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The Study of a ZigBee and Power Line Communication Connectivity-enabled Home Area Network Solution for Smart Grid

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Abstract: The choice between wired and wireless networks is commonly driven by grid topology and geographical environment as these factors have enormous influence on network performance and infrastructure cost. By analyzing and comparing their strengths and weaknesses of two leading communication technologies, a hybrid solution is proposed to operate Smart Energy Profile 2.0 over two underlying MAC/PHY technologies. The proposal solution provides a seamless connectivity between ZigBee and Power Line Communication networks to reap benefits from their respective advantages. Since the two technologies are complementary media, the combination is more appropriate than a single application or installation scenario. *Copyright © 2013 IFSA.*

Keywords: ZigBee, Power line communication, Home area network, Smart grid, Smart energy profile, Smart meter.

1. Introduction

Smart grid is a future-oriented power grid that uses sensing and communication technologies to gather and handle information, such as the consumer behaviors, and employ an automated fashion to improve the efficiency, reliability, economy, and sustainability of the production and distribution in electricity. The emergence of smart grid technology also means a fundamental reengineering of the electricity services industry, especially in the infrastructure.

2. Home Area Network

Smart grid deployments allow the utilities to manage and control energy distribution to their customers, and also allow the homeowners to better manage their energy usage through Home Area Network (HAN). The HAN is being developed from the need to facilitate communication and interoperability among electronic devices present within the close vicinity of a home or similar building structures, where smart appliances can be remotely controlled and monitored through a data concentrator and established a two-way communication to smart grid through an energy gateway.

As the name implies, the HAN is a dedicated network that enables connection and communication among smart appliances including HVAC (Heating, Ventilation and Air Conditioning), security, lighting and so on. These load control devices can be incorporated into an overall system. Today, the most civil high energy usage comes from heating/cooling, cooking, lighting, washing and drying [1]. These home appliances are beginning to become smart with connectivity features in order to reap benefits from smart metering and variable tariffs.

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Fig. 1 demonstrates a set of smart appliances that are interconnected within a HAN: In-Home Displays (IHDs) can work for power-consumption monitoring; Smart appliances can respond to time-of-use pricing signals; Smart thermostats can cycle the air conditioning in response to peak-load-reduction signaling from the utilities; Smart plugs can monitor power consumption and control appliances. These abilities of inspecting and governing devices within the HAN can be made available to both the consumers and the utilities. This can helps the consumers to better manage consumption and cost, also helps the utilities to better supervise supply and demand, and to react quickly during emergencies. In Fig. 1, HAN contains two types of gateways: one for smart grid, and the other for the Internet. The following will introduce how to combine these two gateways.

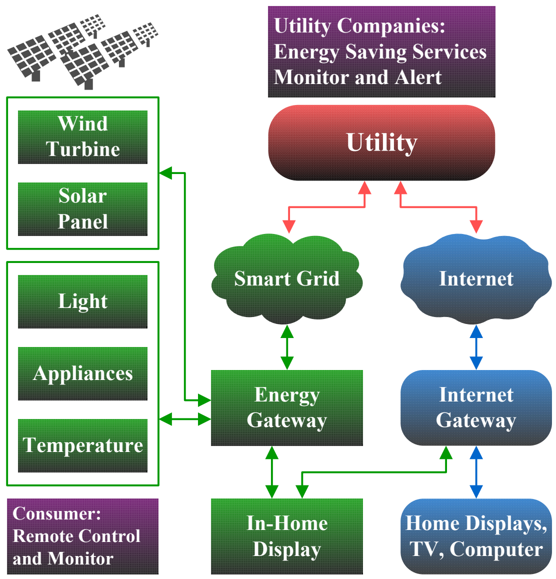

Fig. 1. The Home Area Network Deployment.

3. Communication Protocols and Standards

The HAN requires robust communications within a neighborhood area before sending information to the utility's central office through a backhaul link. Some communication technologies are up to date, but are not uniform because they have been developed in an evaluative fashion. Smart appliances in the HAN might communicate with each other via wired and/or wireless solutions, using multiple different communication protocols and standards.

