A Survey on Smart Home Networking

Jin Cheng and Thomas Kunz

Department of Systems and Computer Engineering
Carleton University
Ottawa, Ont., Canada

TABLE OF CONTENTS

LIST OF FIGURES

I. Introduction

As [1] suggested, a smart home is understood as an integration system, which takes advantage of a range of techniques such as computers, network communication as well as synthesized wiring to connect all indoor subsystems that attach to home appliances and household electrical devices as a whole. In this way, smart home techniques enable households to effectively centralize the management and services in a house, provide them with all-round functions for internal information exchange and help to keep in instant contact with the outside world. In terms of convenience, they help people in optimizing their living style, rearranging the day-to-day schedule, securing a high quality of living condition and in turn enable people to reduce bills from a variety of energy consumptions in a house.

Home automation [2], which initially originated in the US, is one of the most fundamental technologies in smart home system design. It employs microcontrollers to monitor ovens, washing machines, lighting, refrigerators, and HVAC facilities (Heating/Ventilation/Air-Conditioning) with respect to temperature or humidity and to adjust accordingly to meet the home owner's requirements. Therefore, it is obvious that home automation to some extent takes responsible for the indoor energy management and supervision with the instructions of household owners.

The rest of the review is organized into four sections. Section II covers the aspects of home appliances control ranging from the power sources and electricity consumption in smart homes, to the specific control scenarios along with the operation mode. Section III further discusses the categories of networks based on their functionalities in a smart home and presents a group of benchmarks targeted for networking technologies available in the areas of home appliance control. Section IV introduces the basic concept of PLC technologies and various PLC protocols, summarizing their performance, solutions feasible to a smart home, potential issues associated with home control networking along with a brief comparison among these protocols. Section V presents relevant protocols in low-rate wireless network technologies, addressing the same issues as PLC technologies. The conclusion summarizes the discrepancies between PLC technologies and low-rate wireless networks and suggests a constructive solution suited for a home control network harmonizing electricity management with other indoor control subsystem.

II. Home appliances control in smart homes

To better understand the networking and control pattern in smart homes from the perspective of energy conservation, it is necessary to investigate the electric power sources that support the normal operation and management in a house, the energy usage in most residences, the specific operation mode of home appliances and renewable energy sources and storage facilities, and then to explore what kind of configuration and control are indispensable to build a smart home. Meanwhile, architectural and functional requirements on behalf of utilities in the design of smart homes should be taken into serious consideration in that home energy control is part of smart grid infrastructures.

2.1 Generation and storage of renewable energy sources

In terms of energy saving and the improvement in efficiency, the energy management in a smart home is also designed in the context of smart grid infrastructures. Conceptually, a smart grid [3] integrates electronics and information technologies into the massive electric systems in such a way as to strengthen reliability, flexibility, security, safety and efficiency as a whole. Put specifically, the implementation of smart grid technologies minimizes the electricity usage during costly peak hours by coordinating the load balance in the systems and leveraging demand-response mechanisms with time-based pricing notification oriented towards residents. As part of a smart grid, it makes great sense that a smart home includes the AMI (Advanced Metering Infrastructure) that is deployed by utilities to enable the management of dynamic tariffs in homes, smart appliances intended for energy-awareness, renewable energy sources and plug-in vehicles as well as the HEMS (Home Energy Management System) [4].

To some extent, distributed renewable sources installed in a house are here to mitigate the peak load in the power grid system in case of unexpected outages or blackouts. It is obvious that renewable energy sources are mostly generated by solar or wind power (Geothermal heating generation systems are limited to geographic locations and climates). The PV (photovoltaic) electric systems or solar panels [5] convert solar energy into electric power while wind turbines [6] utilize the kinetic energy in wind to produce electricity. Meanwhile, power conditioning units such as DC/AC (Direct Current/

Alternating Current) inverters/converters are deployed in residences for the convenience of household appliances and the power grid systems. Thus, the surplus electricity output generated by the PV system or the wind turbine could be fed back into the power grid system and in turn offset the residential energy consumption by the adjustment of AMI.

A PEV or PHEV (Plug-in Electric Vehicle /Plug-in Hybrid Electric Vehicle) [7] is a vehicle with a rechargeable battery that could be connected to an electric power source by a built-in plug. The PEV/PHEV is charged flexibly in terms of time range and energy sources. In other words, the PEV/PHEV could be charged during off-peak hours responding to the time-differentiated prices in AMI or be charged by the PV system or the wind turbine when natural powers are available in time for energy conversion.

In addition to reducing the consumption of fossil fuels and the emission of greenhouse gases, the PEV/PHEV mainly serve as a temporary energy storage bank intended for the power grid system and residential consumption [8]. For one thing, the massive aggregation of PEVs/PHEVs plugged in the power grid tremendously contributes to the peak demand and thus vehicle owners could get credit through the operation of AMI; for another, the energy bank built in the PEV/PHEV also act as a temporary power supply for home appliances in case of emergency. Currently, the main issues associated with the vehicle batteries include unacceptability in supporting longer mile ranges, shortness in battery life cycle, affordability in terms of cost and size, as well as the consumer safety coming with the vehicle innovation [9]. Even so, the author in [10] established a model simulating a renewable ecosystem based on statistical data and then concluded that the combination of renewable energy generation systems along with PEVs/PHEVs plays a significant role in operational cost and environmental influences in terms of reduction in petroleum consumption and carbon dioxide emission.

The deployment of HEMS integrated with renewable energy facilities owned by residents is illustrated as follows:

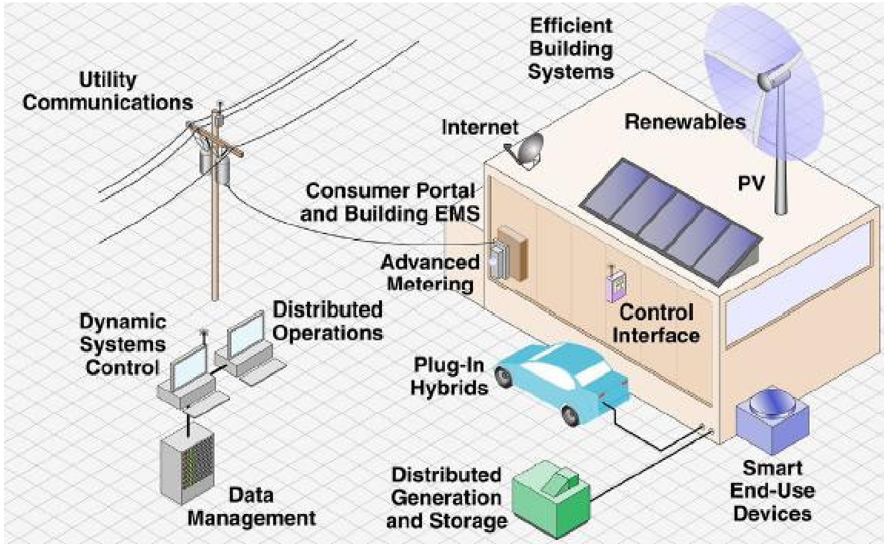

Figure 1 Household renewable energy management in the context of smart grid [4]

In addition to supervising the energy consumption by home appliances, the HEMS is also capable of managing the operations of solar panels and wind turbines, as well as the charging of PEV/PHEV as the back-up energy source. Specifically, the control interface in the HEMS acts as the central controller intended for home energy management and coordination. Based on the resident's preferences, the central controller cooperates with a smart meter deployed by utilities to schedule the usage of energy for home appliances. In such case, the dynamic pricing notifications are issued by utilities via power line or through other communication mediums to the smart meter. Following that, the central controller determines whether to introduce other energy sources available in the house, including PV system (solar panels), wind turbine and PEV/PHEV. If necessary, the central controller directly cuts off the power supply for a couple of home appliances and postpones their execution to off-peak periods (at night) for cost saving. Meanwhile, the central controller could be connected to the Internet for the purpose of remote monitoring.

One of the enabling technologies behind HEMS is the home automation network or the home appliance control network, where the control interface functions as the control platform/residential gateway in essence.

2.2 Categories of energy usage in residences

Based on the concept of a smart home, Figure 2 illustrates an example of the composition of a smart home, equipped with the control network, sensors and actuators:

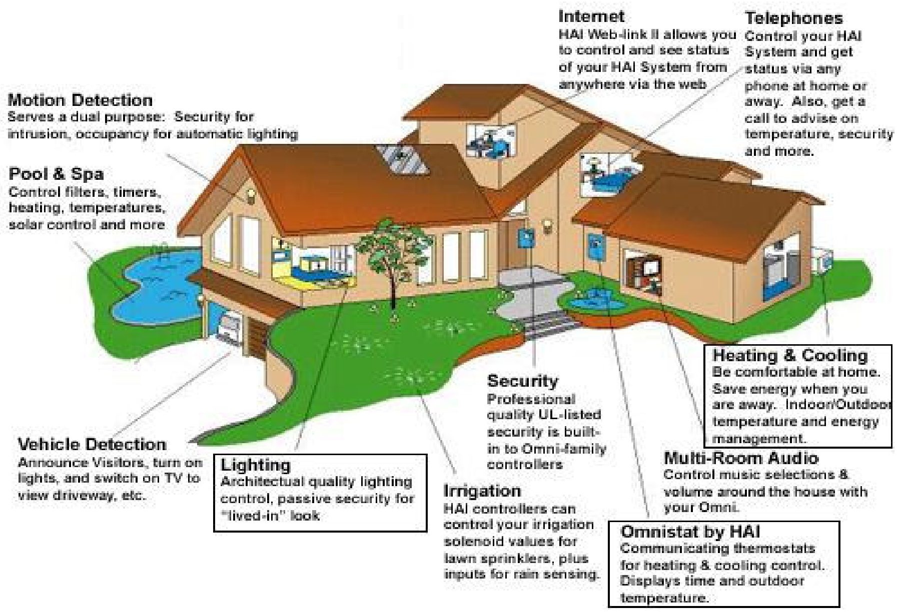

Figure 2 Functional composition of a control-oriented smart home [12]

The main sources of energy consumption are the home appliances associated with heating and cooling, kitchen devices as well as lighting facilities. Among them, the operation of heating and cooling accounts for over 56% out of the total residential electricity consumption [13].

Even worse, a considerable amount of energy is not fully utilized by residents and energy waste takes place all day. The author in [14] listed a group of factors that led to energy loss in a house as follows:

1) Endless working status of healing/cooling system in unoccupied houses and rooms
2) Overheating or overcooling to compensate for the temperature difference due to the constraints of a centralized thermostat.
3) Potential energy leakage due to appliances in a turned-off or standby mode (detailed data evidence was also found in [13]).

Inevitably, the improper applications of household appliances along with the lack of a smart energy infrastructure contributes to unnecessary energy consumption or waste in most residences.

2.3 Redefinition of the operation mode in a smart home

In terms of energy management, the operation mode is intended for two categories: home appliances, and renewable energy sources covering PV systems (solar panels), wind turbines and PEV/PHEV.

The home appliances are classified into four groups based on their own operation mode and redefine their schedule for execution or closure considering the practical demand of electricity.

1) HVAC system integrated with thermostats and Infrared/motion sensors

- Device registration when plugged in initially
- Switched on partially for the room when the room is occupied
- Switched off totally when nobody is at home
- Switched off according to the demand-response notification during peak hours
- Postpone normal tasks to off-peak hours (i.e. at night)
- Cut off from the power board(namely the distributed power board with multiple outlets that allows a couple of devices to be plugged in simultaneously) when the house is unoccupied in case of electricity leakage
- Adjust the temperature/humidity in the room for occupants (i.e. at night) with the support of thermostats

2) Daily appliances (i.e. refrigerator with thermostat, water heater with thermostat, washing-machine, clothes dryer, dish washer, oven, etc.)

- Device registration when plugged in initially
- Switched off according to the demand-response notification during peak hours
- Postpone normal tasks to off-peak hours (i.e. at night)
- Cut off from the power board when unused

3) Lighting system connected with temperature sensors and dimmers

- Device registration when plugged in initially
- Switched off when the house or the room is unoccupied
- Cut off from the power board when unused
- Adjust the strength of lamination for occupants (i.e. at night) with the support of dimmers and temperature sensors

4) Digital entertainment appliances with Infrared or motion sensor (i.e. TV, video recorder, Hi-Fi equipment, etc)

- Device registration when plugged in initially
- Switched off when the house or the room is unoccupied
- Cut off from the power board when unused

In general, the effective measurements of energy conservation are to turn off the appliances when unused, to adjust the electricity level to the indoor environment including brightness, temperature and humidity, and to suspend the scheduled tasks to off-peak hours. In terms of specific commands and instructions from the perspective of home appliance control, they can be grouped into four parts: device registration, switching on/off, suspension/resumption of the operation schedule as well as the adjustment of degree based on the dynamics of environment.

The operation mode targeted for renewable energy sources are classified into two parts due to the difference between generation facilities and storage devices.

1) PV system/wind turbine

- Device registration when plugged in initially
- Request for power supply both in a house and in the power grid

2) PEV/PHEV

- Device registration when plugged in initially
- Request for power supply both in a house and in the power grid
- Switched off according to demand-response notification during peak hours

- Postpone the charging task to off-peak hours (i.e. at night)

Even though these sources are connected to the control network, there is no guarantee that the backup energy is always ready for use in that they are susceptible to the weather condition and the battery storage capacity/status.

