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Green Buildings and Ambient Intelligence: case study for N.A.S.A. Sustainability Base and future Smart Infrastructures

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SOMMARIO

Con la diffusione delle smart infrastructures, espressione con cui ci si riferisce collettivamente ai concetti di smart cities e smart grid, i sistemi di building automation vedono il proprio ruolo espandersi oltre i tradizionali limiti degli ambienti isolati che sono progettati per gestire, supervisionare ed ottimizzare. Da sistemi isolati all'interno di edifici residenziali o commerciali, stanno iniziando ad ottenere un ruolo importante su scala più ampia nell'ambito di scenari più complessi a livello urbano o a livello di infrastruttura. Esempi di questa tendenza possono essere le attuali sperimentazioni in varie città del mondo per automatizzare l'illuminazione pubblica, complessi residenziali diffusi (spesso denominati smart connected comunities) e microgrid locali generate dalla federazione di varie unità residenziali a formare cosidette virtual power plants. A causa di questo processo, ci sono aspettative crescenti circa il potenziale delle reti di automazione di introdurre funzionalità sofisticate da un parte ed efficienza energetica dall'altra, ed entrambi gli aspetti su vasta scala. Sfortunatamente questi due obiettivi sono per diversi motivi in conflitto ed è dunque inevitabile individuare un ragionevole compromesso di progettazione. Questa ricerca realizza una caratterizzazione delle attuali tecnologie di automazione per identificare i termini di tale compromesso, con un'attenzione maggiormente polarizzata sugli aspetti di efficienza energetica, analizzata seguendo un approccio olistico, affrontando diversi aspetti del problema. Indubbiamente, data la complessità del vasto scenario tecnologico delle future smart infrastructures, non c'è una finalità sistematica nel lavoro. Piuttosto si intende fornire un contributo alla conoscenza, dando priorità ad alcune sfide di ricerca che sono altresì spesso sottovalutate. Il Green networking, ovvero l'efficienza energetica nel funzionamento di rete, è una di tali sfide. L'attuale infrastruttura IT globale è costruita su attrezzature che collettivamente consumano 21.4 TWh/anno (Global e-Sustainability Initiative, 2010). Questo è dovuto alla scarsa consapevolezza del fatto che le specifiche dei protocolli di comunicazione hanno varie implicazioni sull'efficienza energetica e alla generale tendenza ad una progettazione ridondante e sovra-dimensionata per il caso peggiore. Questo problema potrebbe essere riscontrato anche nelle reti di automazione, specialmente data la tendenza di cui si discuteva sopra, e in tal caso, queste potrebbero introdurre un ulteriore carbon footprint, in aggiunta a quello della rete internet. In questa ricerca si intende dimensionare tale problema e proporre approcci alternativi agli attuali modelli di hardware e protocollo tipici delle tecnologie di automazione in commercio. Spostandosi dalla rete di controllo all'ambiente fisico, altro obiettivo di questo lavoro è la caratterizzazione di sistemi di gestione automatica dei plug loads, carichi elettrici altrimenti non gestiti da alcun impianto di building automation. Per tali sistemi verranno mostrati i limiti e le potenzialità, identificando potenziali problematiche di design e proponendo un approccio integrato di tali sistemi all'interno di sistemi più ampi di gestione dell'energia.

Infine, il meccanismo introdotto nella parte di green networking è potenzialmente in grado di fornire informazioni in tempo reale circa il contesto controllato. Si tratta di un potenziale sfruttabile per sviluppare soluzioni di Demand Side Management, allo scopo di effettuare previsioni di picco e di carico. Questa analisi è attualmente in corso, attraverso una partnership con Enel Distribuzione.

ABSTRACT

With the advent of smart infrastructures, collective expression used here to refer to novel concepts such as smart cities and smart grid, building automation and control networks are having their role expanded beyond the traditional boundaries of the isolated environments they are designed to manage, supervise and optimize.

From being confined within residential or commercial buildings as islanded, self-contained systems, they are starting to gain an important role on a wider scale for more complex scenarios at urban or infrastructure level. Example of this ongoing process are current experimental setups in cities worldwide to automate urban street lighting, diffused residential facilities (also often addressed to as smart connected communities) and local micro-grids generated by the federation of several residential units into so-called virtual power plants.

Given this underlying process, expectations are dramatically increasing about the potential of control networks to introduce sophisticated features on one side and energy efficiency on the other, and both on a wide scale. Unfortunately, these two objectives are, in several ways, conflicting, and impose to settle for reasonable trade-offs.

This research work performs an assessment of current control and automation technologies to identify the terms of this trade-off with a stronger focus on energy efficiency which is analyzed following a holistic approach covering several aspects of the problem. Nevertheless, given the complexity of the wide technology scenario of future smart infrastructure, there isn't a systematic intention in the work. Rather, this research will aim at providing valuable contribution to the knowledge in the field, prioritizing challenges within the whole picture that are often neglected.

Green networking, that is energy efficiency of the very network operation, is one of these challenges. The current worldwide IT infrastructure is built upon networking equipment that collectively consume 21.4 TWh/year (Global e-Sustainability Initiative, 2010). This is the result of an overall unawareness of energy efficiency implications of communication protocols specifications and a tendency toward over-provisioning and redundancy in architecture design. As automation and control networks become global, they may be subject to the same issue and introduce an additional carbon footprint along with that of the internet. This research work performs an assessment of the dimension of this problem and proposes an alternative approach to current hardware and protocol design found in commercial building automation technologies.

Shifting from the control network to the physical environment, another objective of this work is related to plug load management systems, which will be characterized as to their performance and limitations, highlighting potential design pitfalls and proposing an approach toward integrating these systems into more general energy management systems.

Finally, the mechanism introduced above to increase networking energy efficiency also demonstrated a potential to provide real-time awareness about the context being managed. This potential is currently under investigation for its implications in performing basic load/peak forecasting to support demand side management architectures for the smart grid, through a partnership with the Italian electric utility.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Automation and control networks have been evolving, over the last few decades, relatively slowly, in terms of global dimension and pervasiveness, if compared to the worldwide data networking infrastructure. The latter has quickly consolidated into a complex, yet coherent, distributed asset, gaining the role of a more than established critical resource, shaping people's life, providing access to knowledge and business opportunities to virtually everyone on the planet. For a number of reasons, the same process has not emerged yet for automation and control infrastructures. Visions such as the "Smart Grid", the "Smart City" and even "Smart Buildings" (all referred to as "Smart Infrastructures", or SIs, within the scope of this document) still suffer from a tangible gap between technical opportunities and actual adoption rate. A thorough estimation of this gap, as well as a comprehensive explanation of its socio-economic reasons, is beyond the scope of this research work, which aims, instead, at focusing on the identification of the foundational technical challenges that will have to be addressed in order to support an economically and environmentally sustainable growth of SIs. This introduction intends to inform the reader about the motivations of this study and the research questions that have been explored throughout the work. In the following paragraphs, an overall perspective will be provided about the structure of the research effort and, especially, how the underlying vision evolved and specialized into the one described here. The work is structured in four distinct lines, one of which is an ongoing effort.

1.1. Structure of this document

The present document is structured as follows. The present chapter introduces the reader to the body of knowledge pertaining to subjects covered within this work.
Chapter 2 describes an original contribution in the field of interoperability among heterogeneous building automation standards. This chapter was also featured as a journal publication in [102]. The work described in this chapter was developed under a research grant at Italian National Research Council (Consiglio Nazionale delle Ricerche) at the Research Area of Pisa, Italy.
Chapter 3 discusses design issues of a green networking prototype model in building automation, developed by the author and published as a journal publication in [103]. This research effort was privately funded.
Chapter 4 and chapter 5 regard research effort conducted within the "Sustainability Base" project for the development of a plug load management system to be deployed at a net zero energy building. The work was conducted under a Fulbright Fellowship grant at N.A.S.A. Ames Research Center, Mountain View, California and is based on the author's collaboration with the Intelligent Systems Division. Chapter 4, in particular, contains both original (and unpublished) author's contributions, as well as reporting on the overall project outcome, featured in more details in [95]. Chapter 5 is dedicated exclusively to author's analysis, exploiting previous results published in [104].
Chapter 6 describes current, ongoing work conducted under a research agreement with the Italian public utility for electrical energy, Enel, aiming at exploiting results

discussed in Chapter 3 for the development of a Smart Grid Demand Side Management system.

Introduction to the body of knowledge, below, is structured in three sections dealing with a brief overview of state of the art technologies and research.
First, an overview of the building automation scenario is presented in paragraph 1.2. This section restructures and summarizes relevant literature material [51] providing the reader with a quick understanding of concepts related to the contribution in Chapter 2 as well as Chapter 5.
The subsequent paragraph provides insight on issues related to energy efficiency in networking equipment in the perspective of the research described in Chapter 3. This survey structure summarizes an overview of relevant literature [62], even though specific work regarding green networking in building automation is not commonly found in other currently published works.
Finally the last section introduces the reader to the concept of Smart Grid, with special regard to Demand Side Management. Only a very brief introduction is provided here, following literature approach as in [105], in the perspective to inform the reader for a better understanding of the research line introduced in Chapter 6.

