A Survey of Communication and Sensing for Energy Management of Appliances

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Abstract— **Concerns about climate change, dwindling legacy energy sources and an aging and under-invested power grid has lead to pressing energy management focus from governments, energy producers, distributors and consumers. From the power stations to the consumers, the appliances at its edge, this aging power grid is large, complex and difficult to manage, but the plethora of new appliances adding to consumption daily are still largely uncommunicative. Progress is beginning to be made with a concept called Smart Grid. Smart Grid is described as the future generation of the electricity network that functions more cooperatively, responsively and organically. However conversations around the outworking of this concept are still ongoing. In this paper we survey communication and sensing for managing the energy consumption of appliances. We begin by looking at the wide range of elements across the power grid, their roles in managing this energy consumption and the communication required between them to fulfill these roles. We go on to describe the necessary characteristics and qualities for these communication and sensing technologies and with these qualities in mind we assess a range of wired and wireless communications, sensing and tagging.**

Keywords-energy management; communication; sensing; smart grid

I. INTRODUCTION

Amongst the conditions driving the need for energy management, two are of primary impact.

The first is well known; global warming and CO2 emitting energy sources have gained high focus in the last decade, most are aware that government targets exist for CO2 reductions and increases in renewable energy sources and visionaries portray a future filled with wind turbines and solar panels.

The second is less well known; in this technological age most of the electricity distribution infrastructure, the power grid, was developed before microprocessors when current questions such as efficiency, customer choice and the environment were not concerns. The power grid is aging and under-invested and has become large, complex and difficult to manage.

The Smart Grid concept has played an important role in moving towards better energy management. Smart Grid is the future generation of the electricity network that functions more cooperatively, responsively and organically [1]. Smart Grid encompasses entities across the entire power network from energy producer to appliances in the home or office and advocates real-time collaboration between these entities to manage power intelligently. Early initiatives include Demand Response and smart meters, but less attention is paid to the appliances themselves. In 2009 the UK supplied a total of 357 TWh. 8% was lost in transmission and distribution but after delivery the domestic sector was the largest consumer with the domestic and service sector together totaling 70% of total consumption. Appliances are a very significant contributor in these sectors and therefore deserve our considered attention.

Existing appliance energy management research projects and technologies focus mainly on two approaches: appliance efficiency and user behavior change, while appliances can continue to squander energy unjustified. Without the right communications technologies, appliances cannot obtain enough information to consume responsibly. They need to be aware of user constraints; they need real-time load data from power distribution systems and they need the right sensing and tagging technologies to make them aware of the context in which they consume and whether that consumption is valid. Appliances also need to publish their real-time state and consumption so it can be better managed by users and by other devices. In the future energy grid, generation systems and storage systems must use communications technologies to connect with distribution systems and appliances to optimally select from available power sources. And to better manage peak load and respond to grid events appliances at the very edge of the power grid must be able to connect with and respond to these power distribution systems.

In this paper we discuss elements in the grid and their roles in achieving energy management. Additionally we discuss the communication required between these elements to fulfill these roles. Through this discussion we arrive at a set of ideal qualities and functional characteristics and it is against these that we survey communication and sensing technologies suitable for energy management.

II. ENERGY MANAGEMENT OF APPLIANCES IN CONTEXT

In order to assess the suitability of different communication and sensing for energy management of appliances in the electric power grid we must first appreciate the context in which these technologies shall operate. The identification of the context implies; understanding the role, the functioning and the location of the many elements required to be connected to manage appliance energy consumption in the grid; understanding the nature of the communications required between these elements to fulfill their roles.

A. Necessary Elements for Energy Management

At the edge of the smart grid elements may include the premises smart meter, various consuming smart appliances, distributed energy generation systems, energy storage systems, environmental sensing and tagging, energy management systems and In Home Displays (IHD). Elements across the grid include Electricity utility services, control centers, power grid distribution systems, appliance manufacturers and other authorized static or mobile devices. All these elements must fulfill their particular role in order to fully manage the energy consumption of appliances. Elements have different requirements and constraints and the nature of these elements will inform the suitability of different communication and sensing. An overview of these elements and their connections can be seen in Fig. 1.

1) Smart Appliances

Typically the primary role of an appliance is to provide a service or a collection of related services to its users or to other appliances. The services could range from heating a room full of people to recording a TV program while a property is empty. Appliances make a major and an increasing contribution to the load on the power grid and as such are a very important part of any strategy for energy management. There are efforts to enable users‟ to change their consumption behavior or to configure automated consumption thresholds, but this is not enough, appliances must be enabled to consume efficiently and intelligently in accordance with their wider context.

Appliances should respond to their environmental context, for example if there is no occupancy, it may be appropriate for Audio Visual equipment to remove power from display and audio, while continuing to record an input channel or it may not be appropriate to continue heating a cold room because all the windows are open. To this end Appliances must be connected with sensing elements and respond to the information they provide.

Appliances should also respond to their power grid context. They should publish their consumption and state information for the cooperative and responsive function of the smart grid. Fine grain appliance interaction will enable utilities to better manage supply in real-time and enable the implementation of more intelligent and effective demand response services for consumers. Appliances may be connected to a Home Area Network (HAN), a network that allows remote connection and control of appliances in the home using cordless or mobile phones, personal computers or dedicated appliance automation systems.

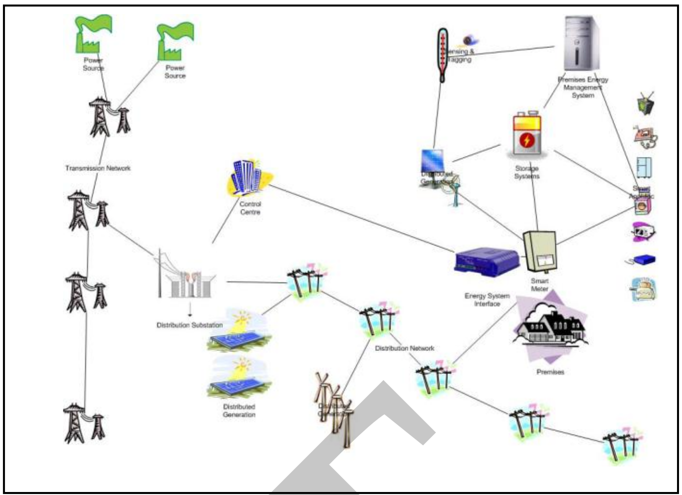

Figure 1. Elements for Energy Management

2) Smart Meter and Energy System Interface

Smart meters are one of the first smart grid remote communication technologies. Early installations record premises energy consumption at regular intervals. In the future, smart meters will be able to notify this consumption to utilities automatically across some kind of communications network.

„Demand Response‟ is another smart grid mechanism by which appliances act on direct grid state or utility pricing notifications and cease or delay consumption or switch to low power modes of operation. Similarly Dynamic Response enables the appliances to detect critical grid state and adjust without notification. „Prices-to-Devices‟ is an arrangement for utilities to communicate real-time pricing to individual devices according to power grid conditions and for devices to respond accordingly. Such arrangements require secure registration and communication between appliances and utilities. This is achieved through a gateway often called the Energy System Interface (ESI). The ESI presents an interface to the energy provider‟s systems and services so they can be accessible from Premises Energy Management Systems (PEMS) or other devices on the HAN. Smart meters are the likely implementers of ESI for demand-response and prices-to-devices mechanisms.

Other potential features incorporated into smart meters include visualizations for user consumption monitoring and analysis and appliance remote control and automation either from in home or on-line.

3) Sensors and Tags

Sensors convert environmental stimulus into an electrical signal that can be measured and stored. There are a variety of sensor types, including: temperature, humidity, light, speed, acceleration, sound, magnetism. A sensor node is a device that incorporates a number of sensors with computation and a communication system. Typically sensors are deployed in hard-to-reach locations, hence they cannot be connected by wire and must therefore communicate wirelessly and operate on low power. The role of sensing in an energy management system is to provide an environmental context in which appliances can validate their mode of operation, for example adjusting the heating system according to a thermostat or turning off lights when there is no occupancy.

Tags are microchips that may be located in or carried by objects, animals or people to allow remote identification or tracking. Radio Frequency Identification technology (RFID) comprises very small tags, composed of an IC and an antenna, and an RFID reader device. The reader transmits a radio frequency and reads the back scattered signal reflected and modulated by the tag to indicate its Id. Tagging can be used to extend the environmental context to indicate the presence of specified people or objects, for example preventing children from turning on high consuming devices or adjusting a fridge or freezer according to its contents.

Raw data from sensors and tags cannot be used directly to control appliances. Some element of the system must provide functionality to collated and interpreted this data to provide relevant environmental information. This information can then be communicated to appliances in order that they might respond with appropriate modes of operation.

It is also possible that this environmental information could provide awareness to utilities and distribution systems of a risk of impending increased load or provide policy makers with environmental information along-side consumption information enabling them to better direct energy saving resources. However, the sharing of environmental sensing does raise privacy issues.

4) Premises Energy Management Systems (PEMS)

PEMS is a software application for managing energy-controllable smart appliances, such as Heating Ventilation and Air Conditioning (HVAC), lighting, white goods and various consumer electronics. PEMS may be a dedicated device or a collection of functions across appliance automation displays, laptops, Programmable Communicating Thermostats (PCT) and so on.

PEMS performs device and consumption monitoring, allows configuration of energy thresholds, constraints and policies, and coordinates interconnection and meaningful communication between elements such as sensors, smart appliances, smart meter, generation systems and storage systems by executing the specified energy management policies.

5) User Interface Devices

A User interface device or In Home Display (IHD) works together with PEMS and ESI to present users with useful information, such as detailed local consumption history, billing and energy management policies. Where utility data is presented, secure mechanisms should exist to carefully manage any preparation and pre-processing possibly using authenticated common services or offloading this function onto utilities.

