Review of Communication Technologies for Smart Homes/Building Applications

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***Abstract*— A customer premises network (CPN) is a critical element to support messaging exchange among smart meters, an energy management unit, load controllers, smart appliances and electric vehicles in a smart home/building environment. Smart grid applications in a CPN generally are driven by the need for Home/Building Energy Management Systems (HEM/BEM). Design of an effective energy management system requires the selection of a proper communication technology. The objective of this paper is to compare commonly used wired and wireless communication technologies for smart grid applications in a premises area network in terms of their standard/protocol, maximum data rate, coverage range, and adaptation rate. These communication technologies include both wired solutions (e.g., Ethernet, ITU-T G.hn, Power Line Communication (PLC), Serial, HomePNA, MoCA) and wireless solutions (e.g., Wi-Fi, ZigBee, Z-Wave, Bluetooth, 6LoWPAN, IEEE 802.15.3a, Enocean, Wave2M, RFID, ONE-NET).**

Index Terms-**Smart grid, customer premises networks, home energy management system, building energy management system, industrial energy management system.**

I. Introduction

In the last decade since electricity demand has been steadily increasing, electric power systems have faced more stress conditions [1]. As the increase in electricity consumption is contributed by the increase in the demand for electricity in both residential and commercial sectors [2], deploying a customer premises network (CPN) can facilitate home/building automation to allow peak demand management, thus alleviating power system stress conditions. It is therefore important to select a proper communication technology for a CPN.

A CPN can be categorized into Home Area Network (HAN), Building Area Network (BAN), and Industrial Area Network (IAN), depending on the environment, i.e., residential, commercial, and industrial. These networks are connected to an electric utility via a gateway, i.e., smart meter or residential gateway, to enable smart grid applications for customers and utilities. A CPN also supports various smart grid applications for an electric utility, such as prepaid service, user information messaging, pricing, load control, and demand response. These applications do not require data to be transmitted at high frequency. Therefore, communication requirements for CPN applications are typically low power consumption, low cost, simplicity, and secure communications.

Typical smart grid applications in a CPN, such as HEM, metering, demand response, etc., are discussed in [3, 4, 5]. In [6], authors propose a comprehensive assessment of various communication technologies for CPNs and develop an approach for selecting suitable technologies for demand response applications. A contemporary look at the current state of the art in smart grid communications and networking technologies as well as assess their suitability for deployment to serve various smart grid applications are discussed in [7, 8]. In [9], authors provide a comprehensive review on smart home architectures and premises network communication technologies. They emphasize that CPNs will play an important role in smart home technologies which are designed based on Internet of Things (IoT) concepts. In [10], authors analyze the reliability and resilience of the IEEE 802.11 (Wi-Fi) communication technology in a BAN. In [11], authors analyze the latency, throughput, reliability, power consumption and implementation costs of commonly used communication technologies, including ZigBee, Wi-Fi and Ethernet, in a premises area network. In [12], authors describe a set of network performance metrics of most prevalent CPN network technologies, including 802.11, 802.15.4 (ZigBee) and P1901 (HomePlug). The authors propose a secure scheme for HAN based on Cloud of Things (CoT), which virtualizes the IoT and provides monitoring and control in [13]. CoT services in a CPN enable a collection of applications that use real-time data from these appliances.

There are many wired and wireless communication technologies, which can meet smart grid requirements for a CPN. Wireless communication technologies have more advantages over wired ones as they are easier to deploy and have more flexibility, scalability and portability than wired networks. However, it is still not clear which communication technology solution is best suited to support which application. The objective of this paper is to compare popular wired and wireless communication and network technologies in term of their standard/protocol, maximum data rate, coverage range, and adaptation rate for a CPN.

II. The Customer Premises Network Architecture and its Operational Requirements

This paper focuses on the customer domain of the smart grid, which includes residential and commercial customers, where electricity is consumed. A premises network for these customers includes HAN and BAN. HAN, together with an HEM system, provides communications for residential customers to monitor and control household appliances and equipment; while BAN with a BEM is for building automation and heating, ventilating, and air conditioning (HVAC) control in commercial buildings.