1.2. Building Automation

Home and Building Automation Systems (HBASs) have been neglected by the scientific community [31] for several years, since their first introduction[1] and until lately. This has led to a fragmented technical scenario where each technology and even each deployed system has traditionally been considered as an isolated instance. As a consequence, ad-hoc solutions and design strategies have proliferated, along with several standardization efforts (although incompatible with each other) and proprietary technologies. In the perspective of an upcoming process of convergence of SIs, as most authors expect (see for example [100]), this fragmentation will jeopardize the overall target coherence and, hence, performance, stability, dependability and cost-effectiveness of SIs. Many, if not most, commercial and residential buildings currently equipped with an HBAS, will not be easily “plugged” into higher-level SIs, and, in a more general sense, protection of past investments will not be maintained in all cases.
On a wide perspective, Home and building automation systems (HBAS) deal with enhancing the process of interaction with and between devices, appliances and systems within indoor habitats, ranging from very small networks to large infrastructures. The latter category has recently expanded from the traditional concept of “buildings” (including office buildings, hospitals, warehouses, or department stores) to define large distributed complexes made of a federation of smaller installations (such as distributed corporate premises, “diffused” residential facilities, connected communities and Smart Cities). The key value proposition leveraged by the building automation market is the perspective of gaining increased comfort levels while optimizing operation costs. Thus, several regulatory efforts have been introduced in order to facilitate, or even mandate the use of HBAS.

[1] Some authors date back HBAS to 1990s [31] and other even before [51]

The principle behind these regulations is that economical and financial considerations suggest that introducing HBAS, although this investment typically results in higher construction cost, is economically feasible if examined by considering the entire building life cycle. In fact, operational costs of a building over its lifetime may sum up to even about seven times the initial investment for construction. Therefore, it is paramount to adopt a building concept that targets optimal life cycle costs, rather than minimum investment. This is also confirmed by the existence of several performance contracting offers. In these models, the financial risk is taken by the contractor, in the perspective that future savings will offset the initial investment within an economically reasonable time. Below a few introductory concepts will be provided to inform the reader about important pieces of knowledge to appreciate the upcoming original contributions. The interested reader will surely find beneficial reading full survey overview of building automation [51] and, for specific technologies, to relevant standardization documents.

1.2.1. Historical overview of Home and Building Automation

The origins of HBAS technologies are tightly connected to Heating Ventilation and Air Conditioning (HVAC), core functionality dedicated to human comfort, and therefore main focus of building automation since early 20th century until today. Early systems were designed leveraging pneumatic-based communication mechanisms, exchanging information based on air pressure levels, within the range between 0,2 to 1 bar.

Then, electrical and electronic systems appeared, in which the information exchange mechanism was instead based on voltage or current levels, e.g. the well-known 4-20mA.

Finally, microprocessors were deployed, and concepts such as Direct Digital Control (DDC), and Programmable Logic Controllers (PLCs), a category of devices exploited both for industrial and building automation, begun to appear.

Supervisory Control and Data Acquisition (SCADA) were then introduced as systems for building management, with the purpose to significantly facilitate operation and maintenance tasks, which could be executed remotely, rather than on-site, at each piece of equipment’s location, reducing the burden and costs to service, troubleshoot and audit large building automation systems.

Historical data logging functionalities were then introduced giving life to so-called Building Management Systems (BMS) enabling assessment of operation costs, analysis of trend logs with the aim of improving the overall system design and optimize control strategies.

1.2.2. Benefits and challenges of HBAS integration

The general HBAS derived benefits mentioned above, that is enhancing of functionality and comfort on one side and reduction of life-cycle costs, reach their maximum as more systems are combined and integrated. Unified supervision and management potentially reduces maintenance costs. Large setups with several buildings spread out geographically over large distances would greatly benefit from an harmonization of the building network infrastructure.

This desirable scenario, however, is currently jeopardized by the fact that different manufacturers use proprietary communication interfaces, and, at the same time, no manufacturer is able to provide a complete offer of user-required applications (nor willing to invest toward this goal). The opposite approach, given by open standards, which define common frameworks, interfaces, communication protocols and even hardware models, facilitate multi-vendor system design.

Beyond the mentioned need to offer a wider range of applications, the concept of system integration is also crucial in that advanced functionalities require as many sources of information as possible in order to adopt suitable decision-making procedures. This concept will be explored in deeper detail in subsequent chapters, since it is at the base of the original contributions of this research work. Here, it is important to outline that correlating multiple pieces of information is necessary both within the HBAS (to enable sensor fusion techniques, for example) and between the HBAS and other systems, such as the IT data infrastructure, as well as standalone security or access control systems, to name a few.

Synergies among systems are becoming more and more feasible also by the trend toward adopting traditional LAN technologies within building automation. Tunneling techniques, as well as native support for IP-based connectivity are very common in HBAS technologies (protocols such as Knx or Bacnet have included such practices within their standards).

Highly integrated systems, however, are typically very challenging due to their complexity. Troubleshooting malfunctioning systems could require extensive knowledge of several technologies and isolating faults within a single sub-system might not be always possible. This can have an undesired impact on collaboration schemes between design professionals and on liability determination. When life safety is involved, this problem becomes strictly critical. For this very reason, fire alarm systems traditionally have been required by building codes to be kept completely separate from other building control systems.

1.2.3. Building Automation three-tier model

The structure of HBAS is logically divided into three layers, to facilitate consistent design and analysis of different systems. This division is usually addressed to as automation pyramid or hierarchy, and is represented in Fig. 1.1. The following paragraphs briefly describe each of the three layers.

1.2.3.1 Field level

The *field level* is the closest to the controlled physical processes. Here is where we have the sensing part (collection and transmission of environmental data) on one side, and the actuating part (physical control of environmental parameters) on the other. Due to their nature, field devices may engage in analog to digital conversions, as well as driving motors, etc. Field devices may be equipped, depending on the specific technology, with various degrees of computational power.

1.2.3.2 Automation level

Data coming from the field is then aggregated and further manipulated by the *automation level*, which introduces logical elaborations and control actions at a higher level of abstraction. At this level, data related to distinct sub-systems may be aggregated horizontally both for further action and for access by the upper layers. The device depicted in Fig. 6.7 (touch screen) is an example of this layer, in that it provides logical functions correlating field-level data as well as coordination of underlying system functions by enacting scenarios (sequences of commands delivered to various field devices upon a single user request).

1.2.3.3 Management level

At the *management level*, information from the entire system is consolidated and made accessible for visualization. This layer is also responsible for logging historical data. Building operators interact with this level to engage in typical maintenance and verification procedures. More complex interpretation of data is also usually executed at this level, since it is composed by devices with significant computational abilities. SCADA systems pertain to this layer.

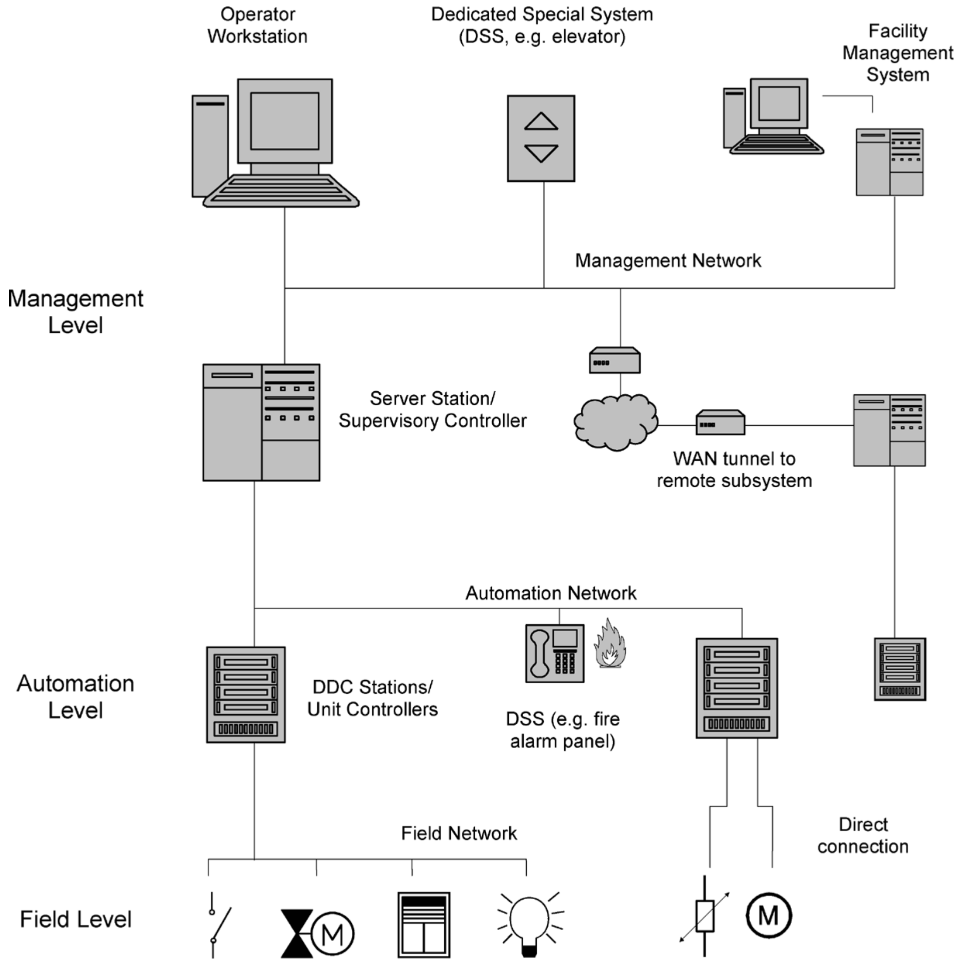


Fig. 1.1 – Automation hierarchy [51]

Common HBAS systems often exhibit hybrid combinations of these three layers. While the field level is always present, the other two might be included only in higher-end installations. Also, coordination functions might be present at field level as well as management tools might directly request action at field level.

1.2.4. Intelligence distribution

In HBAS networks, nodes (sensors, actuators and controllers) are connected to a shared network and communicate using a common protocol. Communication procedures may be horizontal (data exchange between sensors and actuators) or vertical (such as in data logging procedures or for commands sent directly to actuators from upper layers, in command-driven, rather than data-driven, models).