From the perspective of energy utilization, what mostly happens in a smart home due to the dynamics of electricity prices is illustrated as follows:

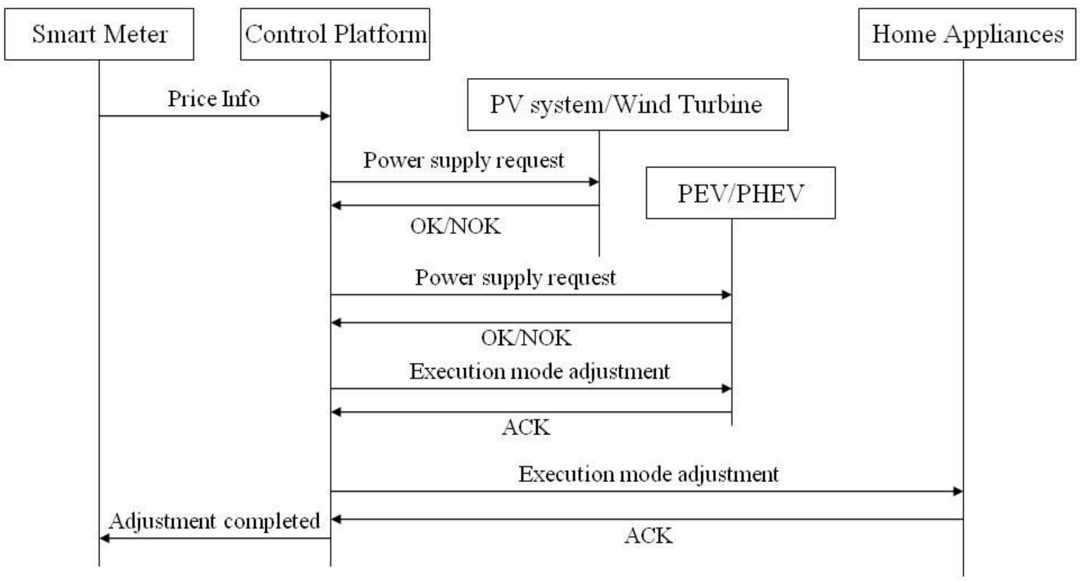

Figure 3 Adjustment of the execution mode based on price notification

Specifically, we assume that the current electricity price becomes higher than previously received. Upon reception of this information from a smart meter, the control platform chooses to adjust power supply and energy consumption as well in the house: Firstly, it checks with the energy generation and storage facilities one by one by issuing a power supply request. If power is available, the facilities automatically switch their output towards the whole residence, with the power grid as a supplement; otherwise, the control platform sends a postponement message to all devices (including PEV/PHEV) featured with high power consumption regardless of their its current operation status and simply cut off power for a couple of devices in case of emergency. If some devices run at task mode (such as automatic defrosting of the refrigerator, heating of the water heater, temperature/humidity adjustment of the HAVC facilities, working mode of the dish washer, the washing machine, as well as the clothes dryer, etc.), they suspend their task immediately and return back to a low power consumption mode with an acknowledgement to the control platform, waiting for the next control message for task resumption.

2.4 Basic configuration and context control of a home control system

Based on the suggestions in [14] [15], the standard components for energy conservation in a smart home are summarized as follows:

- Home control platform or gateway intended for the control and management of the control network
- A intelligent utility electrical meter that keeps track of the power usage and serves as a portal of electricity information between utilities and household owner
- Renewable generation sources (solar panels/wind turbine) and energy storage facilities(PEV/PHEV)
- Wired (through power line) and wireless networking protocols and smart devices
- Networked programmable thermostats intended for cooperation with HVAC/refrigerator/water heater/lighting system to adjust and schedule tasks based on parameters sampled from target sensors [16]
- Sensors intended for strength of light, temperature, humidity and motion of objects
- Networked power boards over power lines connected to home appliances

A simplified example of the configuration is illustrated in Figure 4(without renewable generation sources and energy storage facilities attached):

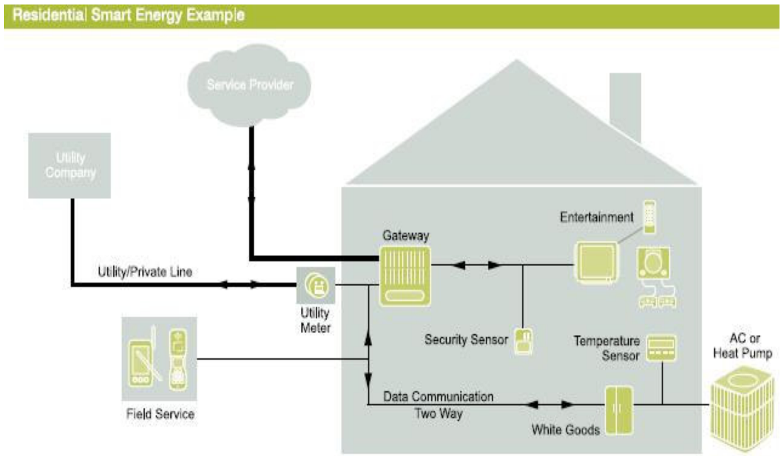

Figure 4 A simplified example of energy conservation networking pattern [17]

Technically, the information about home appliances is registered manually or automatically in the database of a home control platform (or home gateway), including its control mode (on/off/suspension/resumption/level adjustment), device type, identification and address, operation status, etc. when they join the network.

With the support of a smart energy infrastructure, the control of home appliances combines the contextual adjustment with flexible strategies of power usage intended for home appliances with high or low power consumption respectively.

Specifically, the smart control mainly consists of three types of scenarios:

1) When the residents stay at home, only appliances currently necessary for the residents are working, whereas others are cut off entirely from the power board to avoid standby mode. Meanwhile, the thermostat of controlled appliances (HVAC/refrigerator/water heater) cooperates with sensors/actuators to maintain a certain temperature suitable for residents.
2) When there is nobody at home, all unused appliances are cut off from the power board except the refrigerator; when the residents return home, the motion sensors may notify the control platform to guide all home appliances with thermostats into normal operation mode (i.e. a timed mode that lasts for a preset time range)
3) When the meter receives the notification of demand-response from utilities, it cooperates with the control platform to temporarily switch off all high-power

appliances in use or to postpone their scheduled tasks to off-peak hours at night when renewable generation sources and energy storage facilities are unavailable for power supply. Meanwhile, the total power of residences could also be calculated dynamically to determine whether they exceed a threshold. This could then trigger the control platform to take actions to further cut off the power of the rest of appliances still in operation based on a strategy of time-based pricing for electricity.

To sum up, smart control can be distributed when the thermostat helps to adjust the operation mode of controlled appliances or be centralized from the control platform to all appliances when a demand-response event or other emergency cases occurs in the house.

2.5 Technology independent requirements of utilities in a smart home

2.5.1 The framework of Home Area Network

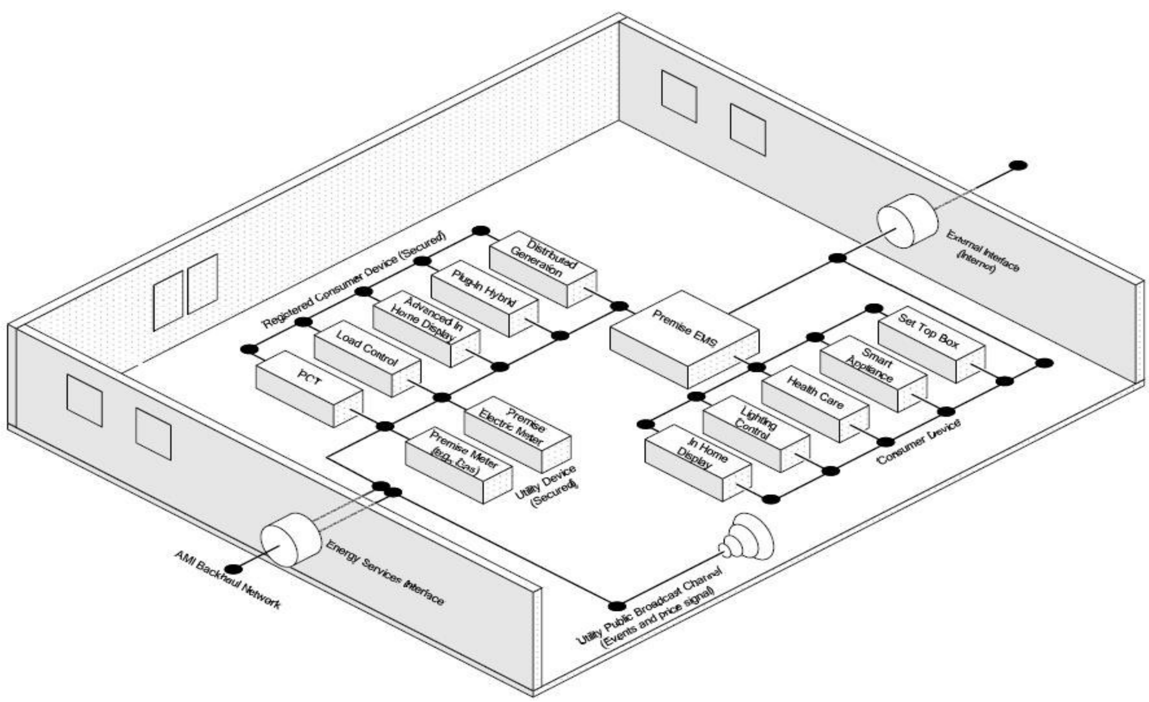

Figure 5 A mature Home Area Network in secure communication with utilities [18]

In order to provide a guideline of serviceability, security and interoperability intended for HAN (Home Area Network) device manufacturing and home network management in terms of electricity control, a couple of technical frameworks and functional considerations have been established and discussed from the perspective of utilities in [18].

Typically, Figure 5 illustrates a complete HAN framework partially under remote control by utilities. In this framework, the key devices are ESI (Energy Services Interface) and Premise EMS (Premise Energy Management System). ESI is an independent device mostly provided by utilities and serves as a gateway between the AMI infrastructure and the HAN. To establish a secure communication connection between utilities and HAN, all HAN customer devices associated with energy management must register themselves via ESI on the utility network. In this way, confidential control data or information sensitive to customer could be delivered through the secure channel from utilities to target devices in the home network. Also, device status information or operation result could be transferred conversely in the same channel to utilities for data recording. As a software program, EMS actually works as an application gateway to other functional components. It controls energy generation, consumption and storage in the HAN, shares the functions with ESI to delivery control commands or events from utilities to smart appliances, and gathers all types of information from HAN devices. It could also connect to other networks in homes for non-energy control, providing a secure channel from the external interface (i.e. the Internet) to the internal network for the purpose of remote access. Normally, ESI resides in a smart meter whereas EMS resides in a computer as an independent gateway with centralized control. Based on similarities in their functionality, the two entities could be integrated into one physical device.

In addition, [18] also provides another alternative to HAN, in which case a third-party gateway (the same functions as EMS) is in charge of all smart appliances as well as renewable energy facilities and directly communicates with ESI so as to fulfill the tasks related to energy control.

2.5.2 The guiding principles targeted for Home Area Network

Given the framework designed in the interest of utilities, it is reasonable to summarize the guiding principles in designing the HAN as follows [18] [19]:

1. The interface between AMI infrastructure and HAN should follow open standards, considering the interest of utilities in their existing infrastructures and future extension in the power grid, smart appliance/energy generation product manufacturers as well as end-users.

2. End-users own the HAN and could grant their (ownership and responsibility of control is decoupled in terms of energy management) privilege of control to utilities by registering their own smart devices via ESI on the utility networks after applying for automatic energy management services. In such case, all energy-sensitive devices are kept under secure control from utilities. In addition, end-users could also pre-program any smart device not to respond to the control command or load event from utilities for their own preference, regardless of electricity price dynamics.

3. The HAN is expected to integrate load control devices (i.e. PCT, electric pumps) used in load adjustment for target devices (i.e. HVAC system), to install output equipment that displays information associated with energy usage and conservation in a timely manner to customers, and to support distributed energy generation facilities (i.e. solar panels, wind turbine), PEV/PHEV as well as other metering applications. Furthermore, sub-meters could be deployed in smart homes to measure the energy load for distributed energy generation facilities and PEV/PHEV.

4. In addition to public price signaling available in normal communication, the HAN should establish secure two-way communications via ESI respectively for consumer-specific signaling and control signaling. Consumer-specific signaling indicates the operation methods, measurement as well as energy information for private use for the perspective of end-users. In this case, customers are able to safely access the data stored in the AMI meter via ESI. Control signaling is intended for load control, demand-response, and communications between target devices and the utility network via ESI for the purpose of control data delivery and device information collection.

2.5.3 Functional requirements in Home Area Network

In addition to the smart device hardware and corresponding installation, operations, maintenance as well as logistics that are supposed to be addressed by product manufacturers or vendors, the main functional requirements in a home energy management network system based on the guiding principles above is divided into three aspects: communication, security and application [18]:

1. Communication requirements are classified into “Commissioning” and “Control” so as to provide reliable data transmissions within the HAN. In other words, “Commissioning” and “Control” mainly specify the communication between HAN devices and ESI. “Commissioning” defines how a device node is added to the HAN, identifies itself and is removed from the HAN. To join the network, smart devices are expected to communicate with ESI by providing device-specific data (i.e. device type and device ID) and preconfigured utility-specific information (i.e. network ID, gateway ID, Utility ID). Meanwhile, ESI could send network configuration data (i.e. private address or ID within the HAN) to the connected device and notify other HAN devices of location-specific data of the new comer. As a consequence, ESI maintains an updated list of all connected device nodes in the HAN. To establish robust and reliable communication channels in the HAN, “Control” mainly involves the network configuration from ESI (i.e. gateway, routing table, address), choice of reliable routes to ESI based on signal strength, self-adjustment to communication channel conditions (i.e. channel hopping/avoidance, signal-to-noise ratio) as well as periodical communication with ESI for the purpose of device information update in ESI.

2. The main goal of the security requirement is to guarantee a secure data exchange channel between HAN devices and the utilities via ESI. Thus, security requirements can be classified into “Registration and Authentication”, “Access Control and Confidentiality”, “Integrity” and “Accountability”. “Registration and Authentication” deals with the process of how a HAN device registers itself with cryptographic methods to the utility network with the support of ESI and the mutual authentication between sources of control signals and HAN devices. “Access Control and Confidentiality” means that the access to data or service on the utility network is supposed to be implemented with cryptographic methods (i.e. encryption, authentication, or digital signatures) based on utility security policies. “Integrity” demands that HAN devices and ESI prevent unauthorized data modification or other malicious attacks in data storage or in data transmission given HAN security policies. By logging crucial operations in terms of security covering HAN and the utility network, “Accountability” guides HAN devices

and ESI within the HAN to monitor and detect all security-associated activities (i.e. access control, authentication, integrity violations, events associated with management/configuration/adjustment etc.)