A CPN system typically consists of three major components: (1) an energy management unit, which provides monitoring and control functionalities; (2) load controllers, which monitor and control loads in a building, and sensors, which gather environmental conditions, such as ambient light and temperature, etc.; and (3) a gateway, i.e., a smart meter or a residential gateway, which receives price or demand response signals from a utility. Customers can monitor and control selected appliances and environmental conditions via an energy management unit, which may include an intelligent algorithm that can manage energy consumption and can guarantee minimum energy/peak demand consumption during a high electricity price period or a demand response event.

Examples of an HEM architecture is illustrated in Figure 1 where an HEM unit communicates wirelessly with appliances via a smart thermostat and smart plugs in a home area network. Figure 2 depicts a smart building environment where a BEM unit communicates with HVAC, lighting and plug load controllers wirelessly in a building area network.

Table I summarizes network requirements for home/building automation applications in terms of typical payload sizes, data collection requirements, reliability and latency [14]. Communication technologies that can support such requirements are discussed in the next section.

III. Various Communication Tecknologies for Customer Premises Networks and Challenges

In this section, various wired and wireless communication and network technologies commonly used in customer premises networks are discussed.

A. Wired Communication Technologies

1) Ethernet

Ethernet is a popular wired communication technology for promises area networks, generally providing local area network (LAN) and Wide Area Network (WAN) connections. Ethernet standard is based on IEEE 802.3. Ethernet implementation requires cables, which can be coaxial, twisted-pair or fiber optic, as well as a hub or a network switch. Ethernet can provide data rates ranging from 10 Mbps to 100 Gbps. Since Ethernet is a wired network, it is noise immune. However, once the network is placed, it is difficult to make changes. Devices can connect to an Ethernet network in a variety of ways using copper "twisted‐pair" cabling or fiber optics. Generally, copper cabling is used in CPNs. With a copper cable connecting to a hub or a switch in a star topology, a variety of speeds can be achieved including: 10 Mbps, 100 Mbps, 1000 Mbps and 10000 Mbps. 100 Mbps is the most common speed found in customer premises.

2) ITU G.hn

ITU-T G.hn is a wired communication and networking standard developed by International Telecommunication Union's Telecommunication, i.e., ITU-T. The goal of G.hn is to unify connectivity of digital content and media devices by providing a wired home network over telephone, coaxial, and data cable networks, as well as residential power line wiring to supply data at rates of up to 1 Gbps. ITU-T G.hn defines the physical (PHY, layer 1) and link (layer 2) layers for home-wired network. Thus, G.hn is designed for high/low rate broadband/narrowband in-home services. It extends its domain into an in-home smart grid area by enabling G.hnem [15].