The whole HBAS restructures the underlying physical process exploiting logical elements known as *data points*, which are made available to the application level. Data points are directly handled by field devices which can manage one or more of them. Logical bindings between data points are then expressed to actually build the distributed application, which defines the procedures to process input data points into output ones. This logical structure can be visualized by means of a directed graph (see below). Note that there is a distinction between the mentioned logical structure and the physical distribution of field devices as well as their physical connections to the shared medium.

1.2.4.1 Functional blocks

Specific functions or subsets of the distributed application, can be identified by logical grouping of points in the data point graph. This groups are commonly known as functional blocks. They represent a convenient design tool in that system builders can conceive the whole distributed application as a connection between several functional blocks.

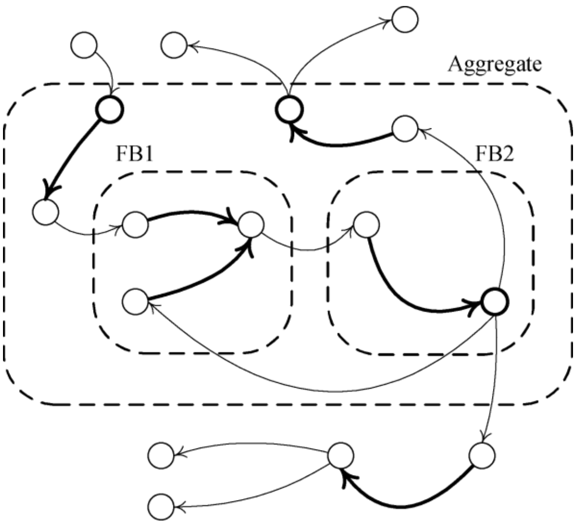


Fig. 1.2 – An example for a data point graph using different functional blocks and aggregation [51]

This concept is illustrated in Fig. 1.2. In the graph, data points (vertices) are grouped into functional blocks FB1 and FB2. Network connections are represented by the thin lines, while processing dataflow is represented by bold lines. As anticipated above, FB1 and FB2 may be implemented by single physical devices or may be spread over many devices. The indicated aggregation box is a further possible grouping of functional blocks at higher levels of abstractions, when convenient for the designer (for example grouping all HVAC-related functional blocks).

1.2.5. Home and Building Automation standard ISO/IEC14543-3

In this section, we will go through standardization aspects pertaining to one of the most representative HBAS protocols, the ISO/IEC 14543-3 [35], commercially known under the brand name KNX™. It belongs to a category of open standards, especially valued among practitioners in that they enable a wide range of building automation applications. Other significant examples of this category of standards are BACnet [81] and LonWorks [84], about which the interested reader might find introductory material in [51].

Beyond these examples, several other protocols are possible and important for HBAS, both proprietary and open. However, purpose of this paragraph is to introduce the reader to the common structure of one of the most general purpose technology, as details of specialized protocols are outside the scope of this work. Also, the technology here introduced is exploited for the subsequent original contributions in the following chapters, especially in Chapter 3, 5 and 6.

With the intention to give life to a Europe wide standard, in 2002 three then common technologies were merged into a new standard. European Installation Bus (EIB), Batibus and EHS (European Home System) were thus merged into the new technology, under the name of KNX, which was then subsequently recognized as ISO/IEC 14543-3 standard.

1.2.5.1. KNX network media

KNX support a variety of network media. Here we will introduce the most significant of them, namely twisted pair cabling and radio frequency.

Twisted pair cables carry both data and DC power to networked devices. Data is transmitted by means of a balanced base band signal, with CSMA/CA network access. Power is delivered by means of 29V DC running on the same physical cable. Collisions are handled through bit-wise arbitration and four priority levels. Twisted pair segments are single broadcast domains, connected into lines by bridges (line repeaters).

KNX RF allocates a band segment within the band reserved for Short Range Devices (SRD), that is the 868 MHz. Since many KNX RF devices typically operate on battery, specifications are defined to allow for simple mono-directional communication (devices only able to transmit commands, such as remote controllers with no feedback indication) along with bi-directional ones. Even with this distinction, KNX RF communication adheres to the general peer to peer approach of the technology.

1.2.5.2. KNX network topology

KNX networks are divided on three levels, namely areas, lines and single devices within one line. Each device then is identified by its unique 16-bit physical address, made up of three dotted figures (‘area.line.device’). Up to 254 devices are allocated on a single line, for a total of over 60 thousands devices on a single installation. Lines are connected to areas with line couplers, while areas are connected to a common backbone.

Communication within KNX networks can be unicast or multicast. The former are only used during commissioning or maintenance (for example for programming the devices) and make use of the device physical address. During runtime, instead, communications are multicast and based on a separate address space, within which nodes are assigned non-unique addresses, called *group addresses*. These are at the core of the KNX structure, in fact, each group address identifies a network variable (or data point, in the terminology used in previous paragraphs) and logical bindings within the distributed application are expressed by assigning several devices to the same group address. For example, a simple switching command is realized by binding the sensor button and the switch actuator to the same group address, for the specific data point. Since each device may contain various data points, a single device may be addressable through many group addresses. Group address routing is executed by the area and line couplers by means of suitable tables. Frames to group addresses are acknowledged in group simultaneously (negative acks override positive ones, therefore success is given by the absence of failing devices). It has to be noted that this choice, however, cannot detect lost communications directed to specific devices.

1.2.5.3. KNX application layer

KNX application model is data driven in that it is based on network shared variables representing a specific elementary unit of functionality. These shared variables are accessible by logically linked devices which can write to (producers) or read from (consumers) them, according to a publisher-subscriber model. Group addresses identify access to each shared variable as exemplified above. Each device holds an internal representation of the shared variable, in so-called group objects. Group objects are modified either from the network (received status update) or from within the device itself (status change to be propagated to the network). Assignment to a group address is defined at group object level. Nodes can contain many group objects, hence they can belong to several group addresses. Communication within members of a group is always peer-to-peer. More in detail, the single device doesn't have visibility over the group composition, and only knows about the related group address. This has implications on security, since there is no underlying authentication.

As anticipated, individual addressing through the physical address (unique for each device) is only used for commissioning. The device is manageable through so-called *system interface objects* and their *properties,* accessible through a client-server model. Properties may contain application parameters as well as other programming details, whereas low level configuration (such as assignment of the physical address) is provided by other specific device services.

As to the hardware model, each KNX device is comprised of a network interface, called Bus Coupling Unit (BCU), responsible for extraction of DC supply from the bus as well as transmission and reception of frames and subsequent handling. In the most common hardware profile, BCUs host the complete network stack and user application (i.e. the logic to handle local group objects) and the configuration tables to hold the configured bindings between group objects and group addresses. In this simple model, an additional module may be attached to the BCU, called the Application Module, communicating with the BCU through a 10-pin external interface (PEI) and providing basic I/O capabilities. In more complex devices, these application modules may contain significant parts of the user application and be equipped with an additional microprocessor, where the computational power offered by the BCU is not sufficient. For such complex devices, the application module's microprocessor can be provided with access to the network stack via the PEI, using serial communication locally with the BCU.

1.2.5.4. KNX interworking

The KNX interworking model is defined to ensure that devices from distinct manufacturers can be coherently commissioned with transparency about their specific hardware implementation, and only taking into account standard data types and functional blocks. Several semantic data types and functional block definitions have been added to the KNX specification over time.

All of this structure can be managed by a design tool called ETS (Engineering Tool Software). Every KNX device must be manageable by this tool, through certified and device specific firmware, that can be uploaded and parameterized onto the device by the PC based commissioning location. ETS is the tool where logical bindings between data points are defined and programmed into end nodes.

1.3. Green networking

Dissemination efforts in the ICT area have enabled, in recent years, an increasing awareness in end users about equipment's energy efficiency both for the immediate economic benefits that green technologies can offer and for the indirect environmental impact.

In this scenario, even small negative contributions receive close attention. EU Directive 1275/2008, published 17 December 2008, deals directly with "ecodesign requirements for standby and off mode electric power consumption of electrical and electronic household and office equipment" and fixes upper boundaries for power drawn by EuP (Electricity using Products) and ErP (Electricity related Products) during inactivity periods. The rationale of this regulation is that energy unconscious design can create huge global impact when very common devices are involved (TV sets and consumer electronics in general, but also typical appliances, battery chargers and other common categories).

Recent studies [12] have investigated the issue of energy efficiency with particular regard to ICT networks, proving that a substantial percentage of energy is wasted and that more careful approaches are available and feasible to reduce such waste. Reasons have been individuated mainly on two levels.

- Electronic design of devices is generally over-provisioned and targeted to the worst case: while this is a solid approach for reliability, unfortunately its side-effect is that efficiency drops to unacceptable values for low or very low workload conditions (this concept is generally referred to as energy proportional computing and will be better examined later and referred to the KNX case).
- Communication protocols are generally designed without any energy awareness. Nodes are expected to be always fully functional to maintain network presence, even when no task is being performed. As a consequence, network devices work in the low efficiency region for most of the time, and even worse, idle periods (0% workload) account for percentages around 75% of time or even more.

This is true for most ICT systems, especially when nodes are power consuming elements, such as desktop PCs or servers, connected to the internet. However, similar inefficiencies have been reported in the literature with regard to HBASs as well. B. Nordman [19] envisions a “Darwinian” future where automated buildings may end up consuming more energy than they used to do until today, with little or no automation in place. Energy unaware design of products and networks will be one of the main factors for this potential unexpected result. As a matter of fact, since HBAS vendors market their systems by leveraging the energy saving potential they can offer, it is un-doubtfully advisable that a coherent approach is applied when designing their own products.