3. Application requirements focus on the operation of HAN devices in communication with utilities and in interaction with customers, as well as the response to their own status change. These requirements cover “Control”, “Measurement and Monitoring”, “Processing”, and “Human-Machine Interface”. “Control” demands that HAN devices correctly adjust themselves according to control messages from the utilities network (i.e. power on/off at time interval/thresholds configured in devices, switch to an energy saving mode, or resume original operation state). “Measurement and Monitoring” deals with how a HAN device monitors its own state and environmental impact (i.e. energy production, storage and usage in the HAN, the operation mode of HAN devices, as well as temperature/humidity, etc.) as input to the HAN for further processing. Thus, HAN devices associated with this requirement include distributed generation facilities and metering devices. “Processing” requires that EMS calculates energy consumption and cost, billing, as well as status and external data collected from HAN devices. In this way, the EMS functions as a data processing center or network management platform. “Human-Machine Interface” addresses the interaction between customer and the HAN, mainly by providing input/output equipments to enable customers to configure the HAN and to acquire the energy usage, status/operation of devices as well as billing/tariff information from utilities via ESI.

III. Networking patterns and technology for home energy control

3.1 Subdivision of network functionality

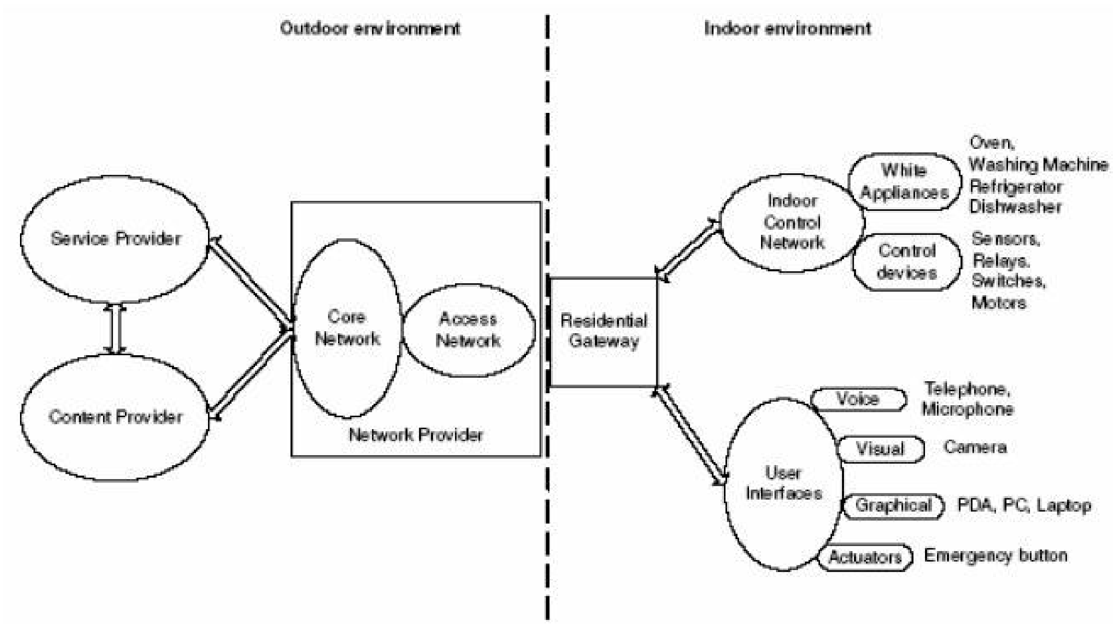

Figure 6 The concept of smart home[1]

The author in [1] depicted the basic framework in a smart home setup as illustrated in Figure 6. The network infrastructure is the basic skeleton for smart home construction in that a smart home unifies home appliances, the system of lighting control, the system of security & surveillance, the system of energy management as well as the interconnection of digital devices for entertainment through the distributed network wiring and centralized operation platform.

The smart home is functionally categorized into two main networks: the broadband communication network mainly for things associated with personal needs such as entertainment, study or home office etc. whereas the control network is intended for the control and management of controlled appliances.

The broadband communication network is mostly attached to home entertainment devices such as a laptop/desktop, digital TV, Hi-Fi system, video recorder, digital camera, etc. and telecommunication terminals such as telephones. In other words, most of the data transmitted on that network are in the form of audio and video, which indicates potential expectations of high bandwidth and high speed for data transmission without stringent constraints on the reliability and consistence in data flow. Since all data exchanged by devices will be pre-processed through the algorithms dealing with signal compression/decompression and data coding/decoding based on the capacity of error-tolerance, error or loss in ordinary condition has little influence in the resolution of data.

The control network mainly supervises the regular operation for all kinds of home devices such as the switching-on/off for lamps and curtains, the start-up and stop of the air-conditioner along with the adjustment of temperature and velocity of wind, the signal collection and execution in security & surveillance system, indoor data measurement through wired or wireless sensors located at different places of the house as well as the adjustment of power usage based on the data indication on electrical meters. Therefore, the control network is loaded with short data used for control and sampling in length which are featured with relatively low signal frequency and accordingly low transmission rate in order to meet their requirements. On the other hand, the expectation of reliability is higher than in the network for entertainment in that it is unacceptable that excessive error or loss of control information happens in the network, which likely leads to the malfunction or even breakdown of target devices.

Both the broadband communication network and the control network converge at the household service gateway, which bridges the single home network to the outside network in a wired or wireless way. The gateway can be equipped with a normal interface for Internet access for indoor web surfing and e-mail retrieval, or with a wireless modem directly attached to it for data exchange through a mobile/wireless network (i.e. GSM/GPRS/CDMA/WiMAX). The OSGi[20] (Open Services Gateway Initiative) platform has been defined by the OSGi Alliance as the general open gateway standard for computerized control of home electrical facilities. Technically, there are two ways to control the home network. One way is to place a computer directly attached to the gateway in which case the computer functions as the indoor centralized control platform for the household owner's use. The other way is to through a computer with a wireless modem to remotely access the homework or a smart phone/PDA (Personal Digital Assistant), remotely taking control of the home network by sending instructions via SMS messages. The only issue here to be taken into consideration is the access security and authentication that is in essence equivalent to the problems in Internet.

3.2 Considerations of networking technologies

Considering the differences in functionalities of the sub-network, a smart home should be built with two independent networks interconnected by a gateway as [1] proposed. Here, we only focus on how to set up the control network for the purpose of power energy saving on the background of smart grid infrastructures, in which case utilities notify residents of the incoming change of the electricity price via the intelligent meter in a wired or wireless fashion and enable them to adjust manually or automatically the schedule of operation for the home electrical equipments to avoid the demand of electricity during the peak hours in a demand-response manner. According to [21], more than 70% of electricity is consumed by home appliances, most of which is for the use of heating, cooling as well as lighting. Thus, the effectiveness and flexibility in electricity management has to be taken into account in the design of home control network since nearly all home appliances in the house are kept under control in this type of network.

There are several basic elements that matter in terms of electricity management:

- Relatively low transmission rate
- Lower power consumption
- Relatively high reliability and security in data transmission
- As little physical deployment as possible
- Low cost as a whole
- The coverage of the network
- Mainly for short control message in size periodically or in the case of emergency
- Seamless communication between the internal control network and utilities

In the normal case, the existing wiring layouts in most of residences are listed as follows: one socket for telephone line, one cable jack for TV or cable modem for Internet access, at least one electrical outlet installed in each room of the house.

Undoubtedly, telephone networking such as HomePNA and cable networking are taken out of consideration due to the cost of extra wiring for each room because of a shortage of outlets which make them less attractive in terms of home appliance control. The same case is in some way true of LAN (Local Area Network) and Wireless LAN (IEEE802.11b). For the control network, higher speed or bandwidth in data transmission is unnecessary in that each instruction or parameter for monitoring and adjustment on the network is short in size and such instructions are issued relatively infrequently. Meanwhile, the cost of deployment mounts with the number of home appliances. Even for WLAN, the APs (Access Points) have to be connected to each other in such a way to construct the network, which also leads to extra cost and inconvenience to residents.

Technically, two types of networking techniques are widely adopted in the field of home appliance control. One is to directly transmit data over power lines, benefiting from the availability and the quantity of electrical outlets in a house. The mainstream protocols in PLC (Power Line Communication) technology are X-10, INSTEON, HomePlug and Lonworks. As a potential competitor to X-10, the alleged high-performance of PLC-BUS is still dubious without compelling evidences from on-site experiments and simulations. The other networking alternative is to exchange data between sender and receiver in a wireless way with a much lower speed than LAN/WLAN. The representative protocols in that case are Bluetooth, 802.15.4/ZigBee and Z-wave.

IV. PLC technologies

PLC(Power Line Communication)[22] technology makes use of the distributed power line infrastructures to transmit data and control signals, in which case the high frequency coded with data is coupled onto the power line intended for decoupling by a modem on the receiver end so as to realize the information transmission and exchange. Originally, the application of PLC was chiefly to secure the normal operation of the electric power supply system in case of malfunctions or faults through the instant exchange of information between power plant, substation and distribution center, thereby making this approach a competitive alternative to smart home networking, considering the benefit of its robustness, ready connectivity as well as availability.

In terms of transmission rate and frequency bandwidth, PLC technology holds no remarkable predominance over other prevalent networking technologies. In fact, the prerequisite of massive adoption of PLC technology is based on the fact that power lines have extended to every residence with multiple outlets installed in each room, which means that device control information and power supply are integrated as a whole through one outlet. There is no extra wiring indoors for the economy and convenience to residents.

Even so, the authors in [22] also suggested a variety of issues to be addressed in PLC technology, which mainly include robust modulation and error coding techniques indispensible for the dynamics of the power line channel at the physical layer, the reflection, fading and attenuation due to multiple-path of the signal propagation model as well as all types of impedance and noise inference from different sources which substantially jeopardize the normal operation in target electrical components and even leads to chaos in the whole network. In addition, competition scheme for shared medium access at the MAC (Medium Access Control) layer and issues dealing with data security in transmission also need to be taken into account.

4.1 X-10

4.1.1 Technical features

As an international general-purpose protocol and a de facto open standard for Power Line Communication, X-10 [23] is applied to all aspects of home automation including house security and surveillance, home appliance control, indoor lighting control, household meter access, etc. Specifically, it makes use of the existing household electrical wiring to transmit digital data between X-10 enabled devices by encoding data onto a 120 KHz power carrier during the zero crossing (a time when the electrical current flows in a reverse direction and thus the unidentified noise diminishes to the minimal level) of the 50 or 60 Hz AC (Alternating Current) power wave, in which case one bit is transmitted at each point of zero crossing.

The system equipped with X-10 protocol normally consists of a controller module with a transmitter and multiple controlled components with a receiver, each of which is distinguished by its own address code, configured by a combination of 16 house codes and 16 unit codes. For each X-10 data packet, it contains an identifier (a start code) followed by a house code and a function code. During the indoor deployment, the controller is plugged into one power socket, while the controlled components with house appliances attached to them are plugged onto other power sockets, in which case the customer is able to input commands and component address code in a programmable way for the purpose of remote control of household appliances.

The main advantages of X-10 protocol over other similar technologies are listed as follows:

- Low cost for the overall deployment
- No requirement of extra wiring indoors
- Easiness in installation for the convenience of household owners
- Interoperability and compatibility among commercial products

Even so, there are still some issues that may retard its sustainable expansion in the field of home control network. The authors in [24] experimented with a home environment control system with X-10 device networking pattern for disabled people, demonstrating that X-10 transmission is susceptible to noises stemming from other appliances plugged into the shared electrical wiring. Meanwhile, other X-10 signals also disturb the normal operation of data transmission over power line. In addition, there is no way to confirm whether or not the target device has executed the incoming instruction due to the one-way communication in X-10.

4.1.2 Application case and performance evaluation

Considering the limitations of speed and intelligence in X-10, the authors in [25] developed a home automation system prototype with a distinctive transmission protocol over power line. The system is composed of one main controlling unit and three client units with master-slave relation in a star network topology. Each client unit takes charge of a maximum of three electrical appliances. The block diagram of the system is shown as follows:

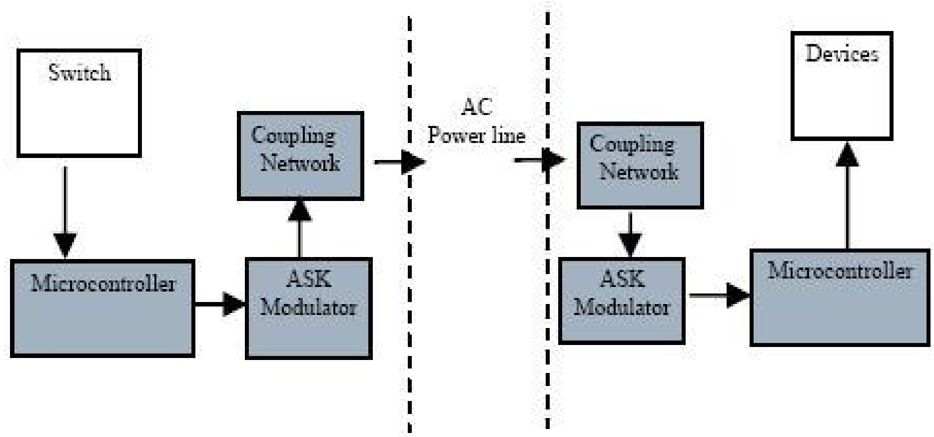

Figure 7 Comparison between X-10 and flood-based protocol [25]

From the perspective of a system designer, the author indicated that the main downsides in X-10 are lack of error handling capability and signal disturbances from indoor electrical devices. In contrast to X-10, their own transmission protocol featured a higher data rate and carrier frequency along with ASK (Amplitude Shift Keying) modulation employing simplex multi-nodes communication based data flooding mechanism and repeatedly sending the same packet to client devices, adopting even-parity detection to reduce the error rate due to noise and high attenuation over power line.