The device also provides an interface to PEMS or ESI for the configuration of local or utility controlled energy management programs.

6) Distributed Energy Generation Systems

Historically, purchase of electric power has been relatively involuntary. Choice has been minimal, payment often made weeks after the supply and no empowerment to consider real-time energy sources during consumption.

Distributed generation employs technology for scattered small-scale generation sources closer to the consumers, both geographically, and often in terms of control and ownership, providing generation participation and choice. Technology can include photo voltaic cells (PVC), wind turbines, damless hydro, biomass and biofuel extracting energy from plants. Smart grid supports distributed generation through the principle of open communication standards for all elements on the grid, allowing sources to cooperate with appliances, storage systems, meters and gird distribution systems exchanging data such as appliance mode and consumption, grid loading, available local power, storage levels and so on.

When grid load is high and local appliance demand is low, locally generated power can be directed to local storage or to a Microgrid, a close cooperating community of electrical generators and consumers. Alternatively power can be sold to a utility. When local generation is high and utility prices are high it can support the local appliances and when local generation is low, appliances can adjust their mode of operation and use other power sources.

7) Storage Systems

The greatest unpredictability in the power grid is in load. Storage can be used during variable load to implement peak shaving bringing cost savings and grid stability. Additionally the increase in renewable energy sources, such as wind and solar and the introduction of distributed personal renewable power generation will see an increased unpredictability in supply. Storage can also be used to bring stability in times of variable supply.

Improvements are predicted in advanced battery and super-capacitor technologies with increases in energy density, lifetime and efficiency. Moreover, It is expected that Plug-in Electric Vehicles (PEV) will also operate as efficient storage and supply devices. These efficiencies can begin to make it worthwhile for consumers to use local storage to buy energy and store it when the price is low and consume when the price is high, while also making some contribution to peek smoothing.

In order to select between storage and supply or sell modes according to load or price on the grid, storage systems require intelligence and common communications with power distribution systems and utility control centres through an ESI at the smart meter as well as communication with PEMS in order to balance supply and demand on the Home Area Network (HAN).

8) Systems on the Power Distribution Network

The systems on the distribution network are responsible for taking power from the high voltage transmissions lines and more recently from distributed generation sources and distributing it to a range of retail consumers. These systems include distribution and collector substation systems, distribution transformers, distributed generation connection equipment and network control centres.

Substations are responsible for transforming voltage from the high voltage transmissions network to a number of output lines on the distribution system and for providing switching to isolate faults, protect equipment, allow maintenance and switch between generation sources. Distribution transformers step down the voltage along the output lines until correct voltage is delivered to household or commercial meters. Distributed generation sources can be connected behind the meter or somewhere along the substation output line.

Where retail consumers support it, distribution substations or control centres can send Demand Response and Load Control (DRLC) instructions to the Energy System Interface at the retail smart meter to adjust individual appliance energy modes, thereby managing smoothing or unexpected load issues with greater granularity. In a similar way substations must manage requests from commercial and personal generation devices which would result in a reduced load and increased voltage, possibly communicating with registered storage devices to offload excess capacity.

9) Control Centers

Distribution Network Operators (DNO) implement control centre systems for distribution network and the Energy Service Providers (ESP) or utility provides centres for retail management. From behind the meter these systems can be accessed through an ESI. Smart devices of the kind described may be enabled to connect and register in different ways. Some may simply access data and services particular to a given retail meter or premises; some may agree to a particular energy management plan and others may even authorize a centre‟s system to control of their modes of operation.

The role of control centres includes the intelligent management of owned or authorized devices in the distribution network in some of the ways described. Control centres also manage retail accounts, remote and secure meter reading and a range of remote and secure billing strategies including pre-payment, credit tokens and regular billing.

B. Necessary Communication for Energy Management

In order to fulfil their role in the management of appliance energy consumption, the elements we have described must intercommunicate with each other, sharing a range of data including real-time appliance consumption data, appliance state, direct appliance commands, tag and sensor data, user constraints, pricing, current demand and emergency grid events. The connected elements and the nature and requirements of the data they communicate will inform the suitability of different communication and sensing.

1) Communication between Sensor Nodes and Appliances

Smart Sensor nodes will register with PEMS and these registered sensors will pull configuration and calibration data from PEMS. Once a sensor node is registered and calibrated PEMS periodically pulls sensor data from it, see Fig. 2. If sensor events are, by nature, occasional, such as occupancy, then an arrangement may be made for nodes to push sensor state transition events to PEMS as they occur.

PEMS maintains environmental dependencies of operational and service modes for each type of registered smart appliance. For example HVAC might depend on temperature, open windows and so on, while lighting might depend on illumination and occupancy. From time to time, upon processing sensor data, PEMS will initiate operational mode or service mode adjustments in given types of smart appliance.

In this manner it is intended that appliances respond to non-transient changes in the environmental context for which they provide their service. For this reason the appropriate rate of sensor communication and the size of the data are unlikely to demand high bandwidth. This condition is also likely to have a favourable impact upon functional lifetime of sensors.

Some of the data in this domain could be considered sensitive, such as occupancy state and appliance control. Because sensor data is commonly communicated wirelessly on an open network, secure communication solutions need to be implemented between appliance, sensor node and PEMS.

2) Communication with Accounting Systems

Advanced Metering Infrastructure (AMI) supports the secure communication of billing data from the utility customer accounting system to the ESI which then redirects the data to registered IHDs. Billing data for further processing on the HAN is communicated under strict guidelines to prevent customer and utility information mismatch.

AMI also supports pre-payment facilities. There are a number of different methods requiring different communication messages. Where credit is managed by the utility customer accounting system secure, it sends credit messages to the ESI at the AMI Smart Meter. Alternative methods include customers adding credit tokens to the AMI Smart Meter. The Smart Meter connects through an ESI with a secure clearing system to authorize the token and the ESI notifies this to utility customer accounting system. The utility system would also be required to submit secure disconnection or emergency provision messages.

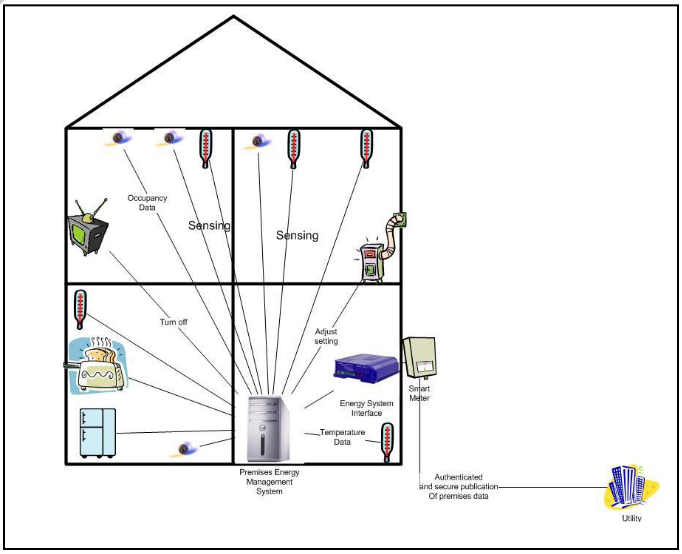

Figure 2. Communication between Sensor Nodes and Appliances

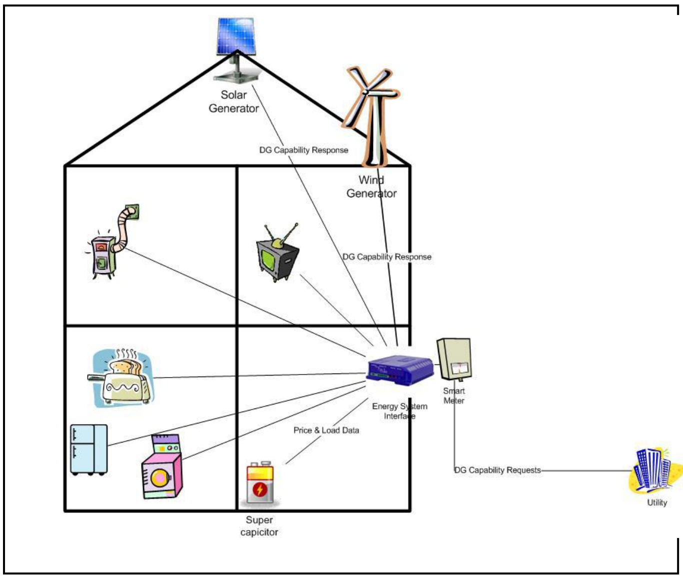

Figure 3. Communication with Distributed Generation Systems

3) Communication with Distributed Generation Systems

The ESI will receive, from distribution network control, DG capability requests which it will direct to DG devices on the HAN. These devices will respond with capability data and the distribution network will proceed with a series of control and monitor messages. See Fig 3.

4) Communication with Control Centers

Smart Appliances send registration message to a Utility or Distribution Network Control Centre through an ESI and the centre sends a registration confirmation. Registration may be at a number of different levels, including establishing access to authorized data for a given premise or ESI, subscribing to a given energy management policy or program or authorizing the control centre to issue a range of direct operational mode commands.

Control Centres or Distribution equipment may send DRLC events sent to an ESI at the smart meter. Messages for a premise are forwarded to a PEMS and message for registered appliances are forwarded to those appliances and acknowledgments are returned through the ESI.

Other messages include secure pricing data which may in a similar way be sent to the meter for the premises pricing or through an ESI to a PEMS or to a registered appliance indicating energy price for a specific device, often called prices-to-devices.