Traditionally, instead, energy conservation has been a major requirement only within wireless HBAS protocols, due to the need to promote battery duration, whereas in wire-line systems this issue has been greatly overlooked.

This work intends to investigate on the subject, focusing on the KNX system and on a real environment study case, providing a first contribution to be further discussed and extended, in the direction of a greener networking in KNX standard (see Chapter 3). Since KNX is widely known as a “green technology” in that it promotes energy savings in the controlled systems, it would not be coherent that possible internal inefficiencies are left in the controlling system.

Limits imposed by the above cited EU Directive are 0,5W in the medium term for the majority of devices and apparently less for specific categories of products and/or functional modes. Evaluation of applicability of EU regulation to HBAS is outside the scope of current work, and it is questionable whether limits should be applied to the single device or to the system as a whole, but the results of current work suggest that power consumption may pose EU compliance issues in the near future.

Apart from regulatory processes, also standardization bodies have been active in defining new protocol versions for popular technologies, in the perspective of reaching lower power demands both on a global and local scale. These efforts involve both wireless and wired technologies. Energy Efficient Ethernet (also known as “Green Ethernet”, IEEE 802.3az) introduces interesting modifications to the standard that would allow network nodes to engage in more energy aware communication procedures. These new features are being analyzed with regard to their impact on Industrial Ethernet automation protocols. One example is found in [8] where the impact of Green Ethernet is evaluated with regard to the Powerlink protocol. Since KNX as well is moving towards the introduction of “IP only” devices, it can be expected that the solutions being discussed in the 802.3az task force will involve possible improvements to be exploited in KNX IP devices.

Moreover, regarding IP, a huge drive towards IP for smart objects can be registered in the scientific community, where small footprint versions of the IP stack are successfully being tested on embedded platforms. Among these efforts, it is worth mentioning the 6LowPAN protocol (acronym for “IPv6 over Low Power wireless Area Networks”) developed within the IP for Smart Objects Alliance (IPSOA). This research area aims at building the basis for the “Internet of things” vision, where intelligent devices are spread ubiquitously in the indoor and outdoor environment. Energy efficiency has been recognized as a foundational requirement for such kind of devices [20]. The drive towards ubiquitous computing through IP enabled smart objects is a future scenario that should not be overlooked by more “traditional” automation networks such as KNX. It can be expected that future smart

homes would greatly benefit from a tight integration between HBAS and Smart Objects, and it is therefore necessary that the former do not interfere with the power efficiency of the latter.
Green approaches have also already entered the Home Automation area, where power-hungry protocols such as UPnP have been revised in the direction of reducing energy impact [21] and research findings have subsequently been recognized by the UPnP Forum and introduced in the standard [22].
Even for well-known power aware protocols, such as ZigBee, research [10] has proved that there is still room for improvement towards more energy efficiency, showing that also very small sources of power consumption should be avoided, if it's technically feasible and economically reasonable.
The experience of Bluetooth Low Energy [25] indicates how it is possible to introduce power-efficient mechanisms and at the same time ensuring backwards compatibility. In the BT Low Energy specification, this is tackled with by allowing manufacturers to produce devices able to operate in a so-called "dual mode" where classic BT circuitry can be maintained and integrated with the new low energy features (even higher energy efficiency can be reached in the "single mode" with completely new BT chips, though at the cost of incompatibility with previous versions).
In this evolving technological scenario, this work intends to raise awareness to the implication of green networking in HBAS (see Chapter 3). This is especially important if we consider that, even though it might be considered not cost-effective to introduce modifications to current standards, it is important, however that the terms of the problem are clearly stated and that future standard developments will be evaluated also with regard to the energy efficiency impact they might have.

1.3.1 Green Networking concepts and techniques

Below, a few classes of solutions found in literature [62] are presented, which map to research directions targeting applications in device, protocol and architecture design.

1.3.1.1. Resource consolidation

Resource consolidation is a first paradigm that stems from the fact that most network devices are underutilized for considerable percentages of time. This approach aims at adapting the level of active over-provisioning to actual network load. While still guaranteeing adequate performance, resource usage will be dimensioned for current network traffic demand rather than for the peak demand. This method may involve shutting down under-utilized routers and rerouting the traffic on a consolidated smaller number of active network equipment. This approach is also very common in related fields, such as data centers.

1.3.1.2. Selective connectedness

Selective connectedness is, among green networking paradigms, the closest to the approach on which this thesis work is based on. Selective connectedness promotes distributed mechanisms enabling single devices to enter idle or low-power states for as long as possible, without affecting QoS and transparently with regard to the rest of the network. This scenario can be actually implemented in several differing ways that will be detailed further in upcoming sections, usually involving the intervention of coordination mechanisms, as well as functional proxies.

1.3.1.3 Virtualization

Virtualization techniques are based on the assumption that a single machine under high workload consumes less energy and power than several underutilized machines operating simultaneously. If the above is true, it might prove convenient to consolidate more than one service on a single machine or device, exploiting virtualized low level resources, in order to masquerade applications from their actual running environment. Thus, resource virtualization (even though not exclusively thought for this purpose) typically results in a lowered overall energy consumption.

Virtualization is a relatively mature field, therefore the interested reader might find more in-depth analysis and survey in [63] from a computer architecture perspective, and in [64] for a networking perspective.

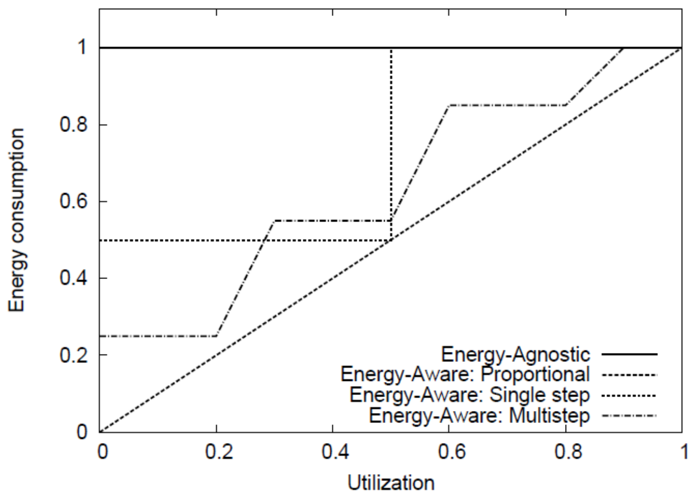


Fig. 1.3 – Examples of energy-workload relationship [62]

1.3.1.4 Proportional Computing

Energy-proportional computing [65] is a general concept dealing with the idea that energy consumption and workload should be tied by a proportional relation. This concept can be applied to entire systems, network protocols (which will be objective of original contributions of this work), as well as to individual devices and even components. Refer to Fig. 1.3 and Fig. 1.4 to better understand this concept.

Fig. 1.3 depicts different profiles of possible relationships between energy consumption and workload for a given entity. The two dimensions have been normalized and expressed as ranging from 0 to 1. Depending on the specific behavior, the following device classes can be identified on the graph:

- *Energy-agnostic devices* (worst case), where energy consumption is independent of the workload. These devices consume maximum power when in operation (single power state).
- *Energy-aware devices* (optimal case), where energy consumption and workload are tied by a proportional relation (continuity of power states).

- *Single step and multi-step devices* (intermediate cases), where the energy-load relationship is coarse grained. More in particular:
    - Single step devices have two operation modes (this means introducing an intermediate operation mode between fully on and fully off)
    - Multi-step devices have several power states.

Energy-proportional computing might be applied at device level, for example in hardware (Dynamic Voltage Scaling at CPU level to adapt energy state to system load), or at network level (Adaptive Link Rate reducing link capacity, to reduce consumption for low levels of network load).

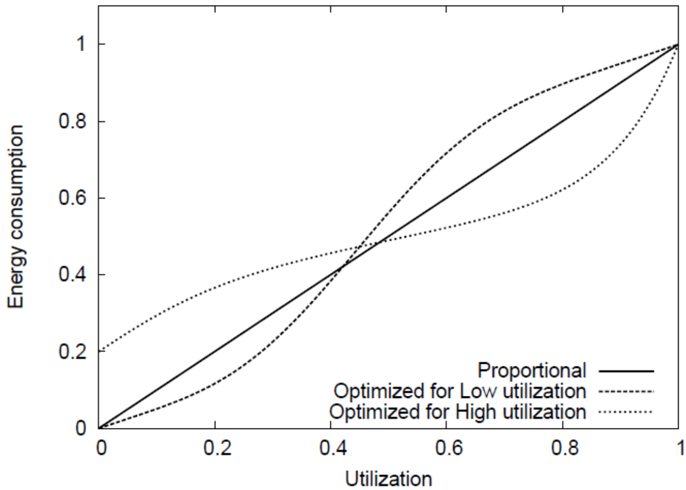


Fig. 1.4 – Energy footprint of different systems, optimized for distinct operational workloads [62]

Since optimal energy-proportional systems are an ideal, and typically unfeasible, case, real systems will mostly fall into the intermediate, multi-step, coarse-grained class. In these systems, optimized design requires accurate determination of the most typical target workload for a given system or device, and the related power state(s). This optimization may prove ineffective in case wrong estimates are taken into account. For instance, Fig. 1.4 depicts two design options: one targeting devices and protocols operating normally under higher workload, and the other one with an efficiency profile optimized for lower workloads. In the remainder of this work, it will be clear that HBAS control networks commonly fall under this second case, therefore, the optimization that the research described here is targeting, aims at introducing coarse grained intermediate power levels acting especially in the low workload region.