A more detailed performance evaluation of X-10 used for HCS (Home Control System) was done in [26] based on the on-site experiment as Figure 8 illustrated:

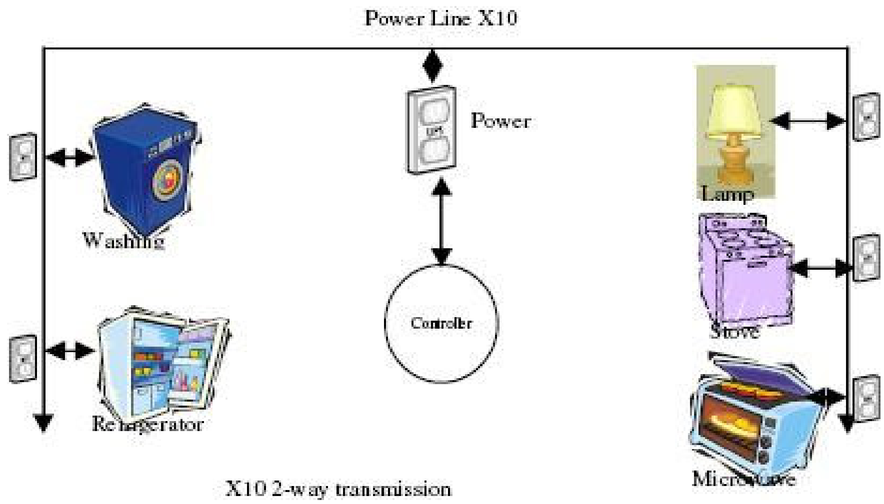

Figure 8 Configuration of Home Control System with X-10 [26]

The concern in [26] mainly deals with:

- Time to response is inversely proportional to average distance for data transmission (the longer the distance is, the slower the response).
- Bandwidth issue associated with overhead occurs when multiple nodes compete simultaneously to communicate over the power line without effective support of medium access mechanism.
- Noise, disturbance as well as signal attenuation due to distance and the quality of the power line severely impact the practical operation.

Meanwhile, the authors put forward their suggestion as an improvement or a possible alternative to X-10, mainly including adoption of a different protocol with a higher data rate as well as a broader bandwidth, modification of the existing protocol frame structure to reduce the overhead in terms of throughput as well as utilization of noise eliminator and ground fault circuit detector to mitigate the noise and disturbance resulting from the power line and other household devices.

4.2 INSTEON

4.2.1 Technical features

Introduced by SmartLabs, Inc. in 2001, INSTEON [27][28] is an X-10 model-based, dual-band mesh technology in home automation that is low in complexity, power consumption, data rate and cost. The main goal of INSTEON is to serve as a replacement of X-10 in the mass market place in the sense that it tries to achieve fast response-time, reliability and robustness in data transmission through the combination of power line and RF (Radio Frequency) channels with a specially designed protocol.

The benefit of employing the combination of two transmission mediums is to enhance the reliability in the INSTEON network. As a matter of fact, there are always a range of technical obstacles encountered in the network deployment over a single physical medium. For one thing, the data signal in wireless channels may drastically weaken by multi-path effect for all types of obstructions in a house along with the mutual disturbance originated from other electrical devices; for another, the power line always comes with issues of phase bridging and harsh electricity noise. Therefore, both power line and RF channel are seamlessly incorporated into the INSTEON mesh network so as to minimize these pitfalls and in turn to secure the robustness of data transmission.

An INSTEON-based device works on a frequency of 131.65 KHz over power line with BPSK (Binary Phase-Shift Keying) modulation and on a frequency of 904 MHz over RF physical channel with FSK (Frequency-Shift Keying) modulation at the same time. Like X-10, zero crossing is also adopted in the INSTEON technology to transmit data packets over power line during the time with the least noise disturbance. With 240 cycles of a 131.65 KHz carrier for one INSTEON packet, each INSTEON packet starts 0.8 milliseconds before a zero crossing and lasts 1.823 milliseconds to finish, whereas the X-10 signal adopts a burst of approximately 120 cycles of a 120 KHz carrier starting at the zero crossing and lasts about 1 millisecond to the end [29]. On the RF physical channel, data packets are modulated onto the carrier by 38,400 bits per second within 150 feet of free-space distance. To sum up, INSTEON is much faster than X-10 on the basis of the fundamental discrepancies in carrier frequency and the transmission method from the perspective of mathematical analysis.

INSTEON establishes a P2P (Peer-To-Peer) mesh network with redundant capability, in which all INSTEON-enabled devices equipped with a transceiver and a repeater are equal to each other in functionalities and act as controllers(or command senders), repeaters intended for message retransmissions as well as responders(command receivers). The message is normally issued by a controller to responders via multiple repeaters without the need of a central controller and complex routing strategies. Each message must be responded with an acknowledgement message except those intended for broadcasting. With the support of the simulcasting mechanism, the same message from the original controller is retransmitted simultaneously by multiple repeaters in the network at the same time within a given timeslot for the purpose of enhancing the signal strength, in which case each responder is capable of receiving the message by means of a relay with multiple hops. In addition, path diversity can be achieved by data transmission on both power line and RF physical channel in the interest of robustness. Specifically, if an INSTEON-enabled device receives a message via power line, it will first relay the message via RF once it acquires the whole packets and then it relays the same message via power line in the next timeslot; on the contrary, incoming messages from RF are first repeated via power line and then via RF in the next timeslot.

To avoid the data storm (the endless propagation of the same message which leads to network congestion or even breakdown) in the network, “Max Hops” and “Hops Left” are defined in the flag fields of a message. “Max Hops” indicates the maximal hops for a message replayed in the network whereas “Hops Left” is the remaining hops of retransmission for the same message. The maximal value of “Max Hops” is 3, which is illustrated in Figure 9:

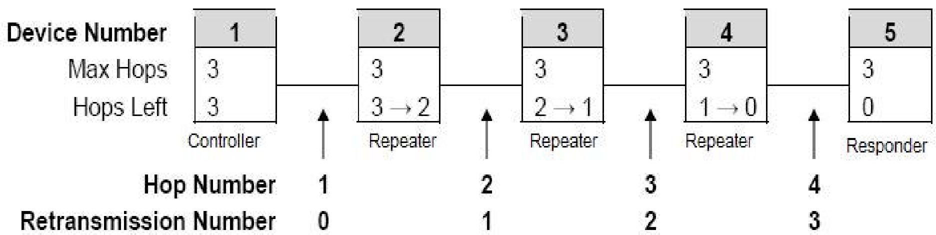

Figure 9 Message hopping and retransmission in INSTEON network [28]

Since each INSTEON-enabled devices holds a unique device identification (DID) initially assigned by product manufacturers, the DID is treated as the source address or the destination address of devices intended for message transmission. Upon reception of an incoming message, the device first compares the destination address with its own DID to determine whether it is the target receiver or not. Following that, the device examines the "Max Hops" and "Hops Left" to decide whether to discard the message if it is beyond its life cycle. Specifically, the device checks the value of "Hops Left" based on the "Max Hops". If the value of "Hops Left" is equal to 0, the device discards it immediately; otherwise, the device subtracts 1 from the field of "Hops Left" and retransmits it in the next timeslot [30].

There are two types of message specified in the INSTEON technology: the standard message and the extended message. The standard message is designed for direct command and control in home automation while an extended message provides the customers with another option by appending a user data field in the message intended for customized data uploading/downloading, sensitive data encryption as well as other advanced applications programmable to end users. Each message includes 3 bytes of source address, 3 types of destination address, 1 byte of flags (covering message broadcasting, group message, acknowledgement for two-way communication, "Hops Left" and "Max Hops"), 2 bytes of command as well as 1 byte of CRC (Cyclic Redundancy Check) intended for message integrity verification. In terms of address space defined in the message, INSTEON is capable of coordinating 16,777,216 devices in the same network, which is more than sufficient for home appliance control.

4.2.2 Networking scenario in smart homes

According to the INSTEON specification of networking and device functionalities, the network deployment could be configured as illustrated in Figure 10:

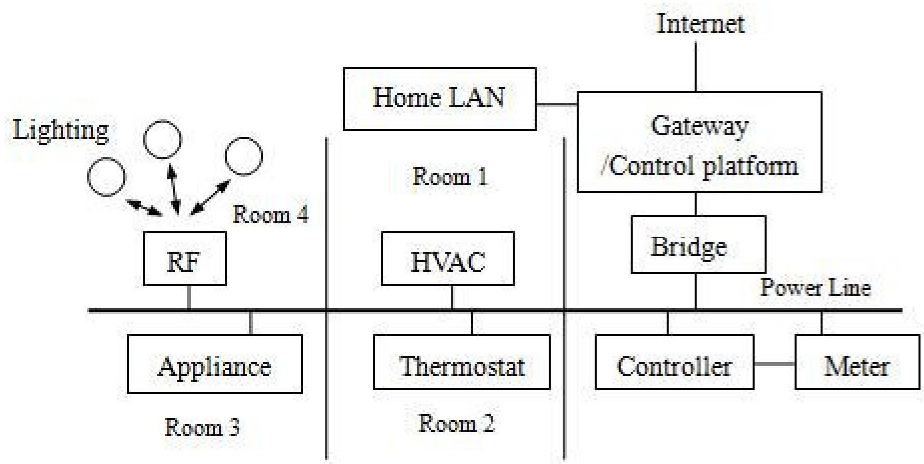

Figure 10 Networking scenario with INSTEON technology

In this configuration, all home appliances including kitchen appliances, HVAC, thermostat and RF converters are directly attached to the power line in each room via INSTEON power line technology while sensors intended for lighting, temperature and humidity could be equipped with an RF module to communicate with an RF converter. Meanwhile, a residential gateway/control platform with connection to the indoor high-speed network and the Internet are indirectly linked to the power line via an INSTEON bridge (a specially designed peer intended for supervising the network traffic and guiding the command control). In the context of energy management, an electrical meter notifies the time-based pricing information with an extended message via a controller to the control platform. Subsequently, the control platform sends standard control messages to corresponding target appliances based on the preset strategies for power consumption targeted for different kinds of home appliances. In addition, thermostats also participate in the adjustment with the authorization of the control platform.

Admittedly, INSTEON technology demonstrates its reliability and robustness only in terms of a theoretical model. Nevertheless, the lack of public academic literatures and substantial evidences from on-site experiments on a large scale due to its proprietary nature prohibit people from being engaged in further research on it and possibly in turn limit the growth of INSTEON in the marketplace.

4.3 PLC-BUS

4.3.1 Technical features

Power Line Communication Bus (PLC-BUS) [31] was introduced by ATS Ltd located in Amsterdam, Holland in 2002 to provide a high-stability and low-cost solution to power line communication compared to other contemporary power line technologies. PLC-BUS technology covers every aspect in home automations ranging from lighting/home appliance/HVAC control to inter-communication between the appliances via the power line.

Similar to X-10, PLC-BUS utilizes the alternate current on power lines to transmit control signals to household electrical devices. Meanwhile, PLC-BUS is capable of checking the ON/OFF status of lights and home appliances via two-way communication as compared to X-10. What is more significant is that PLC-BUS takes advantage of a proprietary Pulse Position Modulation(PPM) [32] technology to encode data based on the location of the modulated pulses determined by the time intervals between pulses which enables data transmission at a rate of 200bps at the frequency of 50Hz on power line. Specifically, the data-encoded frame corresponds to every half cycle of the sinus wave on alternate current close to the zero-crossing, in which case the frame is divided into four parts and the location of the pulse in each part denotes two bit. As a result, one byte-length data is encoded in every two cycles of the sinus wave. In addition, PLC-BUS coexists and interoperates with other power line technologies such as X-10, or Lonworks by providing a signal transfer for the conversion of data.

The frame format of PLC-BUS protocol is composed of four parts as follows:

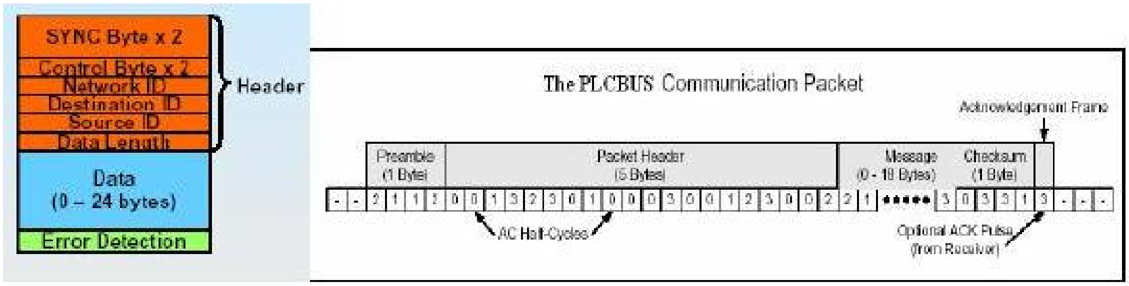

Figure 11 Frame format of PLC-BUS [32]

Specifically, the address code of a target device is composed of Network ID and Destination ID. Network ID is used to uniquely identify each house, while the Destination ID consists of a room code and a unit code in a house. Source ID is mainly used to distinguish the device type of a transmitter from the perspective of controlled appliances. As indicated in the Figure 11, the robustness in PLC-BUS is partially achieved by providing error detection and one byte-length checksum for data verification in the construction of the frame.

4.3.2 Networking pattern in smart homes

PLC-BUS is mainly composed of three units: transmitter, receiver and equipment associated with system configuration.

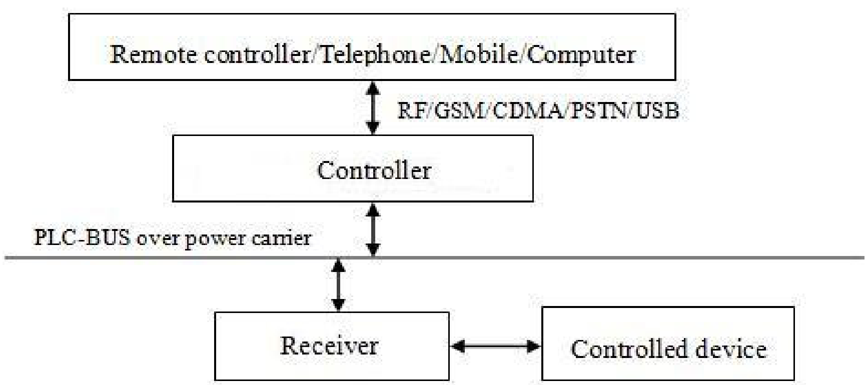

Figure 12 Networking with PLC-BUS units in a smart home

As Figure 12 shows, the controller with a built-in transmitter receives commands wired or wirelessly from a variety of communication terminals and converts these commands into PCL-BUS control signals that are transmitted via power line to a receiver to be executed for the purpose of indirect manipulation of household electrical devices.