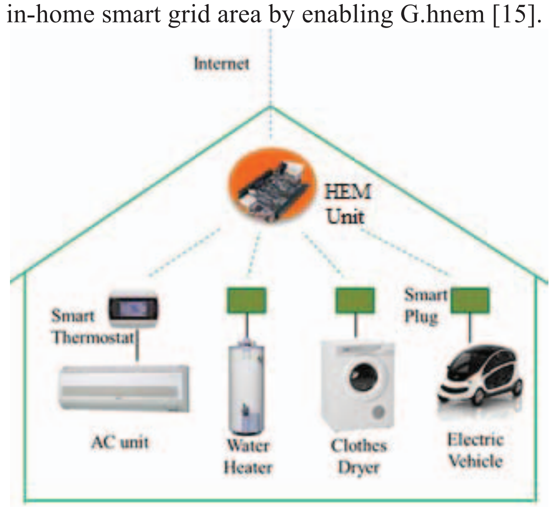

Figure 1. An example HEM architecture

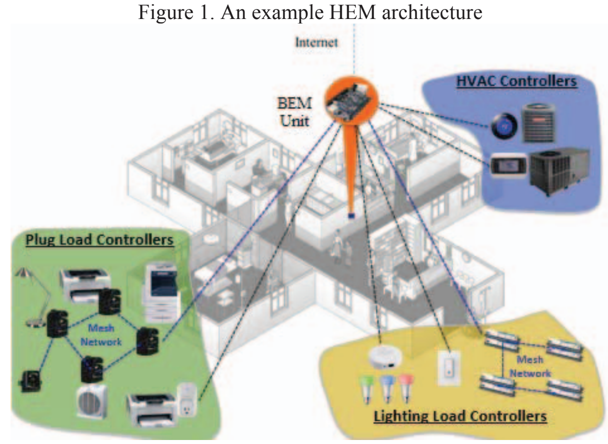

Figure 2. An example BEM architecture

TABLE I. NETWORK REQUIREMENTS FOR SMART HOME/BUILDING APPLICATIONS

Application	Typical Data Size (Bytes)	Typical Data Sampling Requirement	Latency	Relia-bility
Home Automation	10-100	Once every configurable period (e.g., one minute, 15 minutes, etc.)	Seconds	> 98%
Building Automation	> 100		Seconds	> 98%

3) Power Line Communication

Power line communication or power line carrier (PLC) uses the power line infrastructure to transmit/receive data. This communication technique injects a high frequency carrier onto the power line and modulates this carrier with the data to be transmitted. It is a cost effective means for data transmission since it uses the existing infrastructure without rewiring or modifications. The data rate of PLC can vary as there are various PLC technologies available in the market. In Europe, PLC is restricted to operate in the frequency spectrum ranging from 85 to 150 kHz, while in North America the frequency spectrum goes up to 540 kHz. For an in-home application, PLC devices usually operate between 20 and 200 kHz. Although PLC technologies are cost effective, they may not be suitable for use in many smart grid applications due to possible interferences, noises, distortions and security concerns. Several HomePlug specifications exist. Currently, there are two HomePlug specifications: HomePlug AV and HomePlug GP. Both of them are complaint with the IEEE 1901 standards. HomePlug AV supports speeds up to 200 Mbps. HomePlug GP is a subset of HomePlug AV specially designed for smart grid applications. It provides a data rate of up to 10 Mbps. HomePlug provides the coverage range of up to 300 m. Security with HomePlug AV is provided via 128‐bit AES Encryption. HomePlug Command □ Control (HPCC) is an alternative to the AV version and is designed for lower speed, very low-cost applications. In addition, □10 is an international and open industry standard that uses power line wiring for signaling and control of home devices. However, it suffers from some issues such as incompatibility with installed wiring and appliances, interference, slow speeds, and lack of encryption. It provides a data rate of up to 120 bps. Insteon addresses these limitations while preserving the backward compatibility with □10 and enables the networking of simple devices such as light switches using the powerline and/or radio frequency (RF). Insteon provides a data rate of up to 13 kbps. □10 provides the coverage range of up to 300 m, while Insteon provides up to 3 km. Other PLC technologies, i.e., LonWorks and CE Bus, are well established in the market. PLC products can be widely used to control lamps and appliances, replace wall switches and to monitor doors, windows and motion in CPNs.

4) Serial

Serial communication is a form of sending/receiving the bits of a byte in a timed sequence on a single wire. Serial communication has become the standard for inter-device communication. This is in contrast to parallel communications, where several bits are sent as a whole on a link with several parallel channels. Many serial communication systems were originally designed to transfer data over relatively large distances through some sort of data cable. RS-232 is the most common serial interface. It only allows for one transmitter and one receiver on each line. It can support the data rate of up to 1 Mbps, but most devices are limited to 115.2 kbps. RS-422 is the serial connection used on Apple computers. It provides the data rate of up to 10 Mbps. RS-485 is a superset of RS-422 and can support the data rate up to 10 Mbps [1□]. RS-232 provides the coverage range of up to 15 m, while RS-422 and RS-485 provide up to 1200 m.

5) HomePNA

HomePNA is an industry standard for interconnecting computers within a home using existing telephone lines. HomePNA allows to share a single Internet connection among multiple devices in a CPN. HomePNA operates at 128 Mbps and it goes up to 240 Mbps. The performance decreases if the network contains more than 50 devices. The range is up to 300m. It is a major competitor of Ethernet and HomePlug, and is considered as a major enabler of an in-house broadband distribution.