The HAN emerged in the late 1990s and fueled in the early 2000 s by the growth of the Internet [2]. The existing communication protocols and standards should expect to welcome the HAN. However, with the present onset and development of smart grid, the authorized smart appliances are entering the HAN filed where their new demands revolve data rates and power consumption. The communication technologies applied in Internet, such as Ethernet and Wi-Fi, have been developed to move large amounts of data quickly through a network at somewhat intermittent intervals (e.g. graphics, music, video, etc.). The most existing home or office networks allow desktop and laptop computers to communicate with each other for resource sharing and often provide a common connection to the Internet. The types of devices on existing networks include media servers, televisions, game consoles and other entertainment devices, all of which meet the intermittent and high bandwidth requirements.

Since the requirements of smart grid are significantly different from Internet, it only requires a relatively low bandwidth but maintains regular communications. These differences open a door for other communication protocols and standards to enter the HAN field. Achieving a vision of smart grid at the consumer level allows user to better understand and manage their energy consumption, thus which will require many new types of devices with lower bandwidth but regular and consistent data stream [2].

There are some standards and protocols striving for dominance in smart grid field. With so many devices needing to be connected to smart grid, the consumers and manufacturers have best interests to identify the most worthy candidates and settle on those for purposes of interoperability, economies of scale and ease of adoption [2]. The following will focus primarily on two leading standards: power line communication and ZigBee.

3.1. Power Line Communication

Using existing wires within a home offers many benefits over installing a new network with the inherent costs and frustrations. The two options that exist in nearly every home are telephone lines and power cabling. There are technologies and standards that exist for both types of wires, but since the major goal of smart grid is to monitor and manage electric power usage, HomePlug Green PHY (GP) may be the best choice to use electrical wiring for data transmission. Another factor not to use telephone lines is the limited coverage of phone lines in home construction.

HomePlug GP is a low-power, robust data communications technology that provides data rates of 4 to 10 Mbps over an electrical wiring. The HomePlug GP specification defines the Media Access Control (MAC) and Physical Layer (PHY) for Power Line Communications (PLC) in HAN and has recently been adopted as a profile of the IEEE Standard 1901 for broadband over power line networks [3]. A complete network stack is achieved by utilizing the TCP/IP protocol suite on top of HomePlug GP. AES-128 encryption is used to ensure the confidentiality of transmissions.

Even though HomePlug GP implements a subset of the functionality decreed by the HomePlug AV specification, HomePlug GP and AV devices are compatible and can coexist within the same network. The most important requirements of HAN are low power and cost, reliable communication, and compact size over broadband capacity. The HomePlug GP devices combine the reduction with the ability to sleep, thus deliver up to 75 % device power savings over HomePlug AV devices [4].

Advantages

a. HomePlug GP operates over the house's existing electrical power lines. Any appliance or device requiring power will be attached this system.

b. Data rates of 4 to 10 Mbps surpass smart grid requirements.

c. HomePlug AV and HomePlug GP standards have strong backing from major sponsors.

d. Unlike Ethernet, no new wiring is required. Moreover, Ethernet requires devices to have two connections: one for power, and one for data. HomePlug GP requires only a single connection—the power cord—that serves both functions.

e. Electrical wiring systems already extend throughout buildings thus alleviating the need, in most cases, for network extending devices.

f. AES-128 in Cipher Block Chaining (CBC) mode ensures confidentiality of the transmissions.

Disadvantages

a. The development on the HomePlug standard began in 2000, and until recently was widely accepted.

b. Limited devices are available on the market. Most HomePlug devices serve as Ethernet-to-HomePlug network bridges.

c. Forward Error Correcting codes (FECs), while necessary, add cost and complexity to HomePlug GP devices that the other technologies do not need.

d. If not properly configured all networks within a building (e.g. apartment building) will intervene each other.