Due to the fact that there is actually no literature evaluating its performance either through simulations or via test-beds, researchers have reason to keep skeptical of the alleged features in PLC-BUS technology.

4.4 Lonworks

4.4.1 Technical features

Lonworks[33], introduced by Echelon Co. in the mid-nineties, is a general-purpose and peer-to-peer control network that is widely deployed in intelligent building and industrial supervision, mainly supporting a range of communication media including twisted pair, coaxial cable, fiber, Infrared/Radio Frequency(RF) and power line. Considering the advantages of robustness, openness and interoperability, more and more home appliance providers choose to cooperate with Echelon in order to incorporate Lonworks technology into all types of home appliances for complete automation solutions for smart homes. Even so, the overall price remains the main obstacle to the field of home automation in the sense that the Lonworks hardware components (including three microcontrollers per chip) attached to each home appliance for data transmission are more expensive as compared to other prevailing networking technologies such as X-10.

The core technology of Lonworks is the Neuron chip that encapsulates three microcontrollers dealing with the embedded LonTalk protocol, which serves as an integration solution at the chip level to fundamentally reduce the cost for application development. Since the LonTalk protocol was developed entirely referring to the seven-layer ISO-Model Protocol Stack and standardized in EIA-709.1[34], each of the three microcontrollers takes responsibility for functions corresponding to specific layers: the first one implements the control and processing at the physical layer and the MAC layer; the second one is in charge of management dealing with network routing and addressing from Layer 3 to Layer 6; the last one executes the services of the operation system and user applications [35]. Meanwhile, p-Persistent CSMA algorithm [34] with a random time-slot based on priority level is adopted at the MAC layer of the LonTalk protocol, in which case it minimizes the delay for medium access in lightly loaded networks and the probabilities of collision in heavily loaded networks.

Normally, each control point called node in Lonworks-based networks consists of a sensor/actuator, Neuron chip with a unique 48-bit ID as well as a transceiver attached to the physical medium [36]. With a 3-layer addressing pattern (domain, subnet and node) and programmable nodes, Lonworks is capable of providing support for a variety of topologies including bus, star, ring, tree or hybrid on a large scale.

4.4.2 Application case in a smart home

The authors in [37] presented a possible networking pattern based on Lonworks technology via power line for smart homes that is illustrated as follows:

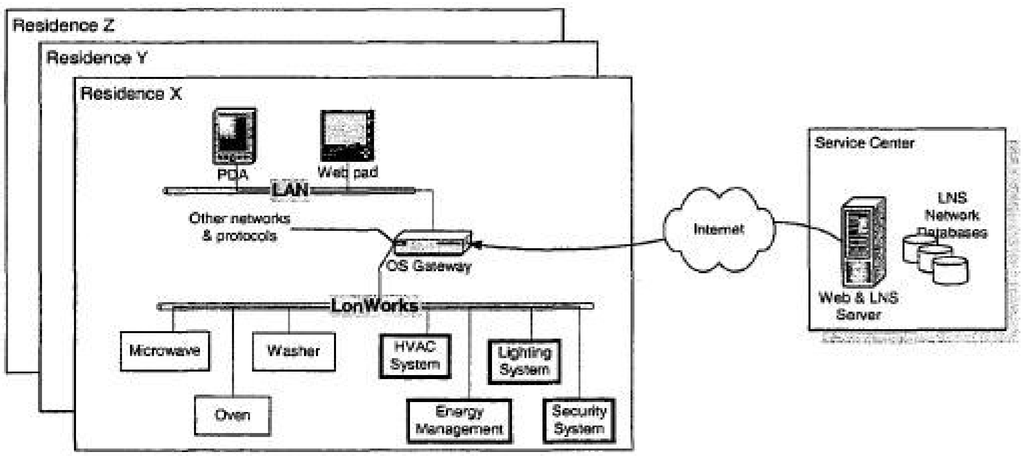

Figure 13 Smart home based on Lonworks networking pattern [37]

The solution in Figure 13 can be seen as a typical application in smart homes in the sense that it explicitly divides the entire home network into two subnets, one of which is mainly control-central for the majority of home appliances. The two subnets communicate with each other through an OSGi-based residential gateway that links the home network to the Internet. In addition, a Lonworks-equipped electrical meter can be installed on the power line and seamlessly interact with an energy management unit on the Lonworks network so as to dynamically adjust the electricity consumption in a house for the benefits of both utilities and residents.

4.5 HomePlug

4.5.1 Technical features

The HomePlug Powerline Alliance(HPA)[38], initiated by leading technology companies in March 2000, is a non-profit group which is intended to provide a platform in order to boost the creation of standards or specifications for in-home power line networking products and services in a cost-effective, interoperable way. Since June 2001, the group has officially released a series of standards with different PHY modulation techniques in succession: HomePlug 1.0 with a rate of 14Mbps for connecting household devices via power lines, HomePlug AV with a rate of theoretically 200Mbps targeted for the transmission of multimedia data in residences, HomePlug BPL for high-speed Internet access to residences and HomePlug C&C (Command and Control) that provides a low-speed solution with extremely low cost for home automation. Normally, the distance of indoor transmission is 300 to 350 meters.

Generally, all specifications of HomePlug include a robust Physical Layer (PHY) and an effective Medium Access Control (MAC) protocol in order to guarantee reliable communication through power line mediums.

To achieve a comparably high data rate without consideration of overall cost, HomePlug employs Orthogonal Frequency Division Multiplexing (OFDM) that divides the data stream into a group of parallel bit streams to be modulated and coupled onto multiple equally spaced subcarriers. In its OFDM implementation, the cyclic prefix and differential modulation techniques are adopted to avoid the need for equalization. In addition, Forward Error Correction (FEC) and data interleaving are used to minimize the impulsive noise originated from household electrical devices.

Meanwhile, the MAC layer in HomePlug is a variant of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol serving as the contention scheme for the channel access medium, including the mechanism of carrier sensing to detect the channel availability for priority-based assignment, as well as a backoff algorithm to increase network utilization based on different priority levels even in heavily loaded networks in the interest of QoS. With CSMA/CA, the PHY can support data transmission and reception in a bursty mode, in which case each connected device starts up the transmitter only when it has data to send. The transmitter is switched off and returns back to the reception mode once the delivery of data is over.

In the catalogue of HomePlug specifications, HomePlug C&C was developed and standardized in recent years to meet the basic consideration of cost and convenience in home control networking, ranging from home appliance monitoring, security to Automatic Meter Reading and electricity conservation based on the Demand-Response mechanism as a feasible extension of the smart grid management technology [39]. Moreover, it specifies the bridge link to other Radio Frequency (RF) networks such as ZigBee and Z-wave, etc.

HomePlug C&C was designed on the basis of the 7-layer OSI reference model as follows:

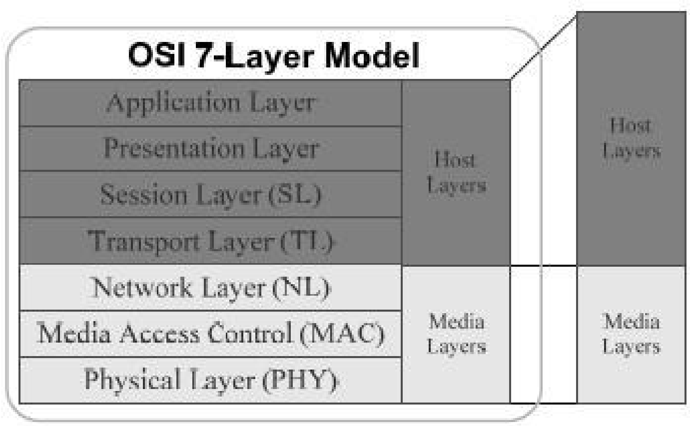

Figure 14 System architecture of HomePlug C&C protocol [39]

In addition to the commonalities consistent with the HomePlug standards, HomePlug C&C also provides other features specific to the environment of home control. Take the PHY layer for instance, its maximal data rate is 7.5Kbps with a patented Differential Code Shift Keying (DSCK) spread spectrum technology to secure robust transmission. Meanwhile, the MAC layer is based on Advanced Encryption Standard (AES) 128-bit encryption with authentication for security, providing support for up to 1,023 logical networks with 2,047 nodes per each network. In addition, the interoperability among household electrical devices configured with the HomePlug C&C protocol stack is specified on the host layer through a common description language that defines the services and actions of devices.

4.5.2 Application case and performance evaluation

The author in [40] suggested a HomePlug 1.0 based networking solution appropriate for a smart home as follows:

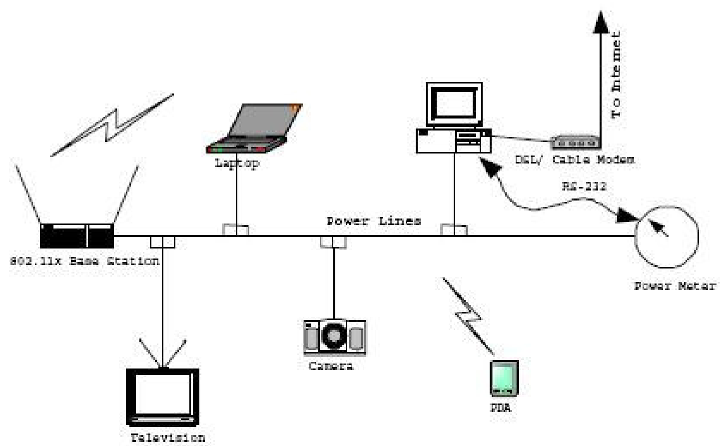

Figure 15 Network topology of smart home via power line [40]

The tree-line networking illustrated above is based on the common power line topology in a North American home. In this case, two power line trunks with different voltage (110V and 220V) are divided into several branches on which data can be transmitted. In Figure 15, home appliances along with multiple computers are connected onto the power line branch for data exchange at high speed. Meanwhile, there is one computer attached to a DSL/cable modem serving as the residential gateway to the Internet. Nevertheless, the solution does not include any device associated with energy conservation or demand-response control. In other words, the solution should address how to deal with multimedia data streams and control messages respectively with preset priorities over the same physical medium within a home if it is required to incorporate entertainment devices and household appliances into a single network for the convenience of management and supervision from the perspective for residents.

On the basis of the existing power line network, the authors in [40] also demonstrated the performance of HomePlug 1.0 for multimedia data traffic in terms of TCP/UDP/MAC throughput and delay with an event-based simulation environment and a real HomePlug 1.0 power line network linked with multiple computers respectively.

In addition, more researchers concentrated on the performance of the MAC layer in HomePlug standards. A new analytical model to evaluate the MAC throughput and delay under both normal traffic and saturation was proposed in [41]. Another modification of the MAC sub-layer by defining a fast collision-avoidance mechanism to increase the throughput regardless of network traffic was simulated and discussed in [42].

4.6 Comparison of PLC technologies

A summary comparison of chief features of these PLC technologies is shown as follows:

TYPE	X-10	INSTEON	PLC-BUS	Lonworks	HomePlug C&C
PHY(Power line)	60Hz Carrier Frequency/ Zero-Crossing	131.65KHz Carrier Frequency/ BPSK modulation	Pulse Position Modulation	Carrier Frequency dependent	DCSK spread spectrum
MAC	N/A	N/A	N/A	Modified p-Persistent CSMA	CSMA/CA with adaptive back-off algorithm
Layering	N/A	N/A	N/A	OSI 7-Layer Model	PHY/MAC/Nework/Host
RATE(bps)	60	180 to 1698	200	3.6K or 5.4K	1.25K to 7.5K
COMMUNCATION	One-way without ACK	Two-way with ACK/P2P	Two-way	Two-way with ACK/P2P	Two-way with ACK
RELIABILITY	Low	High with simulcasting	High	High	High
ADDRESS SPACE	256	16,777,216	64,000	32,385 nodes per domain	2,047 nodes per network
STANDARD	Open	Proprietary	Proprietary	Open	Open
COST	Low	Low	Low	Expensive	Low
DEPLOYMENT	Simple	Simple	Simple	Complex	Simple

Figure 16 Comparison of PLC technologies

As shown in Figure 16, one-way communication with low reliability remains the main issues in X-10. For one thing, all control messages are issued by senders without any feedback from receivers, in which case the final status of the target device is unknown to senders; for another, normal signals without any protection or recovery mechanism are susceptible to electrical noise from other home devices and even falsely recognized as different commands. INSTEON and PLC-BUS hold the same issues including the proprietary nature patented by a single private company and the lack of compelling support by independent experiments and simulations. Lonworks enjoys widespread acceptance in intelligent building and monitoring in manufacturing industries, but the cost of the sophisticated protocol stack chips makes it unaffordable to most house owners. In addition to the reliability and robustness guaranteed by the technology itself, the openness of the protocol stack, interoperability of devices, as well as further extension for advanced applications are also key factors taken into consideration for network deployment. Hence, the protocol standard specified in HomePlug C&C seems to be a reasonable candidate for the backbone of home appliance control in terms of PLC technologies.

V. Low-rate wireless network technologies

Due to the complexity and cost of re-wiring and potential retrofit in a house, a variety of short-distance wireless technologies are emerging to provide flexible networking patterns convenient to residents without the considerations of physical wiring and deployment. These technologies, including WLAN, Bluetooth, ZigBee, Z-Wave etc., mostly work in the Industrial Scientific Medical Bands(ISM Bands), especially the 2.4GHz frequency range. In terms of the control network in a smart home, the commonalities of those wireless technologies are associated with low speed, low power consumption, high cost-effectiveness, flexibility in networking and deployment as well as the coverage of a house.