1.4. Smart Grid

Smart Grid efforts deal with increasing cost-effectiveness of the electric power grid by optimizing energy efficiency and reliability of the whole process, which involves four macro-phases, namely *generation, transmission, distribution* and *demand.*

While utilities have been enhancing their processes with regard to the first three items, the demand side still is an open technical and research challenge. Up to recent times, loads have been regarded mostly as passive elements of the grid, hard to be managed directly and to predict.
Demand-side has, nevertheless, an important influence both on the grid's energy efficiency and on its stability. Since line loss is proportional to the current squared, it is easily observed that a grid is more energy-efficient with a flatter demand curve, and of course with lower demand levels, when transmission issues are considered [105]. Much more importantly, flattening the demand curve is crucial in that it enables utilities to avoid over-provisioning their power supply, in the perspective of possible critical peak conditions. Hence, at demand-side, Smart Grid performance improvement involves activities such as load shaping, peak shifting and, more in general, reliable forecasting. All of these objectives are collectively known as Demand Side Management.

1.4.1. Demand-side management

Demand-side management (DSM) is the set of strategies and activities that utilities perform in order to reach the above mentioned objectives. A DSM definition can be found in [85], where it is stated that DSM means "*to plan, implement and monitor activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape*". DSM is traditionally associated with six load shape objectives, out of which two are most relevant for the above mentioned energy efficiency goals:

- peak clipping: reduction of peak load
- load shifting: shifting of load from peak to off-peak periods

These two techniques combined imply a general flattening of the energy demand curve and an increased grid stability. At local, user level, complying with these Grid's objectives would typically imply various methods of demand planning and load scheduling, which could definitely benefit by the existence of an HBAS.

1.4.2. Demand-Response

The enforcement of Grid policies is very hard to perform due to the low level of information and control capabilities (if any) the utilities have upon final users (Chapter 6 will present current efforts of this research toward the objective of increasing these Grid's capabilities upon end users). Therefore desired runtime behavior can currently almost only be indirectly influenced with particular programs usually called Demand Response (DR). A DR program is "*a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized*" [86]. In other terms, DR programs aim at the general Grid optimization objectives by making desired user behavior more economically convenient and discouraging undesired ones.

1.4.2.1 Demand-response programs

DR programs follow two possible models: price-based or incentive-based, that will be briefly described in the following paragraphs.

Price-based Demand-response

Price-based DR programs are based on variable tariffs, which change over time reflecting (more or less closely) the actual real-time energy cost. Two sub-categories are possible: *critical peak pricing* and *time-of-use pricing*. The latter implies distinct time intervals within the day, with different tariffs, whereas the latter (also referred to as *dynamic peak pricing*), involves more unpredictable changes in energy price, and customers are notified in advance of critical peak times during which the tariffs will increase.

In price-based DR, a typical undesired phenomenon may be experienced at the end of a high tariff time interval, when several appliances and loads are possibly reconnected simultaneously, with serious consequences on grid stability. This phenomenon is known as *rebound effect* [88]. See also Chapter 4 for a more practical demonstration of this problem on a real study case.

Incentive-based Demand-response

Incentive-based DR programs are based on reward mechanisms for users actively participating and complying with run-time requests from the Grid. Participation might be in the form of an overall energy demand reduction at the customer's premises during peak times, for which users receive a credit or a rebate (*peak-time rebate* programs [89]). Another kind of user participation might be in the form of accepting direct control by the utility over a certain appliance or set of appliances or building subsystem (*direct load control* programs [86]).

1.4.3. Automated Demand-response architectures

The original contributions in Chapter 6 aim at making it feasible for utilities and users to manage such kind of participating relationships with the highest degree of flexibility, thus increasing user acceptance.

The general concept of *Automated Demand Response (ADR)* is based on the idea that more efficient operation can be provided by the deployment of both grid-level and local (home or building) level automation, such that load management can be orchestrated without side effects, such as the rebound effect mentioned earlier and both the Smart Grid and the user can maximize their objectives relying on automatic enforcement of mutually agreed policies. At the core of any DR architecture is the Advanced Metering Infrastructure (AMI) which features automatic meter reading and updated tariff information.

Below, a brief overview of some existing ADR architectures, depicted in Fig. 1.5.

1.4.3.1. OpenADR

OpenADR (Open Automated DR) [90] is an open specification aiming at DR interoperability based on standard data models. DR signals induce automatic action through local building or industrial automation networks. The OpenADR architecture (see Fig. 1.5(a)) is based on the central *DR Automation Server* (DRAS) which is accessed by Utilities, on one side, to manage DR programs and participants, on the other, through a distinct interface to opt in and opt out of DR programs, provide feedback and perform biddings.

1.4.3.2. Whirlpool Smart Device Network

Whirlpool Smart Device Network [91] is an ADR architecture based on a collection of web services, aggregated by the *Whirlpool Integrated Service Environment* (see Fig. 1.5(b)) providing interfaces to both Utilities and DR participants (refer to the role of OpenADR DR Automation Server). The Integrated Service Environment also controls the load management algorithms hosted by the *Smart Device Controller* and providing energy management functionalities at HAN level.

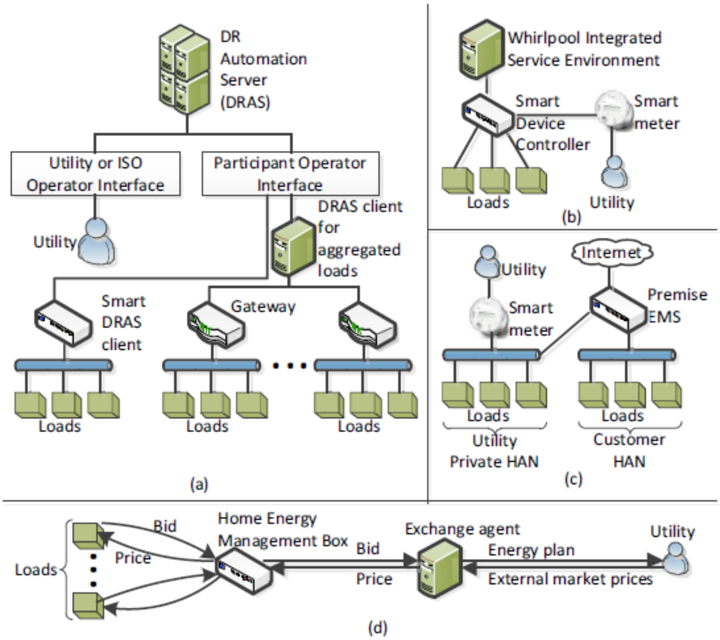


Fig. 1.5 – Demand response architectures [105]

1.4.3.3. Australian HAN guideline

The Australian HAN guideline [92] is a very interesting architecture, whose concepts will be also exploited in the DSM research contribution within this work (see the concept of virtual DSM circuit in Chapter 6). This architecture subdivides a general Home Automation Network into two logically separate portions: a *Utility Private HAN,* including the collection of HBAS/HAN devices directly manageable by the Utility, and a *Customer HAN*, bridged by a *Premise EMS* (Energy Management System) (see Fig. 1.5(c)), including the HBAS/HAN devices outside of the Utility's range of action.

1.4.3.4. PowerMatcher

PowerMatcher [93] (see Fig. 1.5(d)) is an agent based model aiming at dynamic matching of supply and demand. Every device hosts an *Exchange Agent* responsible for bidding and buying/selling from/to the electricity market. User's preferences are taken into account by the *Home Energy Management Box* in order to implements optimal local strategies.

2. SERVICE ORIENTED ARCHITECTURE FOR HBAS INTEROPERABILITY

The potential of current technologies in smart automation has been largely unexploited. Pervasive computing [58] vision is still far from being achieved, especially with regard to Domotics and home applications [55]. In fact, even though many implementations have started to appear in several contexts, few applications have been made available for the home environment and the general public. This is mainly due to the segmentation of standards and proprietary solutions, which are currently confusing the market with a sparse offer of un-interoperable devices and systems.

Although modern houses are equipped with smart technological appliances, still very few of these appliances can be seamlessly connected to each other.

Moreover, inter-working capabilities are required beyond house boundaries, towards external services and towards other houses as nodes of a global network.

Therefore, the main goal of this research is to find solutions to the problem of interoperability that will be in line with open and widely recognized standards.

The result is a computing framework based on open communication standards, capable of abstracting the peculiarities of underlying heterogeneous technologies, and letting them co-exist and interwork, without eliminating their differences. Interoperability can thus be made potentially feasible between any domotic technology, both currently existing, and still to be defined.

Currently, domotic technology vendors concentrate on building closed relationships with their customers, and leveraging their economic investments by establishing barriers against new manufacturers entering the market.

Examples of current domotic protocols are X10, KNX, LonWorks, UPnP, HAVi, and Jini supporting various communication standards (Ethernet, FireWire, Bluetooth, ZigBee, IrDA and proprietary buses). However, no domotic technology currently has the potential to actually play a leading role. Within this wide and heterogeneous framework, the market logic is to tie consumers to a particular domotic protocol, which then forces them to only purchase conforming devices in order to keep a consistent level of interoperability.

In recent years several interesting and innovative solutions have emerged, with a reasonable level of scalability and dependability, providing interoperability among heterogeneous home systems.

Twente University [61] has proposed a solution that aims at supporting heterogeneous technologies (including legacy ones) with a “cluster cultures” approach. The architecture outlines a “touch and play” system which, at device registration time, enables a zero-configuration environment for the exchange of credentials among its gateways and to register device services in a hierarchical structure. The architecture provides a high level of security by using cryptographic algorithms.

Waseda University [61] have proposed a framework designed to easily enable the integration of legacy middleware and legacy services and clients, with a predefined path for the inclusion of new, future, middleware. This is accomplished mainly through the use of a Virtual Service Gateway. This connects one piece of middleware to another by exploiting a Protocol Conversion Manager, whose task is to convert the different middleware protocols into the specific internal protocol used by the Virtual Service Gateway. Information about the location and functions of services is provided by a Virtual Service Repository.