6) MoCA

MoCA is knows as Multimedia over Coax. It is a coax cable technology that is commonly used in a lot of homes especially in North America. It delivers the same high-speed network connection through an Ethernet cable, and delivers it through the existing coaxial cable. It provides a data rate of up to 800 Mbps. It uses an Ethernet-like frame and an Ethernet-like MAC layer. It has triple DES security, which is also very good to protect the network. It is suitable for enabling whole-home distribution of high definition video and content in CPNs. Maximum cable distance supported between the root and the last outlet is □0 m.

B. Wireless Communication Technologies

1) WiFi

WiFi is the most popular wireless technology used in a CPN. It is based on IEEE 802.11 standards: 802.11b-11 Mbps; 802.11g-54 Mbps; 802.11a-54 Mbps and 802.11n-300 Mbps. It can operate in 2.4 GHz, 3.5GHz and 5 GHz unlicensed ISM (Industry, Scientific and Medical) frequency bands. It provides the coverage range of up to 100 meters. It also provides reliable, secure and high-speed communications. However, it supports short-range communications. The cost and power consumption of WLAN products are also higher than other short-range wireless technologies such as □igBee and □-Wave.

2) ZigBee

□igBee is a wireless personal area network (WPAN) standard based on an IEEE 802.15.4. It is used in a network that requires low data rate, i.e., up to 250kbps, and long battery life, i.e., up to 10 years. A typical □igBee transmission range can be up to 100 meters depending on power output and environmental characteristics. This distance can be extended up to 1,□00 meters with □igBee-Pro. □igBee networks are secured by 128-bit symmetric encryption keys. It has 1□channels in the 2.4GHz ISM band (Worldwide), 10 channels in the 915MHz band (Australia and US) and one channel in the 8□8MHz band (Europe). When comparing □igBee data rates with those of other technologies, it may appear that □igBee has much lower data rates than others. In addition, □igBee can be deployed in a mesh network, which allowing □igBee in a mesh configuration to have high reliability and broader coverage range.

3) Z-Wave

□-Wave is a reliable, low-power, low-cost proprietary wireless communication technology that is suitable for short-range communications. It is designed specifically for remote control applications in residential and light commercial environments. It supports the data rate of up to 40 kbps and the coverage distance of up to 30 meters. □-Wave supports mesh networks, which makes it a good candidate for CPNs. However, it provides short-range communications and has low data transmission rate. It operates in 900MHz unlicensed radio frequency band used in Australia and North America, while 2.4GHz is unlicensed band used worldwide including Australia. Generally, 900MHz solutions provide significantly longer range and lower power. In addition, the freedom from Wi-Fi interference allows for a standardized low bandwidth control medium that can be reliable alongside common wireless devices.

4) Bluetooth

Bluetooth is based on the IEEE 802.15.1 standard, which describes a wireless personal area network. It operates in the 2.4□2.4835 GHz unlicensed ISM band and provides a data rate of up to □21 kbps. Bluetooth provides the coverage distance of up to 100 meters. It is typically used for portable personal devices. Bluetooth has no strong security layer to prevent eavesdropping. Therefore, it cannot satisfy tough security requirements, as compared to other wireless communication standards. Also it provides lower transmission coverage. It has some interference issues with 802.11. It covers both the physical access and the MAC layer and its very designed to operate in noisy environments.

5) 6LoWPAN

□LoWPAN is known as IPv□ over Low power Wireless Personal Area Networks. It is a networking technology that allows IPv□ packets to be carried efficiently within small link layer frames, such as those defined by IEEE 802.15.4. While □LoWPAN is originally conceived to support IEEE 802.15.4 low-power wireless networks in the 2.4-GHz band, it is now being adapted and used over a variety of other networking media including Sub-1 GHz low-power RF. □LoWPAN takes advantage of the strong AES-128 link layer security defined in IEEE 802.15.4. Its characteristics make the technology ideal for markets such as home automation with sensors and actuators, street light monitoring and control, residential lighting, smart metering and generic IoT applications with Internet connected devices. Today both 2.4 GHz and Sub-1 GHz bands can be used, building on the IEEE 802.15.4 advantages including support for a large mesh network topology, robust communication and very-low power consumption. The 802.15.4 standard provides 20□ 250kpbs data rates depending on the frequency. It is suitable for short distances from 10 to 100 meters.