III. THE TECHNOLOGIES

The technologies will be assessed according to certain functional characteristics and according to some relative qualities for energy management. Values for functional characteristics are presented in tables in section 4. Table 1 lists the relative qualities‟‟ short names and descriptions. Entries in further tables in section 4 reflect the technologies‟ weak or strong relative contributions to desired qualities. Contributions are relative to all technologies discussed in the paper, not just those in the table. An empty entry indicates a lack of significant contribution.

Given the diversity of element types and locations, the grid will not be served by a single communication medium. Amongst the medium characteristics to be considered are range and interference. Requirements will vary according to which elements are being connected. For example, connecting lighting to occupancy sensing will have different requirements from connecting an appliance to a property meter in a large commercial building or connecting a meter with a substation. We must also consider the qualities of the elements themselves, such as functional lifetime, cost, form factor, and installation and configuration effort. For example, most appliances are connected to the power infrastructure, but elements such as sensing must be able to manage power efficiently.

TABLE I. DESIRED QUALITIES

Quality	*Description*
Cost	Low collective cost/benefit for license, certification, development, installation and operation of equipment, for example adapters, routers, wiring and subsequent power and maintenance costs.
Form factor	Small relative size of components such as adapters and especially tags and sensor nodes which often require embedded or unobtrusive locating.
Installation	Low cost in money, time and inconvenience to deploy and configure equipment.
Transport	Good potential to support widely common network and transport protocols such as TCP/IP.
Adoption	Attracting wide industry support and acceptance for applicability in a manner that could lead to mass adoption.
Ubiquitous	Possessing technical characteristics which support the potential for installation anywhere and for everybody.
Maturity	Using a relatively long established published standard, well adopted by industry and tested in the market place.
Standards	Using an open and free standard published and certified internationally.
Stakeholders	Having potential to benefit a wide range of stakeholders. Not benefiting the consumer to the detriment of the utility or the product manufacturer.
Media	Having an affinity between two or more communication media. For example, a communications LED as main lighting infrastructure may be considered a candidate as a VLC –PLC adapter.
Applications	Having good potential to support relevant application level protocols in the domain of environmental sensing, Advanced Metering Infrastructure and other smart grid functions.
Security	Considering the medium and the higher communication layers, having good potential to prevent interception of communication and unauthorized access to or control of network elements.

Given diversity across the power network from source to appliance and given the collaborative aims of the smart grid, interoperability is an important quality for our technologies. It should be considered whether our communication technologies have the potential to support a common transport layer, what affinity they might foster amongst mixed communication media and whether inter-working can be achieved with emerging power grid elements such as smart meters.

Finally we have a number of non-functional qualities, such as; the technology‟s potential for wide adoption and whether its design supports ubiquitous deployment; the status of its standard, whether it is open and free and how widely it is certified; and the technology‟s potential for benefit to a wide range of stakeholders, including consumers, utilities and appliance manufacturers.

We have divided the technologies into three categories; wired communication, wireless communication, and sensing and tagging. In the final section we give brief overviews of a selection of existing and proposed appliance energy management architectures and discuss the communication and sensing technologies they use.

A. Wired Communication

In this section we assess wired communication technology suitable for energy management of appliances. Essentially there are two suitable mediums; dedicated local home and office data network wiring, typically Ethernet, and the power lines that supply power from an electricity distributor to the appliances in homes and offices.

1) Power Line Communication (PLC)

Historically, Power Line Communication (PLC), over-viewed in [2, 3], has been a popular communication medium for appliance control. PLC technology uses power line infrastructures for data and control and its primary advantage over other wired network medium is its pre-existence in virtually every part of every building. PLC can use sockets for power and communication and provide a pre-existing line back to the Utility, though there can be performance issues over long distances and over complex legacy power networks. A number of open and proprietary standards exist for this medium.

While there is no doubt that new technology is beginning to manage power line problems better, this is still a legacy hostile and unstable medium often requiring the intervention of compensating devices. Much of the technology is proprietary and existing standards are limited. Devices are location restricted and the network is difficult to extend making this an unlikely medium for realizing context awareness.

2) X10

X10 [4, 5] is a long standing open standard for home automation device communication. Its primary medium for data and control is the residential power line network making it a candidate for ubiquitous appliance communication. Data is encoded on a 120 kHz carrier which is transmitted in bursts one bit is sent at or within a specified proximity to each zero crossing of the 50 or 60 Hz AC alternating current wave. This method is standardized in IEC 61334 also used for electricity meters, water meters and SCADA.

However, the X10 code protocol sends 1 bit at a time. Four bits (code value 1 - 16) are used to represent the property/building, four for the device and four for the command, making support for DRLC and retail services unlikely. Due to retransmissions and other issues the data rates may be only 20 bit/s, meaning X10 is only really suitable for turning devices on or off or sending very simple instructions. As a carrier for energy consumption data or as a backup medium for environmental sensor data X10 would be seriously limited. X10 does define a radio frequency (RF) protocol, but the primary purpose is to allow control from remote keypad and not to provide a second medium through which to access appliances. The packet data sent from the keypad is much the same as the PLC X10 code protocol sent from a PLC control device.

Additionally a range of other users devices attached to the PL network can contribute to issues with attenuation, impedance and noise and the protocol itself presents issues of speed and collision. X-10 networks commonly require phase couplers, blocking filters and signal boosters for larger power line networks, failing to meet goals of self-configuration and one-off easy deployment. Given its maturity, X-10 is not significantly low cost and form factor is medium to large.

X-10 protocol provides limited security in the form of secure device addressing. This is manually configured on the device only during the installation state and is unlikely to be suitable for billing and other sensitive data. Moreover X-10 is not design to work well with common transport protocols such as TCP/IP. Together these qualities make X-10 an unlikely candidate for wide scale adoption and unlikely to be seen as supporting the requirements of all energy management stakeholders.

3) Insteon

Insteon is designed and owned by Smart-home Technology. The company has been in Home Automation for almost 20 years and Insteon is a mature product at nearly 10 years. This hybrid peer-to-peer mesh network uses proprietary INSTEON Power line protocol and INSTEON ISM band RF protocol and is intended chiefly for automated home control [6]. Devices may be single or dual medium. The network is self configuring, though mapping is required of buttons on controllers to device functions.

The INSTEON Power line protocol can coexist with X10 and developers can implement devices that support and interface these protocols together. Insteon supports integration of existing X-10 only networks and devices, but extends speed and number of devices. Insteon achieves a sustained raw data 2,880 bps operating the dual medium. The network employs a Non-routing topology where all nodes receive and repeat messages. In order to take advantage of common transport protocols such as TCP/IP Insteon devices must be fitted with purpose built serial interfaces such as USB, RS232 or Ethernet and connected with other digital devices which support bridging to other "Insteon incompatible" networks such as a Local Area Network (LAN) or the Internet.

TABLE II. WIRED COMMUNICATION FUNCTIONAL CHARACTERISTICS

Name	*Data Rate*	*Range*	*Power*
X10[17]	60bps (Bit Rate) or 1 command/s	Not published	2w (adapter)
Homeplug 1.0[3]	85Mbps (Bit Rate)	200m	5w (adapter)
Homeplug AV[3]	150Mbps	200m	5w (adapter)
Lonworks Twisted Pair[16]	78,125bps	2200m maximum	3w (adapter)
Lonworks PLC[16]	4800bps	Tx: 80dB +9 S/N < 20km	Not published
Insteon PLC[6]	1698bps max	1 mile	< 1w
UPB[17]	480bps (Bit Rate) or 5 commands/s	Not published	2w (adapter)
Ethernet[14]	1Mbs - 10 GBps (Bit Rate)	100m	<200w (switch)
KNX PL110[16]	1200 bps	Tx: max output, 122 dbμV, Rx: min sensitivity, 60 dBμV	Receive: 5 V @ 30 mA / 24 V @ 1 mA Transmit: 5 V @ 30 mA / 24 V @ 10 mA – 50 mA

Recently North America‟s biggest distributor for electricity utilities, "HD Supply Utilities", will be offering to utilities packages of smart grid solutions using integrated smart grid configurations of SmartLabs Inc‟s certified Insteon devices. Offerings are expected to provide demand response, home devices, AMI, management of meter data and security. In contrast Insteon does less well in the area of environmental sensing. Insteon‟s devices are large form factor, expensive and are all battery powered, characteristics do not support the ideal of ubiquitous environmental context awareness.

Finally, Insteon‟s proprietary nature makes wide adoption unlikely. Through paid membership of the Insteon Alliance one may have the opportunity to influence Insteon design, but its specification is not approved by European or International standards bodies and is copyrighted by and only available from Smart-home Technology. Dependency on such proprietary technologies may constrain ubiquitous deployment.

4) Lonworks

Lonworks was designed to address the needs of building control applications and meter reading. Although developers have extended its application field, Lonworks still has issues with flexibility and scale-ability [7], which make other applications difficult. The platform is based on protocols developed by The Echelon Corporation. The Lonworks network employs a connectionless domain-wide broadcast topology with loop-free learning routers and repeaters. Lonworks is an approved national standard in America, ANSI/CEA 709, in Europe, EN 14908 and in China GB/Z 20177. While most of the Lonworks protocol is public and open, layers 3 to 7 of the standards are closed and proprietary [7]. Additionally Lonworks wiring system is proprietary. Echelon have designed The Neuron Chip, which builds in much of the Lonworks protocols and addressing, providing for economical development and a benchmark for the standard. This brings down cost and benefits installation, but while Echelon no longer make the use of their chip a requirement for certification, in practice manufacturers find it difficult to work without the chip and this tie in may be a detriment to wide adoption.