Another interesting project is the “Domotic House Gateway.” [60] It implements an event-based mechanism which is used to exchange messages between the single device and the system. These events are internally converted into logical events so as to clearly separate the actual physical issues from the semantics that goes beyond the devices and their role within the house. One level of the architecture implements a rule-based core that can be dynamically adapted either by the system itself or manually through external interfaces. Each device needs a device driver, which is responsible for translating its low level or hardware states and activities into events that can be managed by the system.

Another promising approach, in line with this research, is proposed by the Open Building Information Exchange group [41] who are working to create standard XML and Web Services guidelines to facilitate information exchange among mechanical and electrical systems in building automation.

One such important European project in this context is Amigo [42]. This project was aimed at Ambient Intelligence features for the networked home environment and the usability of the system was among its main goals and included three major guidelines: user-friendly interfaces [57], interoperability, and automatic discovery of devices and services.

All these projects resolved the interoperability problem with several approaches, all of which are different from the one described here,

Lastly, it is worth mentioning a prototype [56] previously created by CNR research laboratory. This solution had the limitation of abstracting each device typology with a Web service implementing their specific functionalities. The implementation of a new ad hoc Web service was needed whenever a new category of device needed to be included in the network. In addition, this prototype solved the problem of cooperation by virtualizing devices belonging to each domotic system onto the others. This solution, however, had a drawback: the same device appeared virtually replicated on every single domotic system, thus creating data replications and possible consistency problems.

2.1. Domonet architecture and interaction model

In order to achieve significant results in the interoperability field, a comprehensive and abstract approach is required, rather than addressing the technology mismatch directly through the use of ad hoc mappings of different specific standards. By focusing on functionalities and semantics, we can first identify a suitable way to describe, and a coherent process to control the devices, using well-proven and standard technologies. The most suitable choice is XML for description, and Web Services for control. Both these technologies are emerging as Internet open standards for organizing and using distributed application capabilities, due to their inner cross-platform nature.

Identifying the functional elements of devices is the preliminary step towards formalizing a semantic structure, through a suitable XML language called domoML. A first abstraction level is thus reached, in which incompatible device capabilities are de-structured towards their most basic control semantics in the overall context of domotics.

Once we have gone through this process of defining and describing single functions (profile definition), the next step is to associate these control information units with corresponding active control elements, which can be identified as services. Since these services all map against the same domoML language, they can be considered as being equivalent as far as interoperability is concerned. They define and constitute a new control layer, which can be seen as a meta-infrastructure of high-level services. Within the scope of this work, this is a Service Oriented Architecture (SOA) [59] based on Web Services technology and is called domoNet [55]. This logical infrastructure binds several single domotic systems, providing them with common information and control exchange mechanisms.
Since the intention is to provide a universal approach rather than an ad hoc interoperability tool, domoNet was created with a modular structure to map the abstraction layer against the actual protocols and peculiarities. Therefore, domoNet has been equipped with appropriate internal plug-in modules called techManagers. This modular structure is there to ensure more protocols can be included in the future, within the interoperability framework. Fig. 2.1 shows that domoNet can be seen as a central network infrastructure and each domotic system represents a sub-network connected through a suitable techManager gateway.

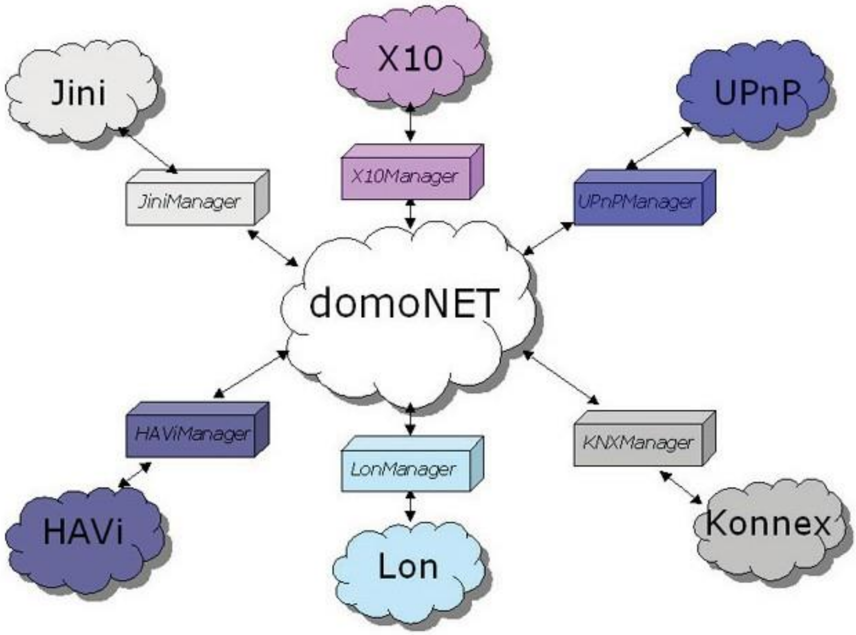


Fig. 2.1 – Domonet architecture

It should be noted that these technology choices are enabling factors for remote control, along with interoperability. The Web service at the core of the infrastructure, called domoNetWS, is, in fact, a real Internet node designed to share environments and services in a distributed fashion with any other domoNetWS regardless of its location.

The research objectives were:

- to create a modular engine capable of managing entire domotic systems without introducing specific drivers for specific device typologies,
- to automate the configuration process by providing an environment to refine it and set the behaviors of devices in the home environment; and
- to make the system scalable both by introducing different techManagers for each technology, and by allowing the distribution to remote locations of several domoNetWSs on the Internet.

2.2. The domotic Xml language

The domoML language is needed to provide a first semantic abstraction of heterogeneous systems. It has been structured as an XML dialect, through the use of XML schemas and plays the role of a common language for domotic interoperability. DomoML defines the specifications for future standardization processes regarding domotic devices, their communication models and their functionalities. Through domoML, data type models are also standardized, providing a suitable intermediate representation, from and to which to convert outbound and inbound values, in order to enable data marshaling among heterogeneous technologies. DomoML is also aimed at formalizing abstract communication messages expected within domoNet and between domoNet abstract devices.

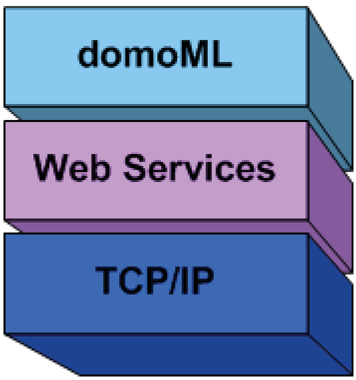


Fig. 2.2 – Domonet protocol stack

As Fig. 2.2 suggests, domoML is the top layer in the domoNet protocol stack and, as such, its role is to define standard communication procedures for high level applications.
In essence, domoML consists of two main elements: domoDevice and domoMessage, which will be detailed below.

2.2.1 domoDevice

domoDevice standardizes parameters in order to describe the characteristics of the devices, their position within the environment, available functions (services), the

process through which interactions with other domoDevices must take place, and supported data types. Each domoDevice contains all the possible services and functionality that are available in all the domotic technologies that are currently supported.
Table 1 shows the domoDevice structure of a bathroom light. In this example, switching the light on is linked to an UPnP multimedia service that plays music.

```
<device description="Bathroom light" id="7"
  url="http://myhost/axis/domoNetWS" manufacturer="Pholips"
  positionDescription="Bathroom" serialNumber="1.1.6"
  tech="KNX" type="light bulb" category="DomoLight"
  sub-category="DomoDimmer">
   <service description="Get state of the light"
     name="getPower"
     output="BOOLEAN" prettyName="Light status" />
   <service description="Set state of the light" name="setPower"
     prettyName="Set status">
      <input description="" name="value" type="BOOLEAN">
          <allowed value="0" />
          <allowed value="1"/>
      </input>
      <linkedService id="42" url="" service="Play"
        ifInput="value" hasValue="1">
          <linkedInput to="mediaRendererId" value="52" />
          <linkedInput to="mediaRendererURL" value="" />
          <linkedInput to="mediaContainerId" value="0/Music" />
          <linkedInput to="mediaContentId"
            value="Music/NESSUNDORMA.MP3" />
      </linkedService>
   </service>
   <service description="Set the intensity of the light"
     name="setIntensity" prettyName="Set the intensity">
      <input description="The intensity" name="value"
        type="INT" />
   </service>
   <service description="Get the intensity of the light"
     name="getIntensity" prettyName="Get the intensity"
     output="INT" />
   </service>
</device>
```

Table 2.1 – DomoML structure example of a domoDevice

At the moment available tags are:

- device (specifies general characteristics of the abstracted device)
- service (describes all the features that can be used by the system)
- input (describes how to interact with a service and the value range allowed)
- linkedService (creates a link between two domoDevices). In order to reference a domoDevice, id and url attributes are used inside the Domonet architecture.
- linkedInput (shares environments and values)

The main attributes of the device are:

- url and id needed to correctly route domoMessages to domoDevices and techManagers in a structured manner
- category and sub-category, the latter provides a more specific description of particular device services, still maintaining uniformity for base functionalities (belonging to category)

2.2.2 domoMessage

domoMessage describes an event, a command or a response. It standardizes the messages that will be exchanged among domoDevices and throughout the framework. A message can belong to different types: command when it requests execution of a service belonging to a domoDevice; success, when the service execution is successfully completed; failure, when the request for the service has not been correctly executed; event, when there is a domoDevice status change.
Table 2 shows an example of a domoMessage, where an event type domoMessage notifies a state change to 'active' with regard to the light service.

```
<message message="setPower"
  messageType="EVENT"
  receiverId="7"
  receiverURL="http://myhost/axis/domoNetWS"
  senderId="7"
  senderURL="http://myhost/axis/domoNetWS”>
   <input name="value" type="BOOLEAN"
    value="1" />
</message>
```

table 2.2 – Schema and tags used to describe a domoMessage

2.3. The domotic system Gateways (the techManager)

The techManager implementation is structured in two parts. One acts directly towards domoNet, implementing the Web Service client that interacts with the system (common for all technologies and therefore not requiring future re-implementation or specialization). The second physically interfaces specified domotic protocol devices. It does this by providing the physical and logical access methods required for correct interaction with physical devices (direct translation occurs at this level). Generally techManager tasks include:

- creating a list of domoDevices related to its sub-network, and submitting them to domoNetWS;
- ensuring correspondence between actual devices and domoDevices;
- translating domoMessages into actual domotic protocol messages (techMessage) expected in its managed subsystem; and
- notifying events that occur within its managed domotic subsystem by creating appropriate domoMessages.