6) IEEE 802.15.3a

IEEE 802.15.3a is known as Ultra-Wideband. It provides a data rate from 20 Mbps up to 1.3 Gbps. It is a very short range communication technology, i.e., 10 meters. It operates in the 3.1 to 10.□ GHz range that was recently approved in the European Union. It provides a little higher rate than the Bluetooth. It is well suited to be the physical layer for a high data rate PANs.

7) EnOcean

The EnOcean technology is an energy harvesting wireless technology, and EnOcean transmitters generate their energy from the environment, i.e., ambient light. This energy harvesting enables wireless and battery-less switches and sensors for building, home and industrial automation. EnOcean technology combines micro-energy converters with ultra-low power electronics. It is more energy efficient than other wireless communication technologies, such as Wi-Fi, □igBee and Bluetooth. It has potential applications in battery-less wireless communication for a control system, with more flexible implementation and operation, as well as reduced installation and maintenance costs [1□]. EnOcean supports the coverage distance of up to 30 meters indoor and 300 meters outdoor operating ranges. Transmission frequencies used for EnOcean devices are 902 MHz, 928.35 MHz, 8□8.3 MHz and 315 MHz. It provides a data rate of up to 125 kbps.

8) Wave2M

Wave2M is designed for ultra-low-power energy consumption and long-range transmission of small amounts of data and low traffic communications. Wave2M operates in the major license-free ISM bands around the world and complies with following regulatory standards - 8□8 MHz (Europe), 915 MHz (North America), and 433 MHz [18]. It provides the coverage range of up to 1000 m. While Wave2M maximizes the link budget to achieve the longest possible wireless range, it is not recommended for use in the 2.4GHz ISM band due to less efficient propagation conditions at the higher frequency. Wave2M supports data rates from 4.8 kbps to 100 kbps. Most Wave2M applications communicate at 19.2 kbps.

9) RFID

RFID is known as radio-frequency identification. It 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. It can coexist with other technologies, such as □igBee and Wi-Fi. RFID operates under a wide range of frequency bands, which vary from 120 kHz - 10 GHz and the detection distance can vary from 10 cm - 200 m. It can provide the data rate of up to 4 Mbps. RFID is used in home area network applications such as lighting control, etc.

10) ONE-NET

ONE-NET is an open-source standard for wireless networking. It is designed for low-cost, low-power (battery-operated) control networks, such as home automation, security □ monitoring, device control, and sensor networks. It is not tied to any proprietary hardware or software, and can be implemented with a variety of low-cost off-the-shelf radio transceivers and micro controllers from a number of different manufacturers. It uses UHF ISM radio transceivers and currently operates in the 8□8 MHz and 915 MHz bands. ONE-NET features a dynamic data rate protocol with a base data rate of 38.4 kbps. It supports the coverage distance of up to 500 m in the open area and up to 100 m inside buildings. It is suitable for home and building automation applications in the smart grid environment.

Table II summarizes these communication technologies for CPNs.

C. Challenges in Customer Premises Networks

Key challenges in CPNs are to integrate various communication technologies and to connect securely the entire house/building network to the Internet for remote monitoring and control. This is especially in today environment where a number of smart home/building products have become available. Examples of different HVAC, lighting and plug load controllers for smart home/building applications are given in Table III. As these commercially available products operate on different communication technologies and data exchange protocols, interoperability is one of the major concerns that needs to be resolved in order for a home/building to deploy any products in its environment. Lastly, consumer privacy is also an important issue that needs to be addressed. Vulnerability assessment in a CPN should be considered at the initial system design stage. Smart grid applications in CPNs, i.e., HEM/BEM, should be secured and protected through best practices available against all known threat models. Possible security attacks against its various key components in CPNs are identified in [19].

IV. Conclusion

This paper compares commonly used wired and wireless communication technologies in a CPN. Communication technologies under discussion are both wired solutions (i.e., Ethernet, ITU-T G.hn, PLC, Serial, HomePNA, MoCA), and wireless solutions (i.e., Wi-Fi, □igBee, □-Wave, Bluetooth, □LoWPAN, IEEE 802.15.3a, EnOcean, Wave2M , RFID, ONE-NET), which are compared in terms of their

Table II. Summary of wired and wireless communications technologies for customer premises networks.