3.2. ZigBee Wireless Communication

The ability of wireless device has great appeal. The wireless market has produced tremendous growth in the past decade. This trend is expected to continue. Wireless technology is moving from laboratory environment into industrial and household arenas. Within these areas there is a focus on low power and low bandwidth versus the traditional wired power and high bandwidth.

ZigBee is a wireless protocol developed specifically for low power and low data-rate communications. ZigBee builds upon the MAC and PHY defined by IEEE standard 802.15.4 (2003 version) for low-rate Wireless Personal Area Networks (WPANs). Like IEEE 802.11n, IEEE 802.15.4 radios operate on the ISM (Industrial, Scientific and Medical) bands. Unlike IEEE 802.11n, ZigBee end devices are intended to be battery operated for up to five years on one charge. ZigBee makes an energy-saving goal through a number of design specifications, namely: a simplified protocol stack, low data-rate transfers, short-range transmissions [5]. Furthermore, ZigBee networks can be configured in either a star or mesh topology. Fig. 2 depicts the architecture of ZigBee protocol stack.

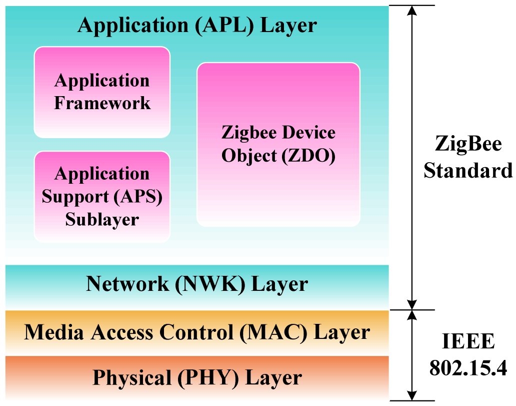

Fig. 2. ZigBee protocol stack.

Table 1 indicates some basic technical details on ZigBee. The data rate of ZigBee varies depending on the ISM frequency used. Full technical specifications may refer to the full standard [5].

Table 1. ZigBee Network Standards.

ZigBee network standards on top of IEEE 802.15.4						
Freq.	Local	Data rate per channel (kbits/s)	Number of channels	Modulation	Approx. indoor range (m)	Approx. outdoor range (m)
2.4 GHz	Worldwide	250	16	DSSS w/ OQPSK	10	75
915 MHz	America	40	16	DSSS w/ BPSK	10	75
868 MHz	Europe	20	16	DSSS w/ BPSK	10	75

Since ZigBee is intended for low data rate, long battery life applications, it is most often used in control physical devices such as: door locks, security sensors, load controllers, thermostats, energy management consoles and remote controls. In addition to the core ZigBee specification, multiple standards have been developed for specialized applications such as: building automation, health care, home automation, input devices, light link, remote control, retail services, smart energy, and telecom services, etc. These areas are almost involved in HAN.

Beside the ZigBee specification, the ZigBee alliance has developed and made some available ZigBee Profiles. These profiles define the functionality of the device and interoperability requirements. The Smart Energy Profile (SEP), Home Automation (HA), Commercial Building Automation (CBA) are a few of the available profiles. Moreover, the devices can be designed and certified to meet specific profiles and can be tailored for specific customer applications.

Advantages

a. Many commercial products are currently available.

b. The certification process helps ensure interoperability.

c. Strong vendor consortiums support it.

d. Low-cost and low-power devices are available.

e. ZigBee Profiles can be applied to other technologies and allow for interoperability between technologies.

Disadvantages

a. Due to underlying IEEE 802.15.4 technology, bandwidth limitations (250 Kbits/second per channel) may limit some smart grid applications for larger networks.

b. Security is optional.

c. Utilizes potentially congested ISM bands.

4. ZigBee-PLC HAN

Our previous research works are to develop and evaluate a versatile HAN installed for a large group of buildings. Considering only wireless solution can not cover more room and not penetrate through thicker wall, and also considering only wired solution can cause wiring problem and increase maintenance cost, our solutions is to provide a seamless connectivity between ZigBee and PLC networks for HAN application.