During the framework start-up phase, each techManager connected to domoNet builds an abstraction for each domotic device belonging to its own sub-network. Thus details are provided about the control of features and services, omitting accessory and descriptive information where not considered mandatory to reach the framework's target interoperability level. Therefore, every single feature of each real device is made available and usable through the framework itself. The implementation of device and service discovery is different for each techManager since it is strictly dependent on the underlying technology. To each device detected by the techManagers, domoNet assigns a unique id and the pertaining Web service url, so that it can be addressed from inside and outside the framework. To keep coherence among distinct address spaces for distinct sub-networks, a global mapping table is maintained, which, for each unique domoNet identifier, associates the actual device address. This address is valid and unique within the specific sub-network involved.

2.4. The Domonet engine

At the core of the framework there is domoNetWS, a Web Services-based engine whose task is to create a real cooperation between nodes. It constructs a unique view of the system including all the devices belonging to all the different technologies available throughout the system.

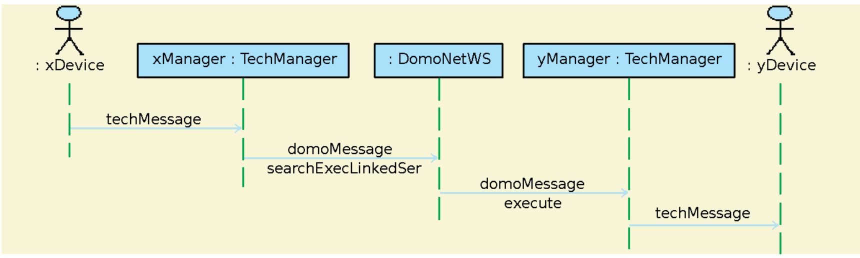


Fig. 2.3 – Use diagram for the interoperability

Fig. 2.3 shows a state modification for a generic device xDevice (where x represents a generic technology): an event is generated, and then subsequently captured, through a techMessage, by the xManager. The xManager translates the techMessage into a domoMessage, converting all possible data into the intermediate format supported by domoML. The xManager is now able to route all the information related to this event to the domoNetWS through the searchExecLinkedSer method.

By analyzing the xDevice description, domoNetWS can identify the service associated with the captured event, and all the information required in order to create the related domoMessage and route it to the right techManager. Its execution is then requested, and data is converted from the intermediate domoNet format into the target one, belonging to the underlying sub-network. The yManager then interacts with yDevice with the final techMessage.

2.5. The Prototype

A prototype has been developed and tested at ISTI-CNR (Italian National Research Council) Domotic Laboratory in Pisa, which conforms completely to the architecture described above.

It is open source software released under GPL license, and freely available [43]. It was developed using Java and only open source libraries and tools.

It was successfully deployed during an Ambient Assisted Living project, at a stable demo center, mounted on mobile panels. It has also been shown at important technology exhibitions. Some very important features have been introduced, which are usually not feasible, by exploiting the integration of domotic technologies.

The implementation features five techManagers related to five home domotic systems (UPnP, KNK, MyHome, X10 and BacNet). UPnP is used to control multimedia devices in order to manage audio and video content; KNX, MyHome, X10 and BacNet are used to manage home appliances and plants.

The prototype implements also an experimental user friendly interface to configure the interoperability relations among devices and an auto-learning system that tries to predict user actions analyzing user habits and creating domotic command rules.

2.6. Conclusion

This research work proves that this system has the potential to be used in cooperation with all existing domotic systems, and manage them without the use of specialized software for each type of device.

The next important step is to enhance the system's robustness, in fact the current system has not yet been tested with a large number of devices. A more solid approach regarding information storage (device descriptions, mapping tables, and so on), currently realized by means of simple file dumping, could make use of a relational db. After this crucial migration, it will be possible to focus on the security of the framework using two main techniques: classical authentication and access control to database records, and communication protection procedures such as message coding, especially between remote domoNet instances.

Another crucial enhancement will involve setting up a really user-friendly interface system, supporting dynamic interface adaptability and reconfiguration. This will be done through the development of a universal remote control, which can also be interacted with by elderly and disabled people. By interacting with domoNet, this remote control, will be able to operate all devices available in the home environment and belonging to any domotic protocol, and will be made so that it will automatically adapt to several different platforms.

Future framework versions will most likely move towards a more extensive semantic approach in the definition of devices and services, allowing for greater context awareness and user friendliness. These Ambient Intelligence features will be achieved by investigating the use of ontology, functional languages such as CAML, and Semantic Web. Research in this field is already being carried out within the NICHE project [52], which aims to define a Semantic Web model in order to increase the usability of the domoML abstraction layer.

Some improvements on the architecture will be performed in order to fully embrace the digital ecosystem philosophy [62] that is now included only in techManager modules. Each techManager is independent from the rest of the middleware and it

follows its “life-cycle” according to its own standard and characteristics, without being subordinate to any hierarchical order (P2P horizontal architecture).
Finally, an important work in its starting phase is to port the software to an embedded platform in order to evaluate performance and power consumption on a large scale. This then eliminates the need to be tied to a dedicated personal computer in order to have an interoperable, domotic house.

3. GREEN NETWORKING IN HOME AND BUILDING AUTOMATION THROUGH POWER STATE SWITCHING

Purpose of this chapter is to demonstrate how energy issues found in general ICT systems affect HBAS networks as well, and what relevant trade-off can be identified in this specific case. More in detail, this chapter will discuss, based on architectural analyses and experimental data, some foundational concepts for the subsequent efforts within this work.

First of all, main architectural and hardware design choices influencing energy demand in HBAS networks will be discussed, both at device and at system level, also providing arguments supporting the need for more sophisticated energy management approaches even in absence of severe constraints, such as battery-powered operation.

Evidence will then be provided regarding the fact that common, off-the-shelf HBAS networks and protocols, based on wired infrastructures, are affected by energy inefficiencies, despite the fact that they are commonly regarded as enabling technologies to introduce energy conservation and optimization into the environment they are supposed to control.

Finally, possible energy conservation techniques will be analyzed in the perspective of their applicability to the HBAS case, suggesting opportunities and limitations and establishing key concepts for the subsequent implementation and simulation.

3.1. Energy demand in HBAS devices and networks

A detailed power characterization of KNX devices proves to be quite difficult due to a general lack of specific usable technical information. The vast majority of product manufacturers do not disclose values regarding instantaneous power consumption and dynamic power behavior on public datasheets. What can be usually found is a single value, with little or no indication whether this should be considered as an average, peak or stand-by consumption, frequently without specifying accuracy or confidence bounds and relation to other relevant parameters, such as temperature, workload, etc.

With regard to load conditions, in particular, there’s typically no information about the influence of bus traffic levels and device configuration on power.

Bus load can be reasonably expected to represent a decisive factor for an increase in power consumption, when a higher number of frames reach BCUs and require corresponding treatment, involving access to memories, microcontroller cycles and transceiver activity.

The complexity of the procedures that have to be performed onto a frame entering the protocol stack is also related to current device configuration, so more crowded systems are likely to be prone to higher spikes during frame handling. In fact, power consumption may be subject to variations when the number of active group objects increases/decreases, or when the address tables grow in size, to allow for several multicast bindings, etc.

In other words, since KNX is characterized by a very solid scalability, making it an optimal solution for very large environments (even beyond commercial buildings, up to urban scenarios, such as the recent award-winning Salzburg public lighting system realized with KNX), efforts should be conducted in order to determine to

what extent bus power consumption is as scalable as other system parameters (e.g. reliability and latency).
Precise power measurements such the ones suggested above would require an extensive work that would necessarily have to include a wide range of products from different manufacturers, hardware models (BCU, TP-UART, etc.), complexity, destination of use and so on. Devices should undergo a benchmarking routine, with a similar approach to the EITT tests for interworking, with variable load conditions and device configurations. A similar power benchmarking test environment, dedicated to networking equipment, has been recently shown in literature [18].
Such an extensive benchmarking and classification activity is beyond the scope of current work, both for economic and conceptual reasons. As to the latter, in particular, this work stems from the preliminary choice to focus rather on investigating the average dynamical power behavior of KNX systems, than providing an exact characterization of specific KNX devices, even though this is expected to be the subject of future works.

3.2. Energy consumption due to HBAS networked devices

In order to obtain an overall characterization of KNX systems with regard to power consumption due to the sole KNX networking, the preferred methodology has been to perform analysis on a real environment, with the intention to extract general enough information. For simplicity, in this first step, a residential home environment has been taken into consideration (future steps may involve different scenarios, such as residential buildings or other intermediate or special application areas).
Therefore, a direct measurement system has been set up in a 140m^2 KNX house with two inhabitants. The KNX system includes 38 active devices attached on a single line, fed by a 640mA power supply unit. Basic lighting control automation and HVAC functions are deployed, making this house an optimal choice for the purpose of reaching general findings.