The Layers MAC and above are based on the published standard [8] ANSI-CEA-709.1. At the physical layer mediums include twisted pair[9]and power line[10] making it a moderate candidate for ubiquitous deployment. These standards are specified as ANSI-CEA-709.3 and ANSI-CEA-709.2 respectively. Recently ISO and IEC have also granted a number of standard numbers. Although there are examples of Lonworks technology working with RF networks and with sensing, Lonworks is not a good supporter of mixed media, since it does not specify an RF standard of its own and can only implement tailored solutions using intelligent gateways.

Support for a common transport protocol is found only indirectly in ISO/IEC 14908-4, IP compatibility (tunnelling) technology. Lonworks security provides authentication, but fails to provide for data encryption.

5) Universal Power line Bus (UPB)

UPB, described in [11], is a mature open low-rate PLC standard developed by PCS Power line Systems for implementation on general-purpose micro-controllers. Its use of Power line makes it a contender for ubiquitous deployment, but the lack of support for alternative mediums impact reliability and application. UPB‟s main competitor is X10 and while UPB is more reliable and faster, its cost is a prohibiting factor and its relatively low rate still limit its application. Though UPB is generally reliable, there are reports [12] that UPB has a vulnerability to being jammed by dimmer appliances. The technology requires manual installation and requires configuration dedicated device and software making wide adoption unlikely.

6) Homeplug

The Homeplug Power line Alliance [13] was setup to standardize and encourage networks over power lines. Homeplug is a mature technology since 2001 and one of the few to overcome many of the inherent difficulties with this medium, providing easy installation, high speed and reliability. Another challenge for power line technologies has been universal standardization and this challenge was met when IEEE P1901, based on the Homeplug de-facto standard, was ratified in September 2010. However, despite its maturity Homeplug has not seen the cost reductions one might have expected. Homeplug was originally developed to extend or adapt an Ethernet network bus and its devices [3] making it perfect for communication over a common transport. Homeplug has since been extended to include „Homeplug AV‟ for Audio Visual (AV), „Homeplug Command & Control (C&C) ‟ for control of Heating Ventilation and Air Conditioning (HVAC), lighting and security and „Homeplug Access BPL‟ for Broadband Power line (BPL) and recently Homeplug Green PHY (GP) ‟. Homeplug C&C and GP are aimed at appliance control and Smart Grid and Smart Energy applications. Work in the upper layers of these appliance and energy standards is ongoing, however in addition Homeplug Alliance have joined with the Zigbee Alliance in the development of ZigBee Smart Energy Profile which will support Homeplug and 6LowPAN RF networks. With Homeplug‟s use of power line, its stability and its universal standard make the technology a strong candidate for ubiquitous deployment, but devices are large form factor and integration with small and dispersed sensors has not been a common feature and there is not yet a clear catalyst for widespread adoption.

7) KNX

KNX [15] is a mature and open but proprietary Home and Building Control standard owned by an industry alliance, The KNX Association. The standard may be obtained either through paid membership of the association or for a separate fee. KNX has gained a number of standards approvals including International Standard ISO/IEC 14543-3.

KNX power line operates in the 90–125 kHz band and at a bit rate of 1200 bps, while dedicated twisted pair wiring achieves 9600 bps and a maximum cable length of 1000m. KNX can also be tunnelled over an Ethernet LAN or the Internet using the KNXnet/IP specification. Ease of installation is a key feature with KNX providing a single tool which supports all implementations and all user levels. KNX is mainly found for lighting and HVAC

KNX is most visible in its home country of Germany [16]. KNX shows some interest in Energy Management and Smart Grid, but its involvement in practice has been limited compared to Homeplug, Insteon and Lonworks. KNX RF has the potential to realize a WSN, but form factor is restrictive for ubiquitous environmental sensing. The restricted openness of the specification and the high cost of membership and certification have been the main prohibiting factors to wide adoption. KNX support for multiple media is a strong asset, but is let down by a lack of security in KNX RF.

8) Ethernet

Less popular for appliance and energy management is Ethernet. Installation effort and cost are high due to the frequent requirement to introduce new wiring, particularly in homes and though common in offices, this effort would rule out ubiquitous deployment and discourage widespread adoption for energy management applications. Having said this, a number of relevant appliance communication standards support Ethernet. KNX protocol for building control includes Ethernet amongst its communication media and Homeplug was developed to extend or adapt an Ethernet network over power line. Ethernet is also provides excellent support for common transport such as TCP/IP.

In the main however, Ethernet is the standard of choice for wired local area networks though it will provide high quality communication for building appliance monitoring and control where wiring already exists. Ethernet is mature and globally standardized by IEEE 802.3 [14] and defines the PHY and MAC layers of a wired Local Area Network. The MAC layer protocol operates Carrier Sense Multiple Access with Collision Detection and specifies half and full duplex operation. The PHY layer is over coaxial, twisted pair or optic and operation can be between 1Mbs and 10 GBps. Ethernet is a shared medium and relies heavily on upper layer protocols for security, though the risk is lessened by switched Ethernet. Although gateways and adapters exist to extend Ethernet to other media such as Wi-Fi, ADSL, PLC and RF, the technology does not have an inherent affinity with other media and form factor is still not small enough for ubiquitous environmental sensing.

TABLE III. RELATIVE WIRED CONTRIBUTION

Quality	*X10*	*Insteon*	*Lonworks*	*UPB*	*Homeplug*	*Ethernet*	*KNX*
Cost			+				
Form factor							
Installation		+	++		+		++
Transport			+		++	++	+
Adoption							
Ubiquitous	+		+	+	+		
Maturity	++	+	++		++	+++	++
Standards	+				++	+++	+
Stakeholders							
Media		+			+		++
Applications		++	+		++		
Security		+					

TABLE IV. WIRELESS COMMUNICATION FUNCTIONAL CHARACTERISTICS

Name	*Data Rate*	*Range*	*Power*
IrDA - Advanced Infrared (AIR)	256kbps – 4Mbps	5 – 10m	Low
Wi-Fi (802.11)	54Mbps (802.11n <600Mbps)	< 250m	High
Bluetooth Classic	1 – 24 Mbps	1 - 100m	1 – 100mW
802.15.4	20 kbps (1 channel) 40 kbps (10 channels) 250 kbps (16 channels)	10 - 20m	Ultra low
Zigbee	20 kbps (1 channel) 40 kbps (10 channels) 250 kbps (16 channels)	10 – 75m	Low
RF4CE	20 kbps (1 channel) 40 kbps (10 channels) 250 kbps (16 channels)	10 – 75m	Low
BLE	< 1 Mbps	1 - 100m	0.025-1.25mW
VLC (802.15.7 - LED)	40 - 500MBit/s	1 - 5m	Low/Mains

B. Wireless Communication

In this section we look at wireless communication suitable for energy management of appliances. Wireless communication has been with us now for over a hundred years. In the last decade however, wireless communication technology has seen sudden growth and in the last five to seven years we have begun to see the kind of technology that might support energy management through widespread environmental sensing. This has come through the inception and advancement of low-power, low-cost Radio Frequency (RF) wireless communication with smaller form factor, greater sensing density and longer functional lifetime.

1) Infrared

With the introduction of teletext in the late 1970s there was a drive to extend the function of remote controls in televisions and we began to see the proliferation of infrared (IR) remote control for a range of consumer electronics. The technology is now mature and a number of essentially public standards have emerged. For infrared remote controls standards evolved informally with two proprietary Philips protocols, RC-5 and RECS-80, becoming the two de-facto standards and now adopted pretty much internationally. With infrared data communications the increasing number of incompatible parallel proprietary protocols threatened the future of this technology for appliance manufacturers and there was collective demand for a common specification, which lead to formation of The Infrared Data Association (IrDA).

IrDA [18] was launched in 1993 with around 70 companies. The newly formed association made cost a high priority, setting initial goals of device adaptation under $5, data rates up to 115 kbps, coverage by a 30 degree half angle cone and a range of at least 1 meter. The standards progressed from versions 1.x through Advanced Infrared (AIR) along with the specification, including 5 meter range at 4 Mbps and 10 meter range at 256 kbps as well as a low-power, short-range category for power consumption constrained devices such as one might find in a sensing and appliance energy management architecture. IrDA has no designed support for energy management however.

While IrDA provides no security, the nature of IR allows communication to be blocked if necessary. With advances in LEDs and ICs, Components have reduced form factor and are found in many devices including mobile phones and USB adapters. For most communication installation and configuration is automatic, however connection to a local area network (LAN) and support for common transport is limited since IrDA"s IrLAN does not offer the required TCP/IP configuration protocols such as DHCP and DNS.

IR remote control and IrDA already has wide adoption, however future adoption for energy management seems unlikely. IR still has issues of range and line of sight and in some cases one-way communication and for these reasons manufacturers are making moves to drop IR in favor of RF technologies. Additionally there is nothing in IR technology that would suggest ubiquitous deployment or provide an inherent affinity with other media.

IR has similar absorption and reflection characteristics to visible light and behaves in a similar way with translucent and non-translucent materials. For communication the wave length is generally in the near infrared band between 780 and 950 nanometer. The authors in [19] suggest the medium has a number of advantages, including virtually unlimited and unregulated bandwidth. Additionally interference or interception can be limited to a single room or building; this also provides a high combined capacity and simplification of inter-room communication for infrared local area networks. These characteristics could be an advantage for energy management architectures enabling management of sensing and appliances in selected rooms while recognizing a collection of rooms as an entire building. Also, intensity Modulation and Direct Detection can prevent the multi-path fading often seen in radio signals where changes in signal strength and phase are common.