Technology	Standard/Protocol	Max. Theoretical Data Rate	Typical Coverage Range	Market Adoption
Wired Communication Technologies				
Ethernet	IEEE 802.3	10Mbps-100Gbps	up to 100 m	Extremely high
ITU-T G.hn	ITU-T G.hn	1Gbps	N/A	Low
PLC	□10	120bps	up to 300m	Medium
	Insteon	13kbps	up to 3000m	
	IEEE P1901, HomePlug AV	200 Mbps	up to 300m	Medium
	IEEE P1901, HomePlug GP	10 Mbps	up to 300m	
	CE Bus	10 kbps	up to 3000m	Low
	LonWorks	1.25 Mbps	up to 3000m	Low
Serial	RS-232	1 Mbps	up to 15m	High
	RS-422	10 Mbps	up to 1200m	Low
	RS-485	10 Mbps	up to 1200m	High
HomePNA	HomePNA	240 Mbps	up to 300m	Low
MoCA	MoCA	800 Mbps	up to □0m	Low
Wireless Communication Technologies				
Wi-Fi	IEEE 802.11	2 Mbps	up to 100 m	Extremely high
	IEEE 802.11a	54 Mbps	up to 50 m	
	IEEE 802.11b	11 Mbps	up to 100 m	
	IEEE 802.11g	54 Mbps	up to 100 m	
	IEEE 802.11n	□00 Mbps	up to 250 m	
□igBee	IEEE 802.15.4, □igBee	250 kbps	up to 100 m	High
	IEEE 802.15.4, □igBee Pro	250 kbps	up to 1,□00 m	
□-Wave	□-Wave	40 kbps	up to 30 m	Medium
Bluetooth	IEEE 802.15.1	□21 kpbs	up to 100 m	High
□LoWPAN	IEEE 802.15.4	250 kbps	up to 100 m	High
IEEE 802.15.3a	IEEE 802.15.3	1.3 Gbps	up to 10 m	Medium
Enocean	EnOcean	125 kbps	up to 30 m	Meduim
Wave2M	Wave2M	100 kbps	up to 1000 m	Low
RFID	RFID	4 Mbps	up to 200 m	Medium
ONE-NET	ONE-NET	38.4 kbps	up to 100 m	Low

TABLE III. E□AMPLES OF DIFFERENT HVAC, LIGHTING AND PLUG LOAD CONTROLLERS WITH THEIR COMMUNICATION TECHNOLOGIES

	Manufacturer	**Product**	**Model #**	**Communication Technologies**						
				Power Line	**Ethernet**	**RS-485**	**Wi-Fi**	**ZigBee**	**Z-Wave**	**EnOcean**
HVAC	Trane	Smart thermostat	ComfortLink II						□	
	Radio Thermostat	Smart thermostat	CT-30				□			
	Magnum energy solution	Smart thermostat	M9-PFC-E020□□							□
	ExactLogic	Smart thermostat	E□L01□10			□				
	KMC	Smart thermostat	BAC-12□□□□			□				
	Danfoss	VFD	VLT series		□	□				
Lighting	Philips	Personal wireless lighting	Hue		□			□		
	WattStopper	Lighting control panel	LMCP or LILM series			□				
	Pulseworx	Lighting control panel	PCS LCP-U UPB	□						
Plug	WattStopper	Plug load room controller	LMPL-201			□				
	Digi International	Smart Plug	□Bee Smart Plug					□		

standard/protocol, maximum data rate, coverage range and adaptation rate. As wireless technologies provide lower installation cost, more rapid deployment, higher mobility and flexibility than its wired counterparts, wireless technologies are recommended in most of the customer premises network applications in the smart grid environment.

It is expected that this paper will benefit researchers and engineers who work in related fields by providing an insight into communication and network technologies for smart home/building applications in the smart grid environment. Additionally, comprehensive assessment as presented in this paper will enable reasonable technology selections for CPN applications.

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