Despite the fact that the InfraRed Data Association (IrDA) [43] technology remains one of the most popular wireless technologies globally, the main issue is that communication only happens directly between two devices within a extremely short distance with no physical barriers located between them. Hence, such drawback inherent in IrDA leaves it out of consideration for in-home wireless networking.

5.1 Bluetooth

5.1.1 Technical features

Bluetooth [43], promoted by the Bluetooth Special Industrial Group(SIG), provides a comparably low-cost solution wireless communication among portable or handheld devices at a maximum data rate of 1Mbps within up to 10 meters. It operates in the 2.4GHz ISM band with as low as 0dBm transmission power and employs frequency-hopping spread-spectrum techniques to overcome interference and multi-path fading in the wireless channel. Meanwhile, Bluetooth adopts Forward Error Correction (FEC) and Automatic Repeat-reQuest(ARQ) to improve reliability by reducing errors in data transmission.

A standard Bluetooth network called piconet consists of a group of Bluetooth enabled devices sharing the same communication channel as shown in Figure 17:

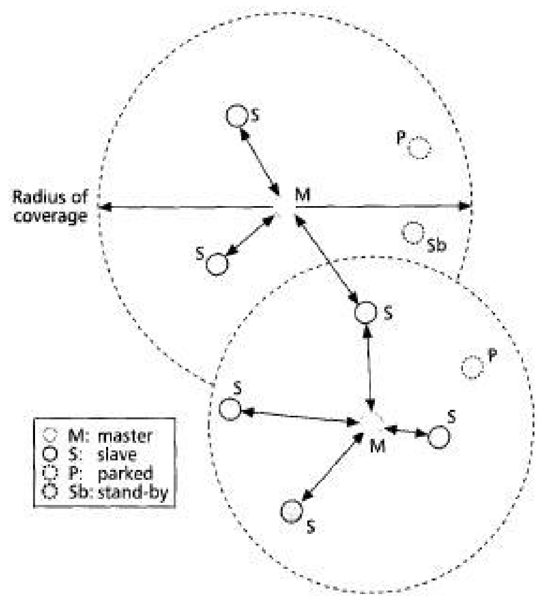

Figure 17 Two piconets interconnected in a scatternet[43]

In the piconet, only one device serves as the master unit that actively synchronizes with other devices, whereas the rest of devices serve as slave units that passively establish the communication with the master unit. Technically, a master unit is able to interact with up to seven slave units at the same time and synchronizes with more than 200 slave units without communication. In order to avoid interference from the same frequency, Bluetooth adopts Time Division Multiple Access (TDMA) technique to separate the communication between master unit and any slave unit in a piconet, which enables the master unit to communicate with other slave units in a peer-to-peer fashion by scanning.

The issues including authentication and encryption are addressed at the physical layer in Bluetooth. Bluetooth devices can not depend on the Public Key Infrastructure (PKI) approach to deal with authentication due to the essence of ad hoc networking. Hence, Bluetooth provides a challenge-response mechanism with a commonly shared secret and a link key produced by a user-provided Personal Identification Number (PIN) in such a way to enable a user to establish a trust domain among personal Bluetooth devices for authentication. Moreover, the link key is intended for generating a sequence of encryption keys for later data transmission after the device authentication.

5.1.2 Application case in a smart home

Considering the basic characteristics of the Bluetooth technology, the authors in [44] presented an End-to-End wireless solution for remote control in a smart home as illustrated in Figure 18:

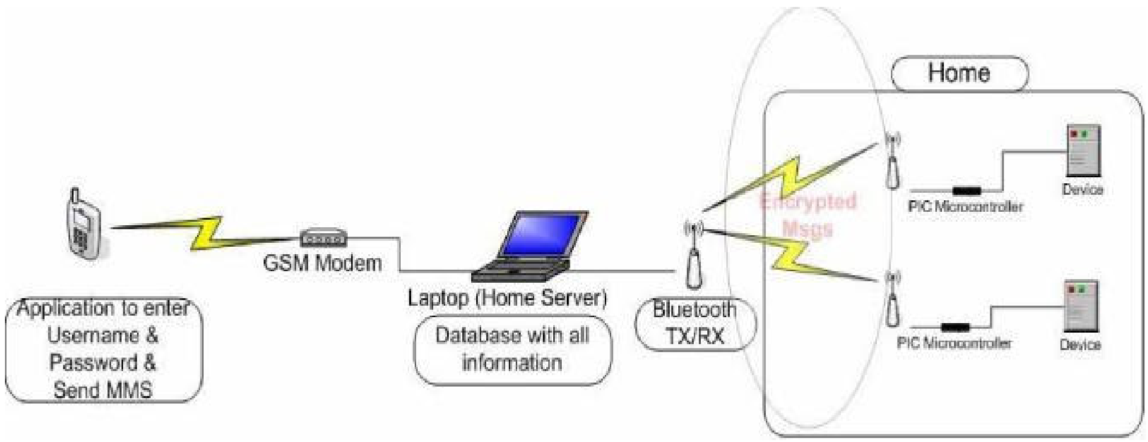

Figure 18 Bluetooth-based smart home architecture via remote control[44]

The system consists of a Java-enabled mobile phone, a computer with a Java server application, a GSM modem attached to the server to the external mobile network, a Bluetooth access point serving as the master unit and a firmware-embedded PIC microcontroller as the slave unit connected to the household devices.

In the mobile network, a mobile phone communicates with the home server based on SMS (Short Message Service) which is sent through a J2ME (Java 2 Micro Edition) application installed on the mobile phone. In the home network, the Bluetooth Point-to-Point over RFCOMM (Radio Frequency COMM) protocol was employed to connect the master unit, in which case the point-to-point communication is established between the master unit and only one device at a time. As a consequence, the security issues are addressed on two sides. The communication in the mobile network is secured by GSM encryption, whereas the internal communication at home is implemented by using Advanced Encryption Standard (AES).

The core of the smart home here is the home server, which is connected to the mobile network via a wireless modem to interact with the mobile phone via SMS messages and which communicates with home devices via the Bluetooth connection. In addition, the responsibility of the PIC microcontroller is to supervise and control the household devices at the hardware level by executing a C application program, in which case the microcontroller receives and interprets commands from the mobile phone via the home server and sends operation instructions to target devices. One of the control diagrams is illustrated in Figure 19:

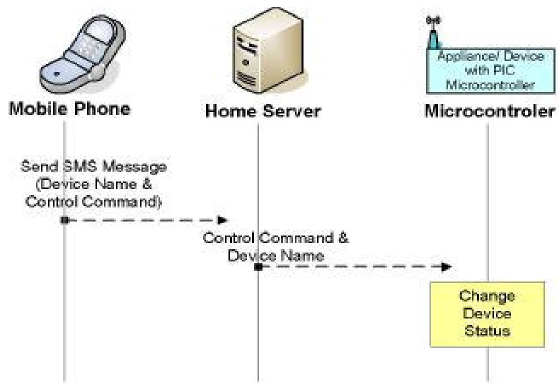

Figure 19 Controlling process of household device [44]

Another Bluetooth-based simplified solution to home control that is fundamentally similar to [44] was also implemented in [45]. The only difference between them was that the PDA/mobile phone took control of the home facilities via direct Bluetooth connection in the house.

5.2 ZigBee

5.2.1 Technical features

ZigBee [46][50] is a bidirectional wireless technology featured with short-range, low cost, low power consumption, low data rate as well as small size, which makes it more suitable for any domains associated with monitoring and remote control that is integrated with functional sensors and actuators. Normally, ZigBee works in the registration-free 2.4GHz ISM band with a data rate of up to 250Kbps and the transmission distance range from 10 to 75 meters, depending on the power output and environmental dynamics [48].

In terms of the protocol stack, ZigBee entirely adopts the IEEE 802.15.4 PHY and MAC as the underlying layers to support reliable data transmission in a harsh environment with noise and signal disturbances as illustrated in Figure 20:

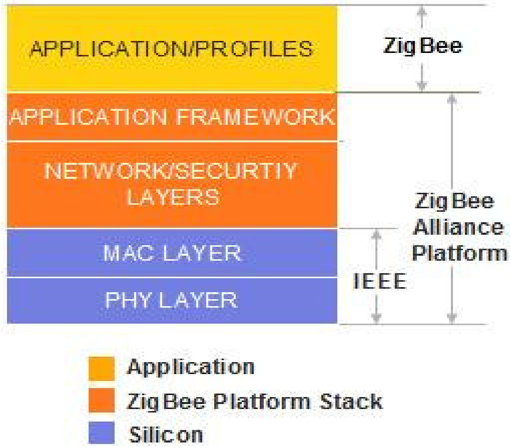

Figure 20 The architecture of IEEE 802.15.4/ZigBee protocol [46]

At the PHY layer, IEEE 802.15.4/ZigBee uses Direct-Sequence Spread Spectrum (DSSS) with two different Phase-Shift Keying (PSK) modulations to minimize interference. At the MAC layer, ZigBee adopts the CSMA/CA channel access mechanism to improve network throughput and minimize transmission delay [47][48].

IEEE 802.15.4/ZigBee mainly adopts three types of devices in the deployment of a network: the powerful network coordinator that maintains the whole network knowledge, the Full Function Device (FFD) that serves as either a network coordinator or a normal router suitable for supporting multi-hop topologies, and the Reduced Function Device (RFD) that is featured with low complexity and serves as a network-edge device [50]. With three types of devices, ZigBee is able to provide support for a range of networking patterns including star, cluster tree as well as mesh as shown in Figure 21:

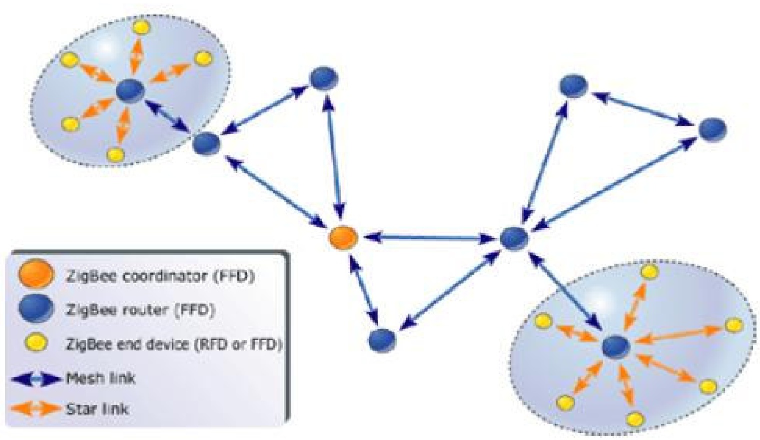

Figure 21 Networking pattern in ZigBee[46]

In the star network, the powerful master device is located in the center of the network and serves as the network coordinator with other slave devices scattered within its coverage. In the mesh network, the data flow is transmitted to the router in the star-form subnet where the router forwards the data to the subnet on a higher layer until the data reaches the sink node.

Technically, the main advantages of the IEEE 802.15.4/ZigBee technology are summarized as follows [47][51]:

1) Low power consumption in terms of the battery life cycle installed in ZigBee devices.
2) Low data rate (250Kbps)
3) Short distance in terms of coverage in a house
4) Low cost, resulting from the low-rate and the simplicity of protocol stack.
5) Supports as many as 65535 devices per network.
6) Robust and self-formed mesh networking allows for reliable data transfer.
7) Flexibility in networking with multiple topologies
8) Data integrity verification and authentication by adopting 128-bits AES encryption algorithm at the MAC layer.

In comparison with ZigBee, the main disadvantages of Bluetooth technology are the price of purchase, the number of network nodes, the limited distance along with the corresponding power consumption in terms of the coverage of home control network as Figure 22 shows:

Comparing Wireless Technologies		
Feature(s)	IEEE 802.15.3 Bluetooth	IEEE 802.15.4/ZigBee
Battery Life	Days	Years
Complexity	Complex	Simple
Nodes/Master	7	65540
Latency	Enumeration up to 10 seconds	Enumeration 30 ms
Range	10 m	70 m–300 m
Extendability	No	Yes
Base Data Rate	1 Mbps	250 Kbps
Effective Throughput	700 Kbps	100 Kbps
Security	64-bit, 128-bit	128-bit AES and Application Layer
Application	File Transfer	Monitoring and Control

Figure 22 Comparison between Bluetooth and ZigBee [49]

Hence, the ZigBee technology is better suited for the control-centralized environment where a great number of devices are equipped with battery-powered sensors, using short-packet transmission. Admittedly, harsh environmental conditions such as disturbances with unknown sources may deteriorate the quality of communication.