2) Wi-Fi

The end of the nineties saw the emergence of the now common place Wireless LAN (WLAN) (IEEE 802.11). 802.11-1997 was the first published RF communication standard for WLAN. The standard defines the characteristics of the PHY layer including frequency and modulation method and the MAC layer using CSMA/CA with Binary exponential back off algorithm. Two Coordination functions are supported by the standard; Distributed Coordination Function (DCF) with asynchronous communication and Point Coordination Function (PCF). PCF is setup in the access point and uses station polling to provide synchronous communication for time critical data such as video. The standard also supports a hybrid coordination function (HCF). The standard is an extension to the Ethernet Media and often an access point to a variety of networks and media, providing wireless mobility and ease of installation while continuing to carry the common networking and transport protocols TCP/IP. WLAN does not possess intrinsically ubiquitous characteristics, but the explosion of laptops and WiFi enabled mobile devices has driven widespread adoption. Widespread adoption in the field of energy management however seems unlikely; the design does not have energy management in mind and for many applications, particularly environmental sensing, WLAN is consider too power hungry and in some cases components are still too large.

A large number of amendments exist to the legacy standard and the technology is now mature with low cost commodity status. These amendments were more recently rolled up into a new base standard, 802.11-2007 [41]. These amendments provide for a range of frequencies including 2.4, 3.7 and 5 GHz and a range of modulation methods including DSSS, OFDM and FHSS. Power consumption of 802.11 exceeds that of 802.15.1 (Bluetooth) and 802.15.4 including Zigbee and other Wireless Personal Area Networks (WPANs).

The early standard supported speeds of 1 Mbps at up to 100m in a 20 MHz channel. The latest amendments to the standard (n) [42] support a 20 MHz channel and a 40 MHz channel with a data rate of up to 150 Mbps and up to twice the range of the legacy standard. Additionally optional features such as A-MPDU and Greenfield preamble can save power consumption. Security is provided through Wi-Fi Protected Access (WPA) based on Extensible Authentication Protocol (EAP) and Advanced Encryption Standard (AES) with the improved WPA2 providing CCMP, a new AES-based encryption. Wi-Fi is the certification for WLAN IEEE 802.11 standard compliant devices.

3) *Bluetooth Classic*

The Bluetooth Standard was formed by the Bluetooth Special Interest Group, initially Nokia, Intel, IBM and Toshiba [43]. The original vision of global very high growth technology has not been realized as far as predicted, but the scale of production has been sufficient for a significantly low cost. Amongst many others, Bluetooth is found in the mobile phone, PC USB dongle, remote printer, keyboard or mouse and in the wireless games controller. Government regulations for mobile phone use while driving, has been seen as the catalyst to Bluetooth awareness and mass adoption in the form of wireless headsets. Form factor can be small, however the inherent power demand preclude the use of Bluetooth for small, low power, long lifetime ubiquitous sensing nodes.

The group increased in size and became the first task group of the IEEE 802.15 WPAN working group and the standard was submitted and ratified in 2002 as 802.15.1. The standard has matured and is currently at 2.1 [44].

Bluetooth is a short range standard for industrial home and office use. Using 2.4GHz ISM band and a Gaussian FSK Modulation the standard achieves a range of 10m and a data rate up to 1 to 3Mbps according to the standard version. This frequency may have some conflict with WLAN 802.11 [45], but it may be possible to configure WLAN to operate on 5GHz. Reliability is managed through FEC and ARQ. There are three classes of radio using power ranging from 1 to 100mw. Bluetooth has a higher power cost to 802.15.4 and Zigbee, though a significantly higher data rate. Bluetooth does not have an inherent affinity with other mediums such as PLC.

The Bluetooth Transport Protocol Baseband layer defines the Piconet topology. Piconet recognizes a slave role and a mater role. Piconets are not formed through any central control, but are started by a master and can include slaves which register with the master. The master allocates addresses, unique within the Piconet, for active slaves, which may not exceed seven. Nodes may have dual role and be master in one Piconet and slave in another forming a Scatternet. Piconet implementations have the potential to be self-installing and self-organizing.

A number of middleware protocols exist. Service Discovery Protocol was added to the basic standard in order that devices could find out what services or application profiles are supported by devices in preparation for using the service where some other function supports it. Radio frequency communication RFCOMM Protocol exposes a serial interface to the transport layer, enabling certain legacy applications to communicate without modification. TCS Protocol enables AT commands to be sent over RFCOMM enabling functions, such as activating mobile dialing through a remotely connected device. More recent protocols from version 2.1 include Secure Simple Pairing to secure private data or safely allow the connecting device to take control of the connected device, using public key cryptography in a number of modes. Bluetooth has a range of adopted protocols including TCP/IP making it a strong candidate for integration into a common transport. Bluetooth provides no direct support however for energy management applications.

4) *IEEE 802.15.4*

IEEE 802.15 Standards address Wireless Personal Area Networks (WPAN). Task Group 4 of the standard is charged with investigating simple low power, low data rate WPAN solutions for applications such as long lived small form factor ubiquitous sensing, remote identification and home and industrial automation. IEEE 802.15.4 defines the PHY and MAC layers and can be found at [20].

At the physical layer 802.15.4 specifies three different bands from amongst the available Industrial Scientific & Medical (ISM) frequencies for various locations, 868-868.6 MHz (1 channel, 20 kb/s), 902-928 MHz (10 channels, 40 kb/s) and 2.40-2.48 GHz (16 channels, 250 kb/s) and more recently 779-787 MHz (802.15.4c) and 950MHz -956MHz (802.15.4d). Different modulations are available for carrying data in the different bands, DSSS and a choice of PSK types may be used. Interfacing with Wi-Fi or Ethernet is common, but there is little affinity with other media such as PLC, IR or VLC.

Network installation is relatively self-configuring. At the MAC layer devices can be full or reduced function, FFD or RFD. Each network segment has a single FFD co-coordinator node responsible for management of the network segment (or Personal Area Network, PAN). FFDs may communicate peer to peer, but RFD may only communicate with the coordinator. A network segment may operate beacon or non-beacon management. If beaconing is enabled, the coordinator node will periodically send out a beacon with detailed information about the network segment and possibly guaranteed time-slots for certain nodes. In the time between the beacons nodes in the network may send data controlled by CSMA-CA. Non-beaconed networks simply send data using CSMA-CA without beaconing. Some security services are provided for upper layers by the MAC, but extended security is implemented at higher layers.

IEEE 802.15.4 is a mature and adopted standard, but the range of IEEE 802.15.4 implementations and networking layers, including Zigbee, WirelessHART, Miwi, RF4CE, 6LowPAN, coupled with a choice of other cheap and mature pre-existing low rate RF solutions mean that economies of scale and ubiquitous ad hoc interoperability still elude this standard. Reducing the cost of entry by network layer implementers, such as ZigBee, may help, but the markets for IEEE 802.15.4 and ISM are very varied and total far less than Bluetooth or Wi-Fi with very mixed returns for stakeholders. Mass adoption catalysts, such as government mobile phone legislation for Bluetooth, seem unlikely, though ZigBee"s RF4CE remote control replacement is a possibility. Some commentators suggest the future of IEEE 802 lies in the supporting networking layer 6LowPAN, interoperable with the common transport IPv4.

5) Zigbee

Zigbee is a self-organizing mesh open wireless networking standard ratified by the ZigBee Industry Alliance in 2004. The standard is optimized for medium range, 10 – 75m, low rate, low power and long functional life-time. Applications include small to medium form factor sensing and communication for industrial, medical and home and building automation and energy management, with The ZigBee Alliance specifying a range of their own application profiles, such as ZigBee Home Automation, ZigBee Smart Energy 1.0 and ZigBee Health Care. Zigbee was developed by the members of the Zigbee Alliance, and is specified in [21].

Zigbee specifies Application, Network and Security protocols and is built on the IEEE 802.15.4 RF standard for the PHY and MAC layers. The network layer defines the stack profile and the network rules, and implements discovery, addressing, routing and maintenance. The stack sets network rules such as level of security, timeout, sizes, maximum routers, children and depth of network. To this end Zigbee specifies three Zigbee devices a layer above 802.15.4, controller, router and end device. Interfacing with Wi-Fi or Ethernet is common, but there is little affinity with other media such as PLC, IR or VLC.

Network installation is relatively self-configuring. There can be only one coordinator device per network. The coordinator initiates the network, selecting network Id, stack profile and RF channel. At the MAC layer it is the Zigbee coordinator that acts as the 802.15.4 PAN coordinator. Routers join the coordinator and other routers joining those routers. Once the network is formed the coordinator also acts as router and can perform other applications as required. End devices join routers.

Routers extend the network coverage, although a minimum network may have no routers. Routers will try to find and connect to the Zigbee coordinator or another router. The router maintains its own set of end devices and neighbor routing tables providing routing and addressing locally and providing routing for other multi-hop messages on the network. At the MAC layer the router provides the FFD 802.15.4 coordinator function.

An end device will find and connect to a router or the coordinator. It has no children and performs no routing. This is the lowest powered node on the network and relies on its router to wake it up when required. At the MAC layer the Zigbee end device provides the 802.15.4 RFD function.

Zigbee uses a tree structured address assignment called CSkip, meaning „Child Skip". Addresses are allocated based on position in the tree. Using the maximum depth and maximum children and router children per depth a CSkip value is calculated for each depth which allows for a sufficient pool of addresses at that depth and for source and destination addresses to be used to calculate a route.

ZigBee is a mature and adopted standard, but as discussed for 802.15.4, mass adoption and economies of scale also elude the ZigBee standard with similar markets and returns for stakeholders. Cost of entry set by the Alliance is certainly a factor in the level of adoption. Zigbee networking standard does not support a common transport, but there are signs that the ZigBee Alliance may be moving away from this part of the standard or at least breaking the sole dependency on IEEE 802.15.4. Version 2.0 of ZigBee Alliance Smart Energy Profile, whose requirements are specified in [22], is medium independent, using the IPv6 common network and transport layer; implementations based on IEEE 802.15.4 will use the IETF 6LoWPAN adaptation layer.