Fig. 3 shows that a ZigBee and PLC connectivity-enabled HAN can manage every aspect of energy consumption in a home building, and establish a two-way communication between the customer and the utility across both wireless and wired media. ZigBee technology allows the devices to communicate with other devices on the air. PLC technology allows ZigBee routers to connect together in different room units and communicate with the remote central office by power line.

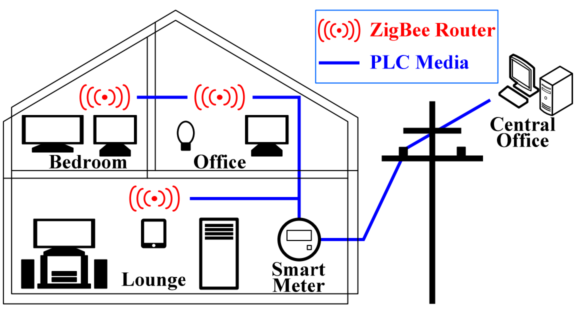

Fig. 3. A ZigBee and PLC Connectivity-enabled Home Area Network demonstration.

4.1. Smart Energy Profile

With the emergence of multiple smart energy devices, it is becoming increasingly clear that all devices interoperate in a network. The ZigBee alliance is working on a specification called the Smart Energy Profile 2.0 (SEP 2.0) to help formalize the requirements for many aspects of the smart energy ecosystem including device communication, connectivity and information sharing requirements [6].

Fig. 4 shows that the physical architecture of the dual media configuration is based on a single combined ZigBee and PLC network, which consists of ZigBee only devices, PLC only devices and ZigBee and PLC dual devices. All physical architecture runs a SEP 2.0 above two different underlying MAC/PHY technologies: IEEE 802.15.4 for the ZigBee and HomePlug GP for the PLC.

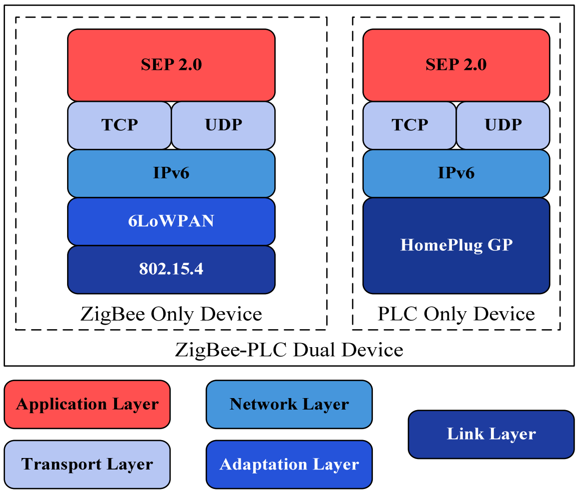

Fig. 4. The physical architecture of the dual media configuration.

SEP 2.0 is an IP-based application specification under development by the ZigBee and Wi-Fi alliances along with other industry groups. SEP 2.0 has also been identified by the National Institute of Standards and Technology as the recommended protocol for energy information and control in the HAN [7]. SEP 2.0 is a PHY diagnostic profile that is designed to run on multiple PHY technologies such as IEEE 802.15.4, PLC, Ethernet, and Wi-Fi. Device manufacturers can implement any MAC/PHY under an IP layer. This is important in the HAN as it allows consumers to purchase different types of SEP 2.0-enabled products and be assured that they will interoperate. It also enables SEP 2.0 devices to be seamlessly integrated with existing IP-based utility IT infrastructure [8].

SEP 2.0 is designed to run on top of an Internet Protocol (IP) stack. Depending on the physical substrate in use, a variety of lower layer protocols may be involved in providing a complete solution. SEP 2.0 replaces the ZigBee Pro protocol stack used by SEP 1.x with the ZigBee IP stack, which uses the 6LoWPAN protocol to encapsulate the proprietary ZigBee packet structure within a compressed IPv6 packet. The ZigBee IP stack also creates a clean interface at the transport layer that allows SEP 2.0 packets to be carried by nearly any IP-based network technology. The most recent draft version of the SEP 2.0 Profile includes support for communication across ZigBee, HomePlug, Wi-Fi, Ethernet, and other IP-capable platforms [8].

