications such as smart home energy management systems [20] door locks [21] and lighting control [22]. For example, when a resident carrying the tag walks into a room, the lights go ON. The system also supports multiple users and customized lighting for each tag with priority.

The benefits and drawbacks of using RFID in HANs are as follows.

Advantages of using RFID in HANs:

- RFID has high transmission speed and a latency of around100ms [23].
- RFID allows bidirectional communication [23].

Disadvantages of using RFID in HANs:

- RFID chips are expensive [24].
- RFID supports relatively low bandwidth as compared to Wi-Fi; hence it cannot be used for multimedia and download applications.
- Collisions can occur when two tags in the same area try to communicate to the reader. Both tags might be unable to respond to the reader [24].
- RFID's accuracy depends on line-of-sight communication.

Table I shows the main characteristics of the RFID protocol.

V. HAN WIRED NETWORK TECHNOLOGIES

Although there are a wide variety of wireless networks that are available, wired protocols are still as prevalent in home area networking since they are more secure and are capable of transferring data at higher rates. The most common wired technologies that are utilized in HANs are RS485, USB, SPI, I2C and PLC. In the following sections, we will discuss the major features of the aforementioned wired protocols.

A. *Universal Asynchronous Receivers/Transmitters (UARTs)*

The recommended standard (RS) 232/422/423/485 is the universal asynchronous receivers/transmitters (UARTs) communication protocol. There are four different standards namely; RS232, RS 423, RS 422 and RS 485. Each standard has different cable length, number of drivers and receivers, data rate, signal level, power consumption and slew rate. Table II summarizes the specification of the existing RS standards. Table 2 shows the RS232 and RS 485 key characteristics which are mostly utilized in home area networks [25].

TABLE II: KEY CHARACTERISTICS OF THE RS-232/4885 SERIAL INTERFACE

Parameter	RS-232	RS-485
Line configuration	Signe-ended	Differential
Mode of operation	Simplex or full duplex	Simplex or half duplex
Maximum cable length	50 feet	4000 feet
Maximum data rate	20Kbits/s	10Mbits/s
Typical logic levels	±5 to ±15 V	±1.5. to ±6V
Receiver sensitivity	±3V	±200mV

The protocol is utilized in several applications within home area networks. For example, it is used in smart meter gateway [26], home energy management systems [27], design and implementation of network-based embedded electricity management system [28] and for Internet of Things gateway [29].

B. *Inter Integrated Circuit (I2C)*

I^2C is a protocol which is suited for slow communication of a microcontroller with onboard peripherals. The I^2C bus follows master-slave serial bus architecture as shown in Fig. 7. The bus uses 2 bidirectional wires: serial data line (SDA) and single serial clock (SCL). The SDA allows data transmission to and from the slave devices. The SLC signal, which generated by the master, is used to clock in or clock out data of the slave devices. Furthermore, the protocol allows multiple master devices to communicate with multiple slave devices using the two signals mentioned above [30]. I^2C is utilized to monitor and control home appliances, and in home patients' monitoring devices.

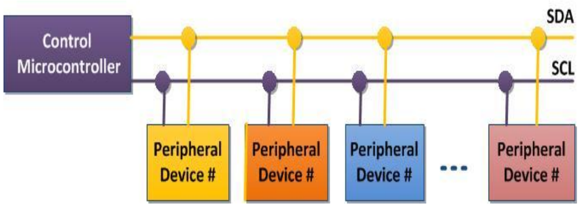

Fig. 7. I^2C Master/salve serial bus architecture

The benefits and drawbacks of using I^2C in HAN are mentioned below:

Advantages of using I^2C:

- I^2C is widely supported and well known. The hardware is widely used and its implementation is simple [31].
- The I^2C interfacing and expansion are not complicated.
- An I^2C system consumes low power [32].
- I^2C protocol is automatically configured (i.e. supports plug and play).

Disadvantages of using I^2C:

- Connections which involve data streaming at high speeds are not well supported by an I2C microcontroller. Additionally, the data rates in I2C are limited as opposed to those in SPI [30].
- The number of nodes in an I2C system is limited by the address space on the bus and load capacitance [32].
- I^2C protocol does not support long distance communication.

Table I summarizes the main characteristics of the I^2C protocol.

C. *Serial Peripheral Interface (SPI)*

SPI is a 4-wire synchronous serial interface serial bus which allows processors to communicate with peripheral devices. The SPI hardware is implemented as a simple shift register which controls data flow by either shifting data in or shifting data out. Similar to I^2C, SPI also follows a master-slave mechanism; however the protocol involves a single master controlling many slaves. The interface is implemented as 3+ N wired interfaces, where N is the number of devices connected to the master on a single bus [33].

The SPI interface is used in smart homes to interface external microcontrollers with various sensors [34].

The benefits and drawbacks of using SPI in HAN are mentioned below:

Advantages of using SPI:

- SPI offers a variety of data transfer rates to choose from. It uses a full duplex connection and hence data streaming is supported.
- The SPI driver consumes low power [30].
- SPI is cost-effective [31].

Disadvantages of using SPI:

- The SPI configuration should be done manually [31].
- The limited number of SPI ports makes it difficult to integrate new devices because each peripheral device requires a slave select.

The SPI protocol is used in smart meters communication [35] and personal health monitoring systems [36].

Table I summarizes the main characteristics of the SPI protocol.

D. *Power Line Communication: Home Plug (PLC)*

PLC is used for sending and receiving data on cables which are also used to simultaneously transmit power to the consumers. The use of power line cables is made possible with the aid of certain modulation techniques in order to allow high speed communication with minimal interference. Each socket acts as an access point to which appliances connect to. The appliances then communicate with each other through the power line. PLC is most suitable for real-time streaming applications.

The benefits and drawbacks of using PLC in HAN are mentioned below:

Advantages of using PLC:

- The setup cost of a PLC network is low since we use preexisting connections [37].
- Using preexisting cables to implementthe system doesn't require additional hardware [37].
- It is easy to integrate the system with a controller.
- High data transfer rates makes the PLC suitable for real-time streaming applications [38].

Disadvantages of using PLC:

- Data signals are susceptible to attenuation.
- Data signals are prone to electromagnetic interference (EMI).

PLC has been utilized in smart home appliances such smart refrigerators [37], smart ovens and air conditioner controls to pre-adjust the temperature and keep rooms comfortable [38].

Table I summarizes the main characteristics of the PLC protocol.

VI. Conclusions

This paper presented a comprehensive review on smart home architecture and home area networks. It discussed the most commonly used wireless and wired communication technologies in HANs. The major characteristics of the above mentioned networks such as data rate, frequency, range and latency were summarized and tabulated. Furthermore, it was found that the HANs will play very important role in smart home appliances technology which are designed based on Internet of Things (IoT) concepts.

Acknowledgment

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