6) RF4CE

RF4CE Consortium was founded by Panasonic Corporation, Royal Philips Electronics, Samsung Electronics Co., Ltd. and Sony Corporation on June 12 2008 to look at overcoming the limitations of Consumer Electronics IR remote controls by using RF technology.

Issues with legacy IR remote control include field of vision, line of sight, one way communication and interference from other light sources such as large HD televisions. While RF4CE"s [23]primary focus is an RF remote control replacement, it could equally support many other applications, such as communication with small form factor automated controllers or sensors.

In March 2009 they teamed with Zigbee providing a Zigbee Alliance published standard for RF remote control [24]. As with Zigbee, cost of license and certification still affects demand and widespread adoption and economies of scale are not yet fully realized. Bluetooth Low Energy published in December 2009 includes Home Automation and RF remote control among its applications and its interoperability with the widely adopted Classic Bluetooth make it a strong contender. However, early indications are that IEEE 802.15.4 based standards have the edge on performance.

The Standard is based on the IEEE 802.15.4 PHY/MAC standard. On top of this is RF4CE simple networking and public application profiles, such as Consumer Electronics Remote Control (CERC), which interface to user applications. The public application profiles may include vendor specific extensions. The operational frequency is 2.4GHz. The network is an asymmetric star topology made up of two types of nodes, controllers and targets, though controllers need not be remote controls and could even be appliances.

Installation effort is relatively low, targets have authority to check channel suitability and for any pre-existing personal area networks (PANs) and then start a new PAN. Multiple controllers can join networks by pairing with targets. Targets can communicate with other targets and join PANs to form a RF4CE network, see Fig. 4. Communication is protected using 128-bit cryptographic key pairs and services for confidentiality, authenticity and replay protection. Power management can be achieved by a range of configurations for enabling or disabling power saving mode, including operating a receiver duty cycle where the sender targets the active period. Channel agility means target devices can after creating their PAN switch channels, if conditions dictate, and controllers will try other channels until communication is re-established.

Through RF4CE and its marriage with Consumer Electronics companies, the critical mass required, for wide adoption and almost ubiquitous deployment for home automation including energy management, could be finally realized [25].

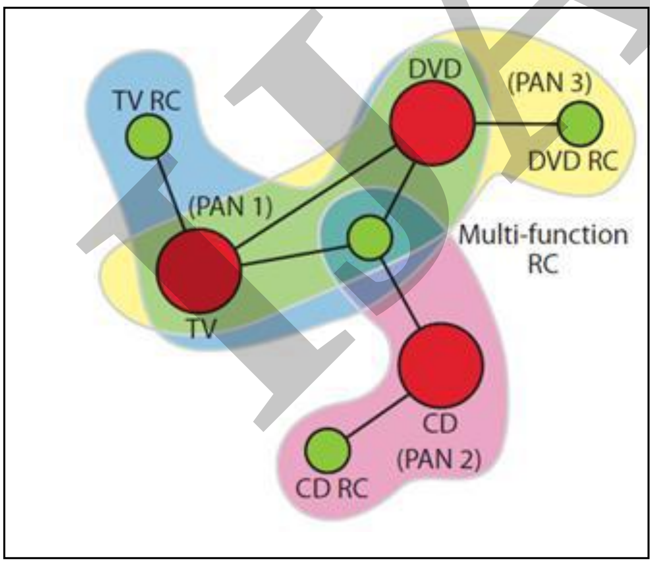

Figure 4. Example ZigBee RF4CE network topology [23

Providing CERC and other profiles with two way RF communications opens the way to a range of new applications to attract consumers and manufacturers. Although RF4CE does not support energy management applications directly, there is support for additional profiles over the same network layer and with ZigBee‟s „Smart Energy‟ profile there may be room for dual function. Communication across the Internet using common transport would require some kind of gateway or tunnelling function.

7) Bluetooth Low Energy

The Bluetooth special interest group began looking into expanding the technology into the low power market in 2000[26]. In 2001 Nokia, a member of the group, were examining the limitations of current wireless technologies. As a result of these examinations, the Nokia Research Center developed Wibree, an adaptation of the existing Bluetooth standard which operated on low power, but minimize impact on the key Bluetooth characteristics.

Wibree was first published in 2004 as a Low End Extension for Bluetooth [27]. In 2007 The Bluetooth SIG and Nokia together adopted Wibree as a part of the Bluetooth Technology plan, calling it ‟Ultra Low Power (ULP) Bluetooth‟. The technology was finalized in December 2009 and added to Bluetooth Core Specification version 4.0 as ‟Bluetooth Low Energy‟ (BLE). Devices were expected to come on-line through 2010.

BLE uses a simplification of the Classic Bluetooth protocol with relaxed RF requirements, shorter packets and greater optimization of power when not transmitting. There are two device types, single-mode devices support BLE only and cannot communicate with a Classic Bluetooth device; while dual-mode devices are Classic Bluetooth devices which simultaneously support BLE communication. The current trend is that dual-mode devices will replace all Classic Bluetooth devices over the next few years. Dual-mode devices are expected to bear much of the configuration load and provide Internet connectivity on behalf of low powered single-mode devices.

Bluetooth low energy uses the 2.4 GHz RF Band and an ultra-low duty-cycle transceiver, using advanced sniff-sub-rating, which allows a host to be woken by a controller for sending and so allows at least a year between single button battery cell recharge. Data is transferred in short packets, connection setup and tear-down is fast giving low latency and speeds of up to 1 Mbps at ranges of up to 100 meters. Accuracy and security are provided through strong 24 bit CRC and Full AES-128 encryption with CCM.

The new technology shares much of Classic Bluetooth‟s radio characteristics and functionality and therefore mitigates cost and promotes manufacturer migration to dual-mode devices with the incentive that a whole range of new applications are enabled by connecting new low energy devices and accessories with an established Classic Bluetooth 1 billion unit base. This will promote wide adoption and allow single-mode small device manufacturers and handset manufacturers to share a common authenticated network.

TABLE V. RELATIVE WIRELESS CONTRIBUTION

Quality	*IR*	*Wi-Fi*	*BT*	*802.15.4*	*Zigbee*	*RF4CE*	*BLE*	*VLC*
Cost	++	++	+				+	+
Form factor	++		+	+	+	+	+	+
Installation	+	+	+	+	+	+		++
Transport		++	++	++				++
Adoption			+			++	+++	
Ubiquitous						+	+	+++
Maturity	++	++	++	+	+			
Standards	+	++	++	++			+	+
Stakeholders		+				+	++	
Media		++						++
Applications				+	+			
Security		++	+	+	+		+	+

Bluetooth low energy is tipped as a strong competitor to technologies such as Zigbee. Applications that connect small form factor sensing with personal mobile devices such as phones could see the technology gain critical mass driving down cost and promoting near ubiquitous deployment. Home automation, Health Care and consumer electronics remote control are already some of the suggested applications for Bluetooth low energy.

8) Visible Light Communication

The latest 802.15 (WPAN) task group is 802.15.7. This group is writing a PHY and MAC standard for Visible Light Communications (VLC). Visible light is defined by the wavelength range 400nm to 700nm. The medium has the Advantage of low power, but with very high bandwidth over short distances, sufficient for common transport protocols, for example by connecting Ethernet installations over a series of lighting fixtures and allowing mobile devices to connect through building LED emitters. Potential deployment characteristics of VLC include a ubiquitous lighting infrastructure, with communication that is low noise, secure and low cost. Additionally with the possibility of an exponential proliferation of Radio Frequency (RF) communication, health and safety critical concerns, regulation and conflict is bound to have a raised profile. Where localized communication is necessary, VLC is environmentally friendly, safe and unregulated and will work alongside safety critical RF applications without conflict. The vision is for installation to be as easy as screwing in a light bulb. The shadowing effect is greatly reduced over IR and cost and power are comparable to RF.

In recent years the light-emitting diode has undergone serious evolution, with increased intensity, efficiency, control and greatly reduced cost. The LED is now a genuine candidate for a ubiquitous illumination technology [28] and therefore a potentially ubiquitous VLC communications infrastructure powered through the existing power grid.

LED form factor is smaller [28] than existing lighting and the communications technology is expected to integrate well with existing technology. Additionally there is a strong potential for affinity between VLC and power line communication [29] [30], indeed many architectures to achieve this are already proposed. Such an infrastructure could be a strong contender for the mission to unite appliances, sensors, meters and other smart grid elements to work together. However though there is already strong industry collaboration and a number of proposed applications, there is yet no clear catalyst for widespread adoption.

9) Others

A number of self-published open standards exist, such as Threshold initiated royalty free One-Net standard, found at [31] [32], whose alliance partners include Texas Instruments and Freescale, and a number of proprietary technologies such as Z-Wave focusing on home automation, though reported to be difficult to install and configure, Wavenis optimized for ultra low power and long range but low traffic and Addinet from Alciom supporting low latency and ultra low power, but currently used by just one Alciom customer, Srett.

C. Sensing

In this section we look at sensors and tags suitable for energy management of appliances.