5.2.2 Application case and performance evaluation

Based on the characteristics of ZigBee, the authors in [50] built an experimental environment for smart home solutions including energy consumption management, entrance guards, indoor security, home automation and real-time message delivery as shown in Figure 23:

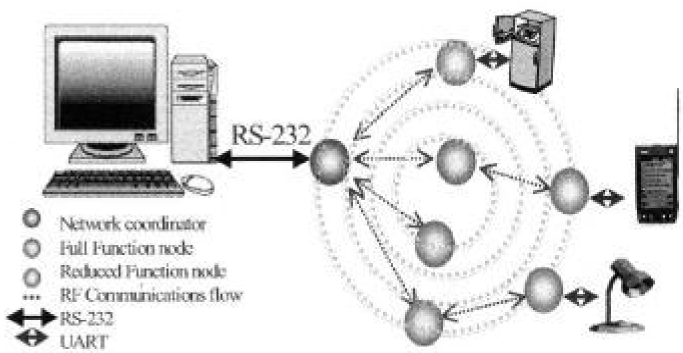

Figure 23 A smart home solution with ZigBee[50]

In this environment, the coordinator is integrated with the home gateway (computer) that handles the control data in the mesh network, whereas the household devices are attached to the router or the reduced function node module. In order to address the problem of interconnection between appliances and the ZigBee wireless module, the authors adopted the SAANet, a lightweight protocol standardized by the Smart Appliance Alliance (SAA) as shown in Figure 24:

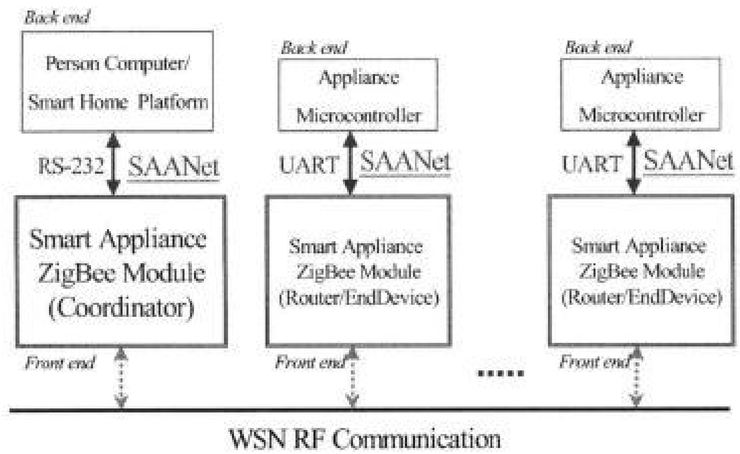

Figure 24 Communication between appliances and ZigBee module via SAANet [50]

Considering the compatibility of the home appliances produced by different manufacturers, a data packet format including Appliance Type ID, Action ID, Service ID as parameter data was defined in the protocol. In the definition, the main control commands in the combination of Action ID and Service ID are opening, closing, run mode and set mode, etc. What is more important here is that the home appliances are specially equipped with a microcontroller and sensors in such a way as to exchange appliance status information and instructions for control between appliances and ZigBee nodes. Another similar but simplified solution with sensors and actuator specially intended for environment dynamics was built in [51], the developer also defined more detailed control messages to the control actuator in XML format including node ID, device ID, category, control level, current status, action(on/off), the length of time, etc.

In addition, the authors in [52] developed a ZigBee-based smart meter solution for the purpose of power management as illustrated in Figure 25:

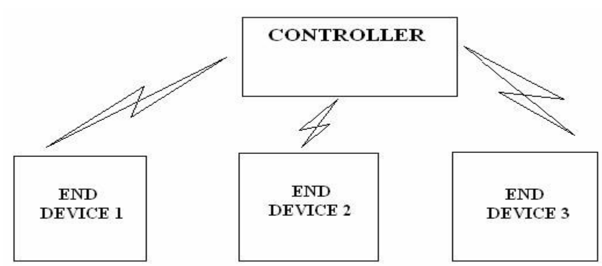

Figure 25 Smart meter solution based on ZigBee technology [52]

In this solution, the ZigBee-based controller is equipped with a GSM modem which receives messages from utilities, whereas the ZigBee-based end-devices are connected to a power factor measurement IC that calculates the power factor from the total power and the threshold stored on the EEPROM. In the normal case, the utilities notify the controller via the GSM network of power adjustments with a new power value. Subsequently, the controller first compares the value with the total power threshold and sends a message of adjustment to all end-devices. Upon reception of the message, the microcontroller in the end-devices recalculates the power value with the power factor and compares it with the stored threshold before taking actions, such as whether to keep the device operating or to switch it off. Specific actions are based on the system definition of low power and high power for devices. In other words, the system is capable of maintaining the operation of the low-power end-device and to stop the high-power end-devices in a programmable way during peak periods in power supply. Meanwhile, the threshold value could be reset periodically based on the dynamics of total electric power.

To explore the network performance and system precision in data transmission, the authors in [53] established a ZigBee-based star network topology in their living laboratory home environment as illustrated in Figure 26, where all electrical devices including home appliances and lamps were tagged with RFID in order to identify themselves to the mobile receiver node carrier by a person.

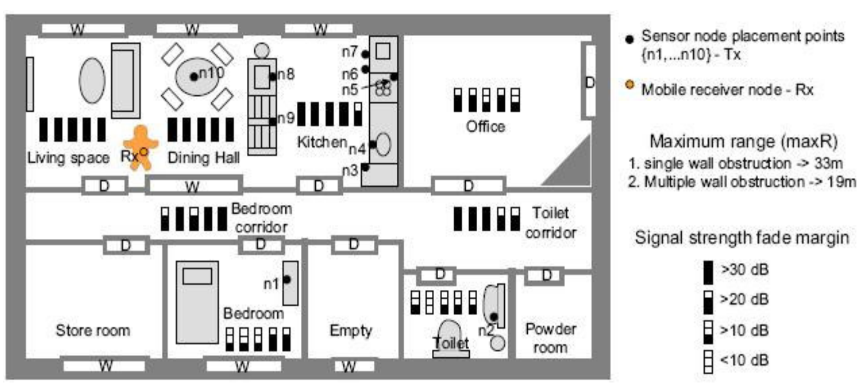

Figure 26 Layout of laboratory home based on ZigBee star networking [53]

While the authors demonstrated an overall promising result of over 90% in terms of precision value and the acceptability of the signal strength measurement, the experiment also indicated that the signal strength fluctuated remarkably with wall obstructions among each room due to the star topology and the average distance between the sensor /sender and the mobile receiver. Meanwhile, the authors only adopted the star topology for its simplicity and naturally excluded all considerations of message forwarding that occurs in other topologies like mesh networks. Also, the layout of electrical devices was designed on purpose, considering the noise sources and unexpected disturbance. Even so, the physical obstruction and disturbance are undoubtedly the key factors that influence data transmission in a ZigBee network.

5.3 Z-Wave

5.3.1 Technical features

Z-Wave [54] is a proprietary wireless technology that was originally introduced by Zensys, a Danish-American Company and later advocated by the Z-Wave Alliance formed by manufacturers who build products based on Z-Wave technology. Specifically, Z-Wave is oriented towards the residential control and home automation with a concise protocol stack appropriate to home facilities in order to reliably transfer the messages in a house. The protocol stack of Z-Wave is shown in Figure 27:

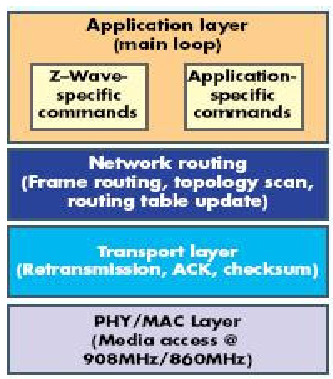

Figure 27 Protocol architecture of Z-Wave [55]

As illustrated above [55], Z-Wave works in the ISM band of both 860MHz (for Europe) and 908MHz (for U.S.A). It adopts Frequency-Shift Keying (FSK) modulation with Manchester channel encoding at the PHY layer at a data rate of up to 40Kbps within 100 meters. At the MAC layer, Z-Wave uses standard CSMA/CA mechanism that manages access to the radio frequency medium when it is in a busy mode.

The transport layer takes responsibility for data acknowledgement and retransmission based on integrity verification during a data transfer between two nodes. At this layer, a successful data reception is confirmed by an ACK frame without data payload. In addition, a checksum byte is placed in the end of a frame for data integrity before data transmission.

The routing layer is in charge of the routing the frame from node to another based on the static location of controller and controlled devices. Actually, a repeater list is included in the frame to ensure the frame to the destination node via designated repeaters. Meanwhile, the routing layer dynamically maintains a routing table for all nodes by scanning the current network topology.

The application layer is intended for decoding and executing protocol-related commands or application-specific commands in the network. The frame in this layer consists of a type header, command information as well as parameters relevant to specific operation. Normally, commands have to include Home ID and Node ID for device identification.

Similar to ZigBee, Z-Wave also defines two sets of nodes to support the self-healing mesh networking pattern: a controller that is in charge of configuring a series of parameters for the establishment of the network (i.e. radio channel, network identification, a group of instructions for operation, etc.) and identification assignment to the new slave node joining the network, and slave devices that server as either end-nodes or repeaters with routing capability for data forwarding. With the support of a dynamic routing selection mechanism in Z-Wave, routes at most 4 hops long are enough to entirely cover every spot for most residences [55].

The main features of Z-Wave are summarized as follows [56]:

1) Simplicity of installation and deployment with automatic address assignment for the convenience of network management.
2) Lower cost based on the integration technology on chip.

3) Ultra low power consumption with the help of the lightweight protocol stack and compressed frame format.
4) Very small in size in terms of the hardware module for the benefit of integration with other devices.
5) Excellent in anti-disturbance with the support of two-way acknowledgement, random back-off algorithm and collision-avoidance [54].
6) Lack of potent mechanism that guarantees data security in communication.

5.3.2 Experimental comparison with ZigBee

To evaluate the performance of a wireless sensor network in a real environment, the authors in [57] established two groups of experimental deployments based on different scenarios for both ZigBee and Z-Wave respectively. The location of the Z-Wave based nodes in the network is illustrated in Figure 28, similar to the topology of ZigBee.

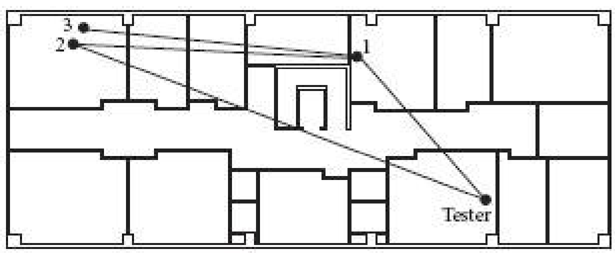

Figure 28 Setup of Z-Wave network [57]

Besides physical deployment of the ZigBee network, the author also built an Opnet simulation environment to analyze the performance based on the measurement of Received Signal Strength Indication (RSSI), throughput, delay and Packet Error Rate(PER) . It is indicated that the experimental findings are consistent with the simulation data and theoretical deductions.

With respect to the Z-Wave, the authors only examined the PER in the preset environment without the support of simulation and theoretical performance analysis due to the proprietary nature of the Z-Wave protocol stack. Despite these restrictions, the experimental results also demonstrated that Z-Wave performs well over one-hop links with a distance longer than 20 meters under attenuation, reflection as well as the link breakages that are caused by the movement of passers-by.

Based on the experiment, the authors suggested that the external factors including signal attenuation, reflection, multipath-effect, man-made interference as well as the location of the deployed node negatively influence the network performance.

VI. Conclusion

The requirement of power energy conservation leads to specific considerations on both networking technology and deployment cost in the smart home design, especially for home automation. Among the emerging technologies popular in the domain of smart homes, PLC technologies and short-range low-rate wireless network technologies have attracted more attention from researchers and home appliance manufacturers and proved themselves to be the de facto standards and deployment specifications.

The main advantages of the PLC technologies superior to other alternatives is the availability of power line outlets in each room for a house, which avoids the costs of additional wiring in most residences and the convenience of the promisingly seamless communication with utilities via power line.

X-10 is the most conventional standard in home automation due to its user-friendliness and simplicity in installation, but the drawbacks are obvious: the reliability in data transmission (i.e. data signal via power line is considered as noise and filtered out) and the lack of security mechanism due to the limitation of frame length. The comparably high price of Lonworks overshadows its excellent performance in the sense that the technology is initially oriented towards building automation. PLC-BUS allegedly outperforms other PLC technologies from all aspects and poses a serious challenge to X-10, but the proprietary nature of this technology possibly retards its growth to some extent. Without extensive experiments on a large scale and the overall evaluation of performance based on both simulation and on-site data, it is difficult to evaluate this technology. The same is also true of INSTEON as another potential competitor to X-10. As an open standard, HomePlug C&C holds many commonalities with X-10, INSTEON and PLC-BUS, showing the promise of providing the solution feasible for smart homes from the perspective of smart energy management.

Despite the fact that the short-range low-rate wireless technologies have features in common with the PLC technologies in terms of installation and cost, there are also other issues to be taken into consideration and to be addressed.

First of all, they possibly operate on the same ISM frequency band which gives rise to the overload resulting from a high-degree of mutual interference with each other [58], especially in the case that a WLAN is deployed in house. Secondly, signal attenuation, shadow fading as well as multipath effect in the wireless environment deteriorate the quality of data transmission. In terms of network security, it is tricky to completely achieve encryption and authentication in the self-organized wireless network due to the dynamics of the network topology and the constraint in computational power and resources for mobile nodes. In addition, those technologies also show vulnerability to malicious wireless attacks such as jamming, forging of random collision frame, etc [59]. For Bluetooth, the main obstacle to the field of home control network is the total cost. As a proprietary protocol, Z-Wave suffers from the same problem as INSTEON and PLC-BUS, lacking substantial analysis of its performance based on massive on-site experiments and simulations.

Generally, there is no perfect solution to address every aspect in smart homes based on either PLC technologies or short-range wireless network technologies. Only considering the aspect of power conservation, it is more desirable to combine PLC technologies with wireless network technologies in some way to meet the practical requirements in smart homes depending on the location, the number as well as the type of home appliances in each room and the quantity of sensors and thermostats that are connected to the controlled devices. In this context, a backbone network of HomePlug C&C plus ZigBee seems more promising for home appliance control in a smart home in the sense that the suggestion also takes other factors into account, such as openness of the protocol stack, interoperability based on layering and cost-effectiveness, etc.