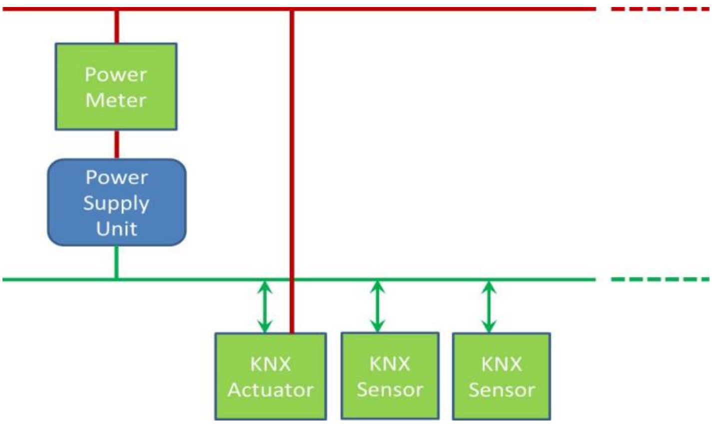


Fig. 3.1 – Measurement System

Measures have been executed be means of a class 1 energy meter with precision of 1/100 kWh, installed as to detect the energy drawn by the KNX bus power supply unit. Fig. 3.1 depicts a schematic of the system setup. With this kind of setup, the energy meter measures the only component due to KNX devices (controlling equipment), independently of the actual energy consumed by house appliances (controlled equipment).
Due to the meter precision, intervals between measures had to be in the range of hours to provide consistent data. Due to this equipment limitation, no information on instantaneous peak values could be extracted. However, coherently with the overall intention of the work, an indirect indication about power variations between high and low load conditions were obtained.
Energy consumption has been measured this way over a period of 68 days, and about 200 measures were recorded. Collected data is plotted in Fig. 3.2.

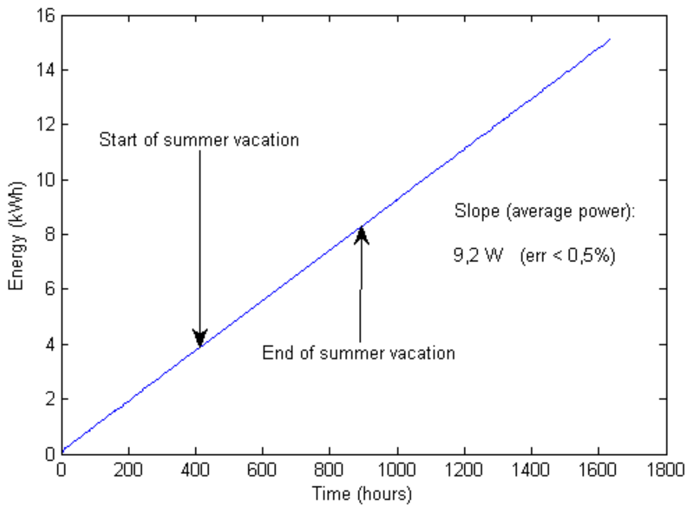


Fig. 3.2 – Energy consumption by KNX network

Measurement shows that, during the test period, an overall consumption of 15,1 kWh took place, due to the KNX system only. This accounts for a not negligible percentage, considering the fact that the average monthly consumption in the study case is around 150 kWh, which yields to a 5% due to supplying power to KNX devices. Discussion whether this may be an acceptable overhead or not is not in the objective of current work, which instead aims at analyzing how this behavior can be improved and with what trade-offs.
Apart from the overall consumption, in fact, the measurement activity aimed at analyzing the dynamical evolution of power consumption, stating whether the power average values measured over variable intervals (starting from a minimum of 1-2 hours due to the equipment limitations cited above) showed relevant variations related to functional conditions and workload. The analysis shows that the power demand (time derivative of energy, hence given by the slope of the

plotted curve) has been substantially constant during the whole test period. As the diagram clearly suggests, KNX bus power demand is independent of the functional conditions and remains fixed even during very low duty phases, such as night times and a 20 days' vacation within the measurement period during which the house was left empty (the formers cannot be easily appreciated in the above graph, while the latter is specifically indicated). In the case considered, the KNX bus consumes a nearly constant average of about 9,2W regardless of the actual occupancy and activity parameters. Dispersion of values around this average has been limited within a range between a minimum of 9,0W (correspondent to the summer vacation period) to a maximum of 10,8W (during a pre-scheduled fine-tuning and re-commissioning of the KNX system, that took place during the test).
This situation is described in the literature [11] as an example of sub-optimal power consumption. Since most computing systems work with a low workload for a high percentage of time, narrow dynamic power ranges always imply low energy efficiency. Design methodologies should be employed so to assure that a better proportionality between power and load is achieved. This kind of design approach is called *Energy Proportional Computing*. A benchmarking parameter has been proposed in [18], namely the Energy Proportionality Index (EPI). The higher EPI is for a given system, the more energy efficient it will be.

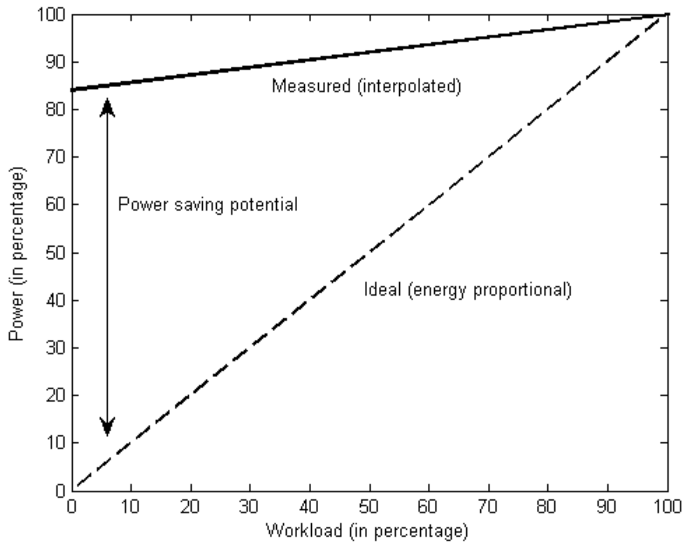


Fig. 3.3 – Power characteristics: ideal and measured case

The values indicated above may be reported on an energy-proportionality graph [11]. We assume that the vacation period corresponds to 0% workload, whereas the commissioning session represents 100% workload. Both these assumptions may be subject to further review, but are reasonable within the scope of current analysis . Fig. 3.3 compares the power characteristic of the measured system

against the ideal energy proportional case (EPI 100%), where power is perfectly proportional to the workload. Even though the ideal case may only be approximated by real systems, efforts have to be conducted in order to make KNX networks exhibit a power characteristic as close as possible to the energy proportional model. The distance between the ideal and real curve accounts for the total power overhead that is factor of inefficiency and that therefore should be subject to optimization.
In the diagram above, we can find a graphical representation of the preliminary observation regarding KNX devices being operated mostly in a full power working state. This is convenient with regard to the Quality of Service (QoS) related to automation (i.e. latency in command execution) but sub-optimal with regard to energy efficiency. The goal would have to be to deliver a comparable QoS with a more sustainable power requirement.

3.3. Assessing the introduction of Power Management techniques in HBAS hardware and protocols

3.3.1. Green Networking Approaches

Energy efficiency in networking devices and protocols requires basically the introduction of mechanisms to let devices switch into low-power working states, whenever workload conditions do not require full performance. This very simple concept hides the underlying complexity of the overall engineering problem behind the two ideas of *low-power working states* and of *low workload conditions*.
How can low-power profiles be introduced and orchestrated is the first step to analyze. Then a specification of when workload is to be considered low and whether it can be defined as such for all parts of the system is needed.
A third important concept is the *responsivity* of the system. In principle one would desire network nodes to go low-power as soon as workload decreases and to turn back to more active modes as soon as an increased load is present. Therefore, two independent processes, workload and device power profiles, have to be matched in the most effective way. Any mismatch in the evolution of these two processes results either in energy inefficiency (when devices respond too slowly to a load downslope) or in degradation of the automation system effectiveness (when devices respond too slowly to a load upslope).

3.3.2. Power – QoS Trade-off

This means there’s a tradeoff between energy efficiency and QoS. If we state that latency for example is a good parameter for evaluating QoS, we immediately verify that a strict energy conservation policy would end up increasing average latency, since more devices will be in low active states and unable to immediately respond to sudden increases in the bus data rate. In [1] this tradeoff between power and QoS has been given a specific acronym, “PoQoS”, highlighting that in order to introduce efficiency we first have to define boundaries in acceptable QoS degradation.
This “PoQoS” tradeoff cannot be statically defined but, actually, it is a run-time parameter related to the context. Depending on the automation system usage scenario in a given time interval, acceptable QoS degradation levels may very significantly [1]. Critical devices will have to be treated with little or no energy efficiency requirements, for example. The important concept to be followed in

system design is that not every node, nor every situation, is critical enough to justify 100% fully operational device uptime.
Moreover, in order to achieve a closer correspondence between load and power, introduction of more than one low-power profile should be considered. If many power levels are available, in fact, more fine-grained adaptation to the context is possible. Of course this has to be traded off, again, with other consideration such as cost [14]. Introducing power profiles has an impact both on hardware cost (for the additional logic) and on power itself (additional circuitry consumption and the overhead due to driving components through state transitions).
However, technological evidence [8] suggests that an effective PoQoS trade-off is possible even in real-time industrial automation protocols where energy savings can be introduced without affecting time-critical behavior of the system. In the Powerlink protocol, in particular, a centralized approach where the Managing Node (MN) determines energy profiles to be activated in Controlled Nodes (