1) RFID

RFID tags are microchips that may be located in or carried by objects, animals or people to allow remote identification or tracking and more recently also for sensing [33]. Radio Frequency Identification technology (RFID) comprises tags, composed of an IC and an antenna, and RFID readers. The reader transmits a radio frequency and reads the back scattered signal reflected and modulated by the tag to indicate its Id. Passive tags are powered remotely by the reader‟s transmission, while active tags are battery assisted and have greater range and capabilities. Read rate is affected by frequency with higher frequency tags have higher read rates. Read rate as a proportion of successful reads is also affected by distance, with active battery assisted tags supporting a higher proportion of the maximum read rate at greater distances. RFID is common for product identification, and communication is through the Electronic Product Code (EPC). The protocol can select from multiple tags using a tree walking technique and supports sending data to tags using amplitude shift- keyed (ASK) modulation. RFID is a very mature and low cost technology and this together with its potential for very small form factor make it a strong candidate for a ubiquitous sensing network. As a networked solution however, RFID has higher installation effort due to its asymmetric topology, its dependence on RFID reader devices and the limited implementation of two way communication, additionally RFID is less secure due to its reduced support for computation. RFID already has a major stakeholder presence in asset tracking and recent interest from global retailers may lead to universal adoption and commodity status. However, widespread adoption in the energy management field is still uncertain due to the integration difficulties and the lack of a common transport.

2) Sensor Motes

Sensors convert environmental stimulus into an electrical signal that can be measured and stored. There are a variety of sensor types, including: temperature, humidity, light, speed, acceleration, sound, magnetism. Progress in electronics and low power communications has seen the inception and advancement of the smart sensor.

In [34] the author describes smart sensors, or sensor motes, as a low power devices equipped with one or more sensors, a processor, memory, a power supply, a radio, and an actuator. These motes can include a number of different sensors and are generally battery powered, though some devices may include a mechanism, such as photovoltaic cells, to harvest energy. Sensor motes generally form wireless sensor networks (WSN) either as a large scattering of motes or as a smaller number of strategically placed motes. Motes can have different roles in the WSN, such as general sensing, data relay or mote management, managing motes join or leave the network. The network also includes a base station or sink, often connected to a fixed powered network.

The memory and processing added to sensors support storage and operating systems, enable protocols and provide services to enhance efficiency in sensor operation and routing. Operating systems include event driven implementations such as TinyOS and Contiki.

WSN use their own protocols from PHY to Transport layer, optimized for ad-hoc and low power. Many such protocols are implemented in published standards such as IEEE 802.15.4, Zigbee, specified in [21], WirelessHART, ISA 100.11, IETF 6lowPAN and the 2009 IEEE 802.15.1 Bluetooth Ver4.0 Low-Energy. Important services include synchronization saving energy by reducing collisions or retransmission or implementing duty-cycles, GPS, anchor base and proximity based localization and methods and tools to balance the need for coverage with the cost of coverage. Other services include security and data compression and aggregation.

The cost of sensor motes is coming down; however number of parallel standards and the range of open and proprietary solutions mean that economies of scale and ubiquitous ad hoc interoperability still elude the sensor mote industry. Moreover, the markets are very varied and total far less than common Bluetooth or Wi-Fi devices with very mixed returns for stakeholders. These factors have precluded wide adoption and the realization of a ubiquitous sensing infrastructure.

The size of sensor motes is reducing, but their miniaturization has been overtaken by the introduction of sensing to RFID which is far less constrained by the need for a power supply. On the other hand sensor motes provide far more computation and are beginning to implement common transport protocols and already support a range of applications and services that are far beyond the capabilities of RFID. Supported energy management applications for sensor node protocols already exist.

The standards for sensor mote communication are reaching maturity; there is good support for security and many networks are symmetric and self-configuring.

3) WISP

In an effort to address functional lifetime and form-factor in sensors, sensing has been introduced to battery free UHF RFID using fixed function, non-programmable sensing, with single bit communication [35, 36]. More recently, the Wireless Identification and Sensing Platform (WISP) project [36] proposed the more flexible RFID Sensor Network (RSN). This project adds remotely programmable computation and implements communication through control of all 64 bits of the Id tag using EPC primitives. WISP sacrifices some range in providing computation, but opens up possibilities for on-board filtering, security and more. Open research issues include balancing computational load with harvested energy, development of new protocols and integration of RSN with WSN.

TABLE VI. SENSING FUNCTIONAL CHARACTERISTICS

Name	*Data Rate*	*Range*	*Power*
Sensor Motes	< 1 Mbps	- 100m	Ultra Low - Low (for example: TmoteSky/TelosB, 3 mW / 3.24 mW active, 6 µW / 15 µW sleeping, 6 µsec wake-up time [38])
RFID (UHF): Passive:	<= 200 tags/s	<30 ft	Harvested Energy (% read rate can be affected by distance)
RFID (UHF): Active:	<= 200 tags/s	<300 ft	Battery Assisted (% read rate can be affected by distance)
WISP (UHF)	1kbps & 2ms/query	10 ft	Harvested Energy (approximate 1 mW / EPC cycle)

TABLE VII. RELATIVE SENSING CONTRIBUTION

Quality	**Sensor Motes**	**RFID**	**WISP**
Cost		+	
Form factor		++	+++
Installation	+		
Transport	++		
Adoption			
Ubiquitous			++
Maturity	+	++	
Standards	+	+	
Stakeholders		++	
Media			
Applications	+		
Security	++		+

WISP technology is of course very immature and new protocols or EPC adaptations are still awaited. However the primary benefits of RSN will come from its very small form factor, long life and ability to operate without an attached power source, allowing it to support applications that require semi-permanent and possibly ubiquitous deployment in inaccessible locations.

WISP has been predicted as the new smart dust in [37], and may, in time, contribute to the concept of a ubiquitous context sensing environment. On the other hand WISP retains many of the RFID integration difficulties described above and may still lack a common transport. Additionally its short operation range and its narrow field of application make it an unlikely candidate for wide adoption or a primary solution to energy management.

D. Energy Management Projects

In this section we give brief overviews of a selection of existing and proposed appliance energy management architectures. In particular we note the communication and sensing technologies they use.

1) Network architecture for home energy management system [39]

Historically the wired medium of Power line Communication (PLC) has been popular in home automation and energy management. Though a number of existing PLC technologies existed at the time of their research, the authors of this architecture proposed their own dispersed-Tone Power Line Communication because it does not hinder regular narrow-band power line communication, but deals with narrow-band noise that other Power Line Communication does not. The architecture also includes a controller (PC) for monitoring and controlling sensors and appliances and a home gateway making possible external monitoring and control. A key component of their work is the Compact Appliance Control Interface (CACI) and the provision of network adapters with CACI to make CACI supporting appliances and sensors network ready without requiring network function.

2) A novel power line network architecture for managing the energy resources of the residential environment [40]

The authors of this architecture also propose the use of Power line Communication to monitor appliances energy consumption, enforce limits of consumption and manage appliances in standby. The architecture employs KNX as discussed above. Consumption may be constrained by user and operator, and the electricity provider may obtain geographical statistics through the Residential Gateway (RG).

One of the key elements in this architecture is an Energy Management Device (EMD). The device provides a bridge between KNX on the IP residential gateway and KNX on the PLC Network of appliances. In addition the EMD provides a uniform KNX API and management primitives for all the connected appliance as well as monitoring energy and providing operation mode changes or auto switch off for standby appliances.

3) Wireless Sensor Networks for Commercial Lighting Control: Decision Making with Multi-agent Systems [41]

In response to the large proportion of US electricity used for lighting in commercial buildings, the authors propose an intelligent automated multi-agent commercial lighting system, implemented as a Wireless Sensor Network (WSN). The authors also propose the implementation of user lighting preference. RFID, a common battery-less building security feature, is discussed, but the authors choose miniature cards with embedded sensor nodes to link with the sensor network and to actuate the user‟s lighting preferences. Privacy may be a concern for users, but person identification could manage operation modes for much more than lighting combining energy saving and personal preference.

4) Wireless networked lighting systems for optimizing energy savings and user satisfaction[42]

In this project the authors use wireless sensor and actuator technologies to implement a lighting control system that optimizes energy management, user preferences and the needs of a modern lighting system. The technologies are networked over the 802.15.4 communication standard using T-Mote Sky sensor nodes. An optimization algorithm is designed to minimize energy use while reading lighting conditions and accommodating notified user preferences. The hardware installation is designed for minimal adaptation of existing lighting infrastructure.

5) Architectural design of home energy saving system based on realtime energy-awareness[43]

The authors of this project propose a Home Energy Saving System (HESS). The key components of the system are the HESS Client and the HESS Server. The system provides no-new-wire client/server linkage through a Power Line Communication (PLC) network or a Zigbee network. The HESS client can be deployed as a wall power outlet adapter or built-in to an appliance power module.

The system monitors and presents appliance power consumption, alarms users when thresholds are breached, monitors for thresholds or standby state in order to manage appliance operational or power state and also detects the user‟s intention to switch an appliance back on in order to reintroduce power.

6) A communication stack over PLC for multi physical layer IPv6 Networking

The goal of this project is to provide a common stable communication stack for operation across multiple media. The solution is implemented with an adapted version of 802.15.4 and 6LowPAN for deployment across PLC and wireless. A testbed is implemented and a range of interoperability tests performed. While this project makes good use of a number of our surveyed standards, its primary theme relates to our quality characteristic for media; the realization that no single technology will meet requirements but that the key to progressing will be in addressing cross-media communication and common transport.

IV. CONCLUSIONS

Climate change, dwindling legacy energy sources and aging and under-invested power grids have forced governments, energy producers, distributors and consumers, with some urgency, to focus significant resources on long term strategies for energy management. The UK supplied 357.2 TWh of electricity in 2009 and the domestic sector was the largest consumer with the domestic and service sector together totaling 70% of total consumption [44]. With appliances contributing significantly in these sectors, it is clear that they should be a very important part of this energy management focus.

In order to contribute to energy management appliances need to collaborate with users, the grid and their environment. Our ideal appliance communication and sensing technologies should enable simple ubiquitous deployment of small low cost self-configuring devices. These devices should automatically and securely connect and collaborate across multiple media over a common transport using a fully adopted and open energy management application protocol. The network should benefit all stakeholders including users, appliance manufacturers, utilities, personal and commercial energy generators and energy policy makers. However, realizing this ideal is a different matter.