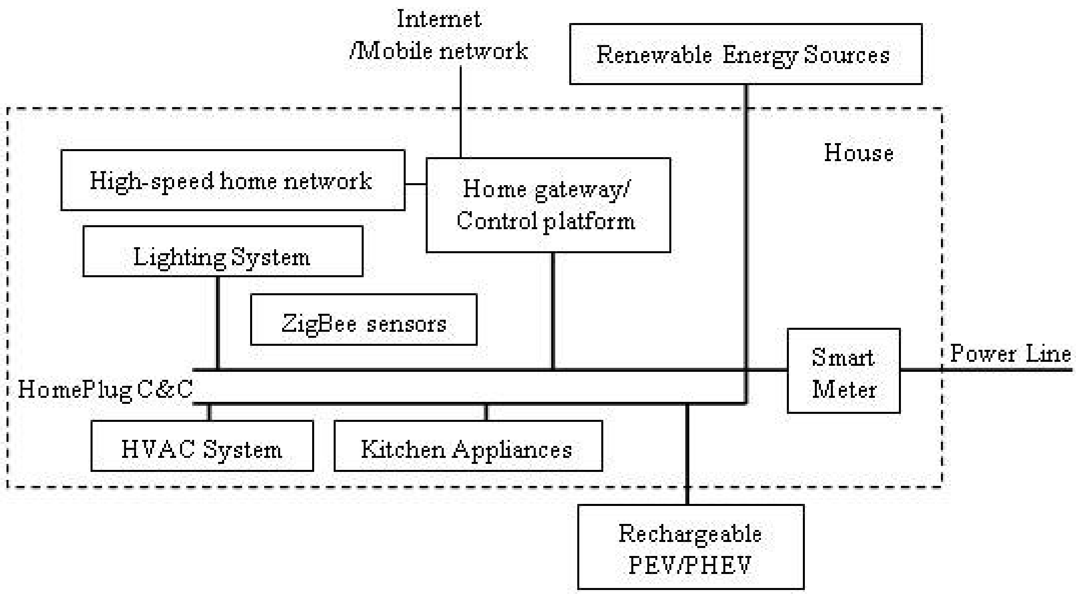

Figure 29 A combination of HomePlug C&C and ZigBee in a smart home

As illustrated in Figure 29, the backbone of home control network system is built with HomePlug C&C via power line. All ZigBee enabled devices incorporated with sensors/thermostats can be flexibly grouped and deployed in each room or in a certain area of a house without obstructions.

Generally, there are mainly three types of messages over the power line in terms of centralized control: initial status registration of controlled devices in the control platform (home gateway) when plugged in, control messages from the control platform or distributed sensors/thermostats to target home appliances, rechargeable PEVs/PHEVs and renewable energy generation facilities (namely solar panels and wind turbines), as well as periodical price notifications sent from a smart meter to the control platform. The registration information is transmitted from controlled devices to the control platform. Depending on the time-based pricing notification from a smart meter that is connected to electricity utilities via power line, the control information associated with price is sent by the control platform in a converse way to the controlled devices, enabling them to switch from one operation mode to another. When ZigBee sensors notice that the house is unoccupied beyond a time limit, they issue messages to urge corresponding devices in their coverage (i.e. lighting system) to cut off the power. In addition, distributed sensors/thermostats are capable of keeping other home appliances (i.e. HVAC system, water heaters, refrigerators, etc.) in a designated mode locally by monitoring and control without direct intervention of the control platform in such a way as to simplify control procedures.

References

[1] Ricquebourg, V., Menga, D., Durand, D., Marhic, B., Delahoche, L., Loge, C., The Smart Home Concept: our immediate future, 1ST IEEE International Conference on E-Learning in Industrial Electronics, Dec. 2006, pp. 23 – 28.

[2] Nunes, R., Delgado, J., An architecture for a home automation system, IEEE International Conference on Electronics, Circuits and Systems, Volume 1,Sept. 1998, pp.259 - 262.

[3] Smart Grid:Enabler of the New Energy Economy, December 2008, http://www.oe.energy.gov/DocumentsandMedia/final-smart-grid-report.pdf

[4] Ontario's Smart Grid Forum, Enabling Tomorrow's Electricity System: Report of the Ontario Smart Grid Forum, February, 2009, http://www.ieso.ca/imoweb/pubs/smart_grid/Smart_Grid_Forum-Report.pdf

[5] Brian Atchinson, Home Energy Use: Making Smart Choices, New York State Conservationist, October 2007, http://www.dec.ny.gov/docs/administration_pdf/1007energy.pdf

[6] Small Wind Electric Systems: A U.S. Consumer's Guide, March 2005, http://www.windpoweringamerica.gov/pdfs/small_wind/small_wind_guide.pdf

[7] FLOYD ASSOCIATES, ADVANTAGES OF PLUG-IN HYBRIDS, APRIL 10, 2009, http://www.floyd-associates.com/phev.pdf

[8] Jim Lazar, John Joyce, and Xavier Baldwin, Plug-In Hybrid Vehicles, Wind Power, and the Smart Grid, January 2008, http://www.raponline.org/Pubs/Jim_Lazar_PHEV_and_Smart_Grid_Final_12-31-07.pdf

[9] The NW Energy Coalition, Plug-in hybrids: A view from the grid, The Transformer Vol.5, No.3, August 8, 2008, http://www.nwenergy.org/publications/the-transformer/2008/pdf-versions/The%20Transformer%2008-06-08.pdf

[10] U.S. Department of Energy, Summary Report - Discussion Meeting on Plug-In Hybrid Electric Vehicles, May 4-5, 2006, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/plug-in_summary_rpt.pdf

[11] Vincenzo Marano and Giorgio Rizzoni, Energy and Economic Evaluation of PHEVs and their Interaction with Renewable Energy Sources and the Power Grid, Proceedings of the 2008 IEEE International Conference on Vehicular Electronics and Safety, Sept. 2008, pp. 84 - 89.

[12] Smart house, http://www.andproperties.com/smart-house.htm

[13] Gonzalo Delgado Huitrón, Reducing Home Power Consumption with Wireless Controllers, http://www.freescale.com/files/archives/doc/support_info/LOW_POWER_CONSUMPTION.pdf

[14] Williams, E.D., Matthews, H.S., Scoping the potential of monitoring and control technologies to reduce energy use in homes, Proceedings of the 2007 IEEE International Symposium on Electronics & the Environment, May 2007, pp.239 - 244.

[15] Helal, S., Mann, W., El-Zabadani, H., King, J., Kaddoura, Y., Jansen, E.,The Gator Tech Smart House: a programmable pervasive space, Computer, Volume 38, Issue 3, March 2005, pp.50 - 60.

[16] Programmable thermostat, http://en.wikipedia.org/wiki/Programmable_thermostat

[17] Matt Maupin, A Green Bee ZigBee is Going Green, http://www.freescale.com/files/archives/doc/support_info/GREEN_BEE.pdf

[18] UtilityAMI 2008 Home Area Network System Requirements Specification,Version 1.04, August 19, 2008, http://osgug.ucaiug.org/utilityami/openhan/HAN%20Requirements/UtilityAMI%20HAN%20SRS%20-%20v1.04%20-%20080819-1.pdf

[19] The ZigBee + HomePlug Smart Energy Marketing Requirements Document, Draft Revision 1.0, March 11, 2009, http://www.homeplug.org/products/ZBHP_SE_MRD_090624.pdf

[20] Kango, R., Moore, P.R., Pu, J., Networked smart home appliances - enabling real ubiquitous culture, Proceedings of 2002 IEEE 5th International Workshop on Networked Appliances, Oct. 2002, pp.76 - 80.

[21] Energy conservation http://en.wikipedia.org/wiki/Energy_conservation

[22] Yousuf, M.S., El-Shafei, M., Power Line Communications: An Overview - Part I, 4th International Conference on Innovations in Information Technology, Nov. 2007, pp.218 - 222.

[23] X10 (industry standard) http://en.wikipedia.org/wiki/X10_(industry_standard)

[24] David Liu, Dao Xian, Home environmental control system for the disabled, Proceedings of the 1st international convention on Rehabilitation engineering & assistive technology, April 2007, pp.164-168.

[25] Rashid, R.A., Sarijari, M.A., Abd Rahim, M.R., Tan Zun Yang, Flood transmission based protocol for home automation system via power line communication, International Conference on Computer and Communication Engineering, May 2008, pp.867 - 870.

[26] Chunduru, V., Subramanian, N., Effects of Power Lines on Performance of Home Control System, International Conference on Power Electronics, Drives and Energy Systems Dec. 2006, pp.1 - 6.

[27] INSTEON, http://en.wikipedia.org/wiki/INSTEON

[28] INSTEON Details, http://www.insteon.net/pdf/insteondetails.pdf

[29] INSTEON Compared, http://www.insteon.net/pdf/insteoncompared.pdf

[30] How INSTEON Works, http://www.insteon.net/about-howitworks.html

[31] Born of PLC-BUS technology http://www.plcbus.com/

[32] How the PLCBUS technology work http://www.andproperties.com/how-the-technology-work.htm

[33] Kastner, W., Palensky, P., Rausch, T., Roesener, Ch., A closer look on today's home and building networks, 7th AFRICON Conference in Africa, Volume 2, 2004, pp.1239 - 1244.

[34] Implementing the LonTalk Protocol for Intelligent Distributed Control, http://www.geocities.com/lonsite/zip/LonTalkProtocolSeminar.zip

[35] Byoung-Hee Kim, Kwang-Hyun Cho, Kyoung-Sup Park, Towards LonWorks technology and its applications to automation, Proceedings of the 4th Korea-Russia International Symposium on Science and Technology, Volume 2,July 2000, pp.197 - 202.

[36] Yanbin Pang, Xiangyu Wei, Youhua Wu, The sensor network based on LONWORKS technology, the 38th Annual Conference Proceedings of the SICE, July 1999, pp.897 - 900.

[37] Sergey Chernishkian,Building Smart Services for Smart Home, Proceedings of IEEE 4th International Workshop on Networked Appliances, 2002, pp.215-224.

[38] Yousuf, M.S., Rizvi, S.Z., El-Shafei, M., Power Line Communications: An Overview - Part II, 3rd International Conference on Information and Communication Technologies: From Theory to Applications, April 2008, pp. 1 - 6.

[39] HomePlug Command & Control 1.0 White Paper, http://www.homeplug.org/products/whitepapers/HomePlug_CC1_White_Paper.pdf

[40] Yu-Ju Lin, Latchman, H.A., Minkyu Lee, Katar, S., A power line communication network infrastructure for the smart home, IEEE Wireless Communications, Volume 9, Issue 6, Dec. 2002, pp.104 - 111.

[41] Min Young Chung, Myoung-Hee Jung, Tae-Jin Lee, Yutae Lee, Performance analysis of HomePlug 1.0 MAC with CSMA/CA,IEEE Journal on Selected Areas in Communications, Volume 24, Issue 7, July 2006 pp.1411 - 1420.

[42] Campista, M.E.M., Costa, L.H.M.K., Duarte, O.C.M.B., Improving the Data Transmission Throughput over the Home Electrical Wiring, 30th Anniversary. The IEEE Conference on Local Computer Networks, Nov. 2005, pp.318 - 327.

[43] Chatschik, B., An overview of the Bluetooth wireless technology, IEEE Communications Magazine, Volume 39,Issue 12, Dec. 2001 pp.86 - 94.

[44] M. Al-Qutayri, H. Barada, S. Al-Mehairi, J. Nuaimi A Framework for an End-to-End Secure Wireless Smart Home System, the 2nd Annual IEEE Systems Conference, April 2008, pp.1 - 7.

[45] Luis Carlos Aceves Gutiérrez,Og Jamir Ramos Juraidini,Carlos Alberto Garza Frias, Wireless control of Bluetooth “on/off” switches in a smart home using J2ME in Mobile Phones and PDAs, http://www.luiscarlosaceves.com/wirelesscontrolofbluetoothswitchesinasmarthomeusingj2meinmobilephonesandpdas.pdf

[46] Matt Maupin, ZigBee: Wireless Control Made Simple, http://www.mobiusconsulting.com/papers/MattMaupin_FreescaleSemiconductor.pdf

[47] Patrick Kinney, ZigBee Technology: Wireless Control that Simply Works, http://www.zigbee.org/imwp/idms/popups/pop_download.asp?contentID=5162

[48] Mikhail Galeev, Home networking with Zigbee, http://www.eetindia.co.in/ARTICLES/2005JUN/B/2005JUN16_NETD_TA.pdf?SOURCES=DOWNLOAD

[49] Gonzalo Delgado Huitrón, Reducing Home Power Consumption http://www.freescale.com/files/archives/doc/support_info/LOW_POWER_CONSUMPTION.pdf

[50] Yu-Ping Tsou, Jun-Wei Hsieh, Cheng-Ting Lin, Chun-Yu Chen, Building a Remote Supervisory Control Network System for Smart Home Applications, IEEE International Conference on Systems, Man and Cybernetics, Volume 3, Oct. 2006, pp.1826 - 1830.

[51] Byoung-Kug Kim, Sung-Kwa Hong, Young-Sik Jeong, Doo-Seop Eom, The Study of Applying Sensor Networks to a Smart Home, Fourth International Conference on Networked Computing and Advanced Information Management, Volume 1, Sept. 2008, pp.676 - 681.

[52] Shah, P., Shaikh, T., Ghan, K., Shilaskar, S., Power Management Using ZigBee Wireless Sensor Network, First International Conference on Emerging Trends in Engineering and Technology, July 2008, pp.242 - 245.

[53] Surie, D., Laguionie, O., Pederson, T., Wireless sensor networking of everyday objects in a smart home environment, International Conference on Intelligent Sensors, Sensor Networks and Information Processing, Dec. 2008, pp.189 - 194.

[54] A Zensys in constant development, Z-Wave Alliance Day Technical Seminar, http://www.z-wavealliance.com/content/uploads/OpenHouse-14Jun05-CPH/t01_Set-up_Maintain(Z-Wave_Open_House_CPH).pdf

[55] Mikhail Galeev, Catching the Z-Wave, http://www.eetindia.co.in/ARTICLES/2006OCT/PDF/EEIOL_2006OCT01_EMS_NETD_RFD_TA.pdf?SOURCES=DOWNLOAD

[56] Z-Wave Overview presentation, 2008, http://www.wirelesstech.dk/C1257306002B260C/sysOakFil/100608_Z-Wave%20technical%20presentation%20ver%203/$File/080609%20Z-Wave%20technical%20presentation%20ver%203.pdf

[57] G. Ferrari, P. Medagliani, S. Di Piazza, and M. Martal`o, Wireless Sensor Networks: Performance Analysis in Indoor Scenarios, EURASIP Journal onWireless Communications and Networking, Volume 2007, Article ID 81864, 14 pages.

[58] Bosheng Zhou, Marshall, A., Wenzhe Zhou, Tsung-Han Lee, Novel Wireless Mesh Networking Architectures for Future Smart Homes, Future Generation Communication and Networking (FGCN 2007), Volume 2, Dec. 2007, pp.43 - 48.

[59] Todd Kennedy,Ray Hunt, A review of WPAN security: attacks and prevention, Proceedings of the International Conference on Mobile Technology, Applications, and Systems, Sept. 2008, Article No.56.