1) Application layer

The SEP is designed to implement a RESTful architecture. The REST design pattern uses HTTP actions (GET, PUT, POST, and DELETE) to define the application services. Fig. 5 shows an example that a personal area network (PAN) can offer to read a meter. The PAN first discovers the service, then, a list of resources is extracted. A meter is then selected and a reading type is chosen. A final GET request is sent to read the meter values.

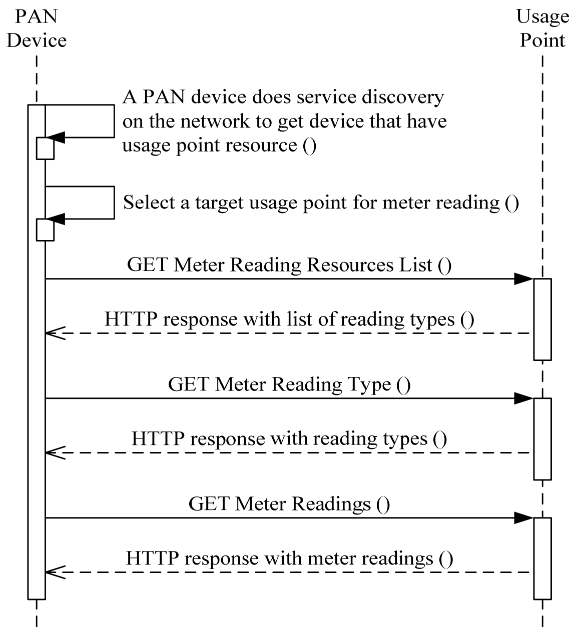

Fig. 5. Use Case - Get meter reading.

Any protocol that can implement the GET, PUT, POST, and DELETE command set could likely be used with SEP 2.0, but HTTP is the required protocol for interoperability. HTTP utilizes TCP as its transport protocol. As a result, TCP manages the session providing delivery assurance and windowing. HTTP also provides a variety of caching and cache management mechanisms that may be used.

2) Transport Layer.

Since the application is based on HTTP, Transmission Control Protocol (TCP) is required. Also, all devices must support the User Datagram Protocol (UDP) beside TCP.

3) Network Layer.

The Smart Energy 2.0 Profile will use Internet Protocol Version 6 (Ipv6).

4) Adaptation Layer.

IPv6 requires the maximum transmission unit (MTU) to be at least 1280 bytes compared to 127 bytes in 802.15.4. Thus, IEEE 802.15.4 devices will use 6LoWPAN adaptation layer. 6LoWPAN protocol provides encapsulation and compression for IPv6 packets to be sent on 802.15.4 networks. An adaptation layer between the link layer and the network layer is necessary to act as a bridge among Ipv6 and selected substrates.

5) Link Layer.

The link layer is based on IEEE 802.15.4. However, ZigBee Smart Energy is designed to work with a variety of protocols such as IEEE 1901 (PLC), IEEE 802.3 (Ethernet), IEEE 802.11 (Wi-Fi), WiMAX, and so on. IEEE 802.15.4 networks are limited to 65535 nodes because the address length is limited to two bytes. In reality IEEE 802.15.4 networks should be far below this limit since large networks are decomposed into small networks.

4.2. Smart Meter

With smart grid deployment in most areas of the globe, smart meter requirements around the world are rapidly evolving in response to market forces and governmental regulations. Smart grid applications such as dynamic pricing, demand response, remote connect and disconnect, outage management, network security, and reduction of non-technical losses are driving the needs for increasing technological sophistication in today's smart meter solutions [8].

Advanced Metering Infrastructure (AMI) is an imperative infrastructure of the smart grid and being deployed by utilities around the world and are rapidly proliferating after the early adopter projects in Western Europe and the United States [1]. Today, AMI projects are being planned and deployed in all regions of the world including some countries such as China, Japan, Brazil, and South Africa.

Smart meter is commonly an electrical meter that records electricity consumption in one hour or less time intervals, and exchanges information with the utility for monitoring and billing purposes. Smart meter performs power or electricity metering and has the capability of transferring key meter data via wired and wireless sensors to form a simple Automatic Meter Reading (AMR) system.

Fig. 6 shows our smart meter design that has the ability to measure energy and transmit metering information via hardwire for PLC and wireless for ZigBee communication modules. These main modules and units include:

1) Metrology.

At the heart of any smart meter is the basic energy measurement function. It is critical that utilities and consumers can rely on the accuracy, security and reliability of this metering capability. Moreover, protecting meter integrity is a key to reducing non-technical losses in the field.

2) Application Processing.

Since the evolving requirements of smart grid across the world continually are impacting meter architectures. For a separate metering host or applications processor, the requirements vary by market and product. In some designs, a low-cost 16-bit MCU with 128 kB flash is perhaps suitable as a host. However, other design may require a 32-bit MCU with 1MB flash to support more advanced metering functions or multiple communications stacks. The most advanced smart meters may use an embedded microprocessor that operates a high-level operating system such as Linux with multi-megabytes memory on the board. The microprocessor must be able to support the multiple applications and external interfaces required in smart meters. Meter data management applications such as DLMS/COSEM and communications stacks such as ZigBee and PLC are all evolving to require larger amounts of memory and processor performance.

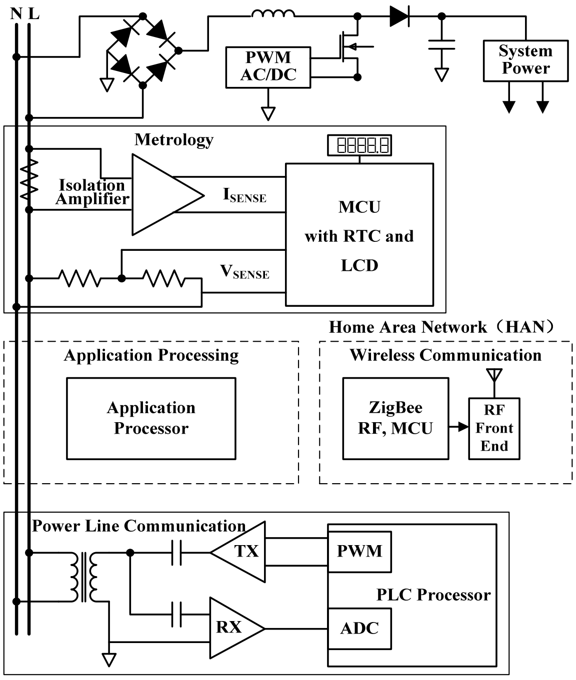

Fig. 6. Smart Meter Architecture.

3) Wireless Communication.

For AMI networks, industrialized ZigBee RF transceivers can offer the best performance for blocking immunity and adjacent channel rejection which means that this solution has a larger link budget and can communicate over longer distances in noisy RF environments. This will improve network performance and lower the costs of utility infrastructures.

4) Power Line Communication.

PLC offers the advantage of reusing existing infrastructure to lower costs, retain reliable performance and maintain scalability to larger network sizes. Modern PLC networks can utilize OFDM (Orthogonal Frequency Division Multiplexing) modulation techniques to increase data throughput rates and reliability in inherently noisy environments such as electric grids.

5. Conclusions

Home Area Networks can be implemented via both wired and wireless solutions, using multiple different communication protocols and standards. Smart appliances can be remotely controlled and monitored through a data concentrator and established a two-way communication to smart grid through an energy gateway. Our ZigBee and PLC connectivity-enabled HAN solution combines the advantages of multiple media to extend the coverage by providing the ubiquitous connectivity. Since ZigBee and PLC are complementary media, the combination of two technologies is more appropriate than a single application or installation scenario.

Acknowledgements

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