We are beginning to see some exciting developments in communication and sensing; improved implementations of Power line Communication (PLC) and the ratification of Homeplug based IEEE P1901 in September 2010; Bluetooth Low Energy, 6LowPAN and the inception of 802.15.7, Visible Light Communication (VLC); Reductions in size, reductions in power and the provision of two way communication sensing and on-board computation using harvested energy [36]. However, many of these achievements exist in isolation.

It is becoming clear that that an imperative to architecting the solution will be in addressing cross-media communication and common transport. Given the diverse nature and location of elements across the grid and inside premises there will be a need for a multi-technology solution, and yet there remains a strong requirement for collaboration. There exists some work in this area already; IEC62480 is the ratification of the work of the Echonet project [45] to specify a design for a common network adapter; there is also work to integrate PLC and VLC [30] and work to integrate PLC and RF [46] over a common transport.

Finally there is an overarching need to address the concerns of particular stakeholders. There is already an understanding and acceptance within the appliance industry that we are progressing towards smart appliances and research shows that there is already some willingness amongst consumers to accept smart operation [47]. However, for appliance manufacturers it is essential that they protect their huge design and development investment their market and their consumers. To Progress the industry from concept acceptance to realization it will be essential that their concerns are addressed. The primary concerns of appliance manufacturers are cost, added benefit to consumers, simplicity, stability and privacy [48]. As the technologies and standards mature we may see media integration, common transport, support for a ubiquitous infrastructure, catalysts for wide adoption and wide support for the energy management application domain; however nothing will be realized if we fail to address the concerns of these stakeholders.

REFERENCES

[1] “The smart grid: an introduction,” Report by Litos Strategic Communication. An account of work on the Smart Grid sponsored by The United States Department of Energy., 2010.

[2] M. S. Yousuf and M. El-Shafei, “Power line communications: an overview - part i” ser. Innovations‟07: 4th International Conference on Innovations in Information Technology, IIT. Dubai, United Arab emirates: Inst. of Elec. and Elec. Eng. Computer Society, 2008, pp. 218–222.

[3] M. S. Yousuf, S. Z. Rizvi, and M. El-Shafei, “Power line communications: an overview - part ii” ser. 2008 3rd International Conference on Information and Communication Technologies: From Theory to Applications, ICTTA. Damascus, Syria: Inst. of Elec. and Elec. Eng. Computer Society, 2008.

[4] “Standard and extended x10 code protocol,” Revision 2.4, 1975.

[5] “The x-10 powerhouse power line interface model pl513 and two-way power line interface model tw523,” Revision 2.4, 1975.

[6] Insteon, “Insteon the details,” 2005.

[7] B. L. Capehart, “Web based energy information and control systems : case studies and applications” 1st ed. Fairmont Press, 2005.

[8] “Ansi-cea-709.1,” Lonworks building control protocol specification for layers MAC and above, 2005.

[9] E. Corporation, “Free-topology twisted-pair channel specification ansi-cea-709.3,” Lonworks building control protocol specification for Free–Topology Twisted–Pair Channel Specification (ANSI–CEA–709.3), 2006.

[10 “Cea-709.2 - control network power line (pl) channel specification,” Lonworks building control protocol specification for powerline PHY layer Rev A, 2006.

[11] “Upb technology description”, Powerline Control Systems, 2007.

[12] Insteon, “Insteon compared,” Insteon White Paper, 2005.

[13] “Homeplug alliance,” Homeplug Alliance Website (http://www.homeplug.org/home), 2000.

[14] “Ieee 802.3-2008 lan/man csma/cd (ethernet) access method”, IEEE 2008.

[15] “Knx association,” (http://www.knx.org) 1999.

[16] A. Kell and P. Colebrook, “Open systems for homes and buildings: Comparing lonworks and knx,” i&i limited, 2005.

[17] “Powerline control systems, inc.”, (http://www.pulseworx.com/), 2007.

[18] S. Williams, “Irda: past, present and future,” IEEE Personal Communications, vol. 7, no. 1, pp. 11–19, 2000.

[19] J. M. Kahn and J. R. Barry, “Wireless infrared communications,” Proceedings of the IEEE, vol. 85, no. 2, pp. 265–98, 1997.

[20] “Ieee 802.15.4-2006 low rate wpan,” IEEE, 2006.

[21] “Zigbee specification including the pro feature set”, Zigbee Alliance, 2007.

[22] “Zigbee smart energy profile 2.0 technical requirements document”, Zigbee Alliance 2009.

[23] “Understanding zigbee rf4ce”, Zigbee Alliance, 2009.

[24] “Zigbee rf4ce specification version 1.00”, Zigbee Alliance, 2009.

[25] C. Links, “Will rf4ce be the killer application for zigbee?” ANTENNA SYSTEMS and TECHNOLOGY, pp. 10–11, JULY/AUGUST 2009.

[26] “Bluetooth technology information site.”, http://www.bluetooth.com/English/Pages/Default.aspx

[27] M. Honkanen, A. Lappetelainen, and K. Kivekas, “Low end extension for bluetooth,” ser. Proceedings. 2004 IEEE Radio and Wireless Conference (IEEE Cat. No.04TH8746). Piscataway, NJ, USA: IEEE, 2004, pp. 199–202.

[28] T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using led lights,” IEEE Transactions on Consumer Electronics, vol. 50, no. 1, pp. 100–107, 2004.

[29] E. T. Won, D. Shin, D. K. Jung, Y. Oh, T. Bae, H.-C. Kwon, C. Cho, J. Son, D. OBrien, T.-G. Kang, and T. Matsumura, “Visible light communication : tutorial,” Tutorial to IEEE 802.15, 2008.

[30] T. Komine and M. Nakagawa, “Integrated system of white led visible-light communication and power-line communication,” IEEE Transactions on Consumer Electronics, vol. 49, no. 1, pp. 71–9, 2003.

[31 “One-net alliance.”, http://www.one-net.info/

[32] “Production-ready one-net 1.5.0 released,”, One-net alliance, 2009.

[33] R. Want, “Enabling ubiquitous sensing with rfid,” Computer, vol. 37, no. 4, pp. 84–6, 2004.

[34] J. Yick, B. Mukherjee, and D. Ghosal, “Wireless sensor network survey,” Computer Networks, vol. 52, no. 12, pp. 2292–2330, 2008.

[35] “125 khz passive rfid device with sensor input mcrf202”, Microchip Technology Inc., 2005.

[36] A. P. Sample, D. J. Yeager, P. S. Powledge, A. V. Mamishev, and J. R. Smith, “Design of an rfid-based battery-free programmable sensing platform,” IEEE Transactions on Instrumentation and Measurement, vol. 57, no. 11, pp. 2608–2615, 2008.

[37] M. Buettner, B. Greenstein, D. Wetherall, and J. R. Smith, “Revisiting smart dust with rfid sensor networks,” in 7th ACM Workshop on Hot Topics in Networks, 2008.

[38] V. Potdar, A. Sharif, and E. Chang, “Wireless sensor networks: a survey,” ser. 2009 IEEE 23rd International Conference on Advanced Information Networking and Applications Workshops (WAINA). Piscataway, NJ, USA: IEEE, 2009, pp. 636–41.

[39] M. Inoue, T. Higuma, Y. Ito, N. Kushiro, and H. Kubota, “Network architecture for home energy management system,” IEEE Transactions on Consumer Electronics, vol. 49, no. 3, pp. 606–13, 2003.

[40] S. Tompros, N. Mouratidis, H. Hrasnica, and M. Caragiozidis, “A novel power line network architecture for managing the energy resources of the residential environment,” ser. 2009 IEEE International Symposium on Power Line Communications and Its Applications. Piscataway, NJ, USA: IEEE, 2009, pp. 211–16.

[41] J. S. Sandhu, “Wireless sensor networks for commercial lighting control: Decision making with multi-agent systems,” in AAAI Workshop on Sensor Networks, 2004, pp. 131–140.

[42] W. Yao-Jung and A. M. Agogino, “Wireless networked lighting systems for optimizing energy savings and user satisfaction,” ser. 2008 IEEE Wireless Hive Networks Conference (WHNC). Piscataway, NJ, USA: IEEE, 2008, p. 7 pp.

[43] C. Kwang-Soon, A. Yang-Keun, P. Young-Choong, P. Woo-Chool, S. Hae-Moon, J. Kwang-Mo, and S. Kyeung-Hak, “Architectural design of home energy saving system based on realtime energy-awareness,” ser. Proceedings of the 2009 4th International Conference on Ubiquitous Information Technologies Applications (ICUT 2009). Piscataway, NJ, USA: IEEE, 2009, p. 5

[44] “Digest of uk energy statistics 2010”, UK Department Of Energy and Climate Change, 2010.

[45] S. Matsumoto, “Echonet: a home network standard,” IEEE Pervasive Computing, vol. 9, no. 3, pp. 88–92, 2010, copyright 2010, The Institution of Engineering and Technology 11416847 1536-1268 echonet home network standard IEC ISO.

[46] C. Chauvenet, B. Tourancheau, D. Genon-Catalot, P.-E. Goudet, and M. Pouillot, “A communication stack over plc for multi physical layer ipv6 networking,” in 2010 First IEEE International Conference on Smart Grid Communications. Gaithersburg, Maryland, USA: IEEE, 2010, pp. 250 – 255.

[47] W. Mert, J. Suschek-Berger, and W. Tritthart, “Consumer acceptance of smart appliances,” A report prepared as part of the EIE project – Smart Domestic Appliances in Sustainable Energy Systems (Smart–A), 2008.

[48] “The home appliance industrys principles and requirements for achieving a widely accepted smart grid”, Association of Home Appliance Manufacturers (US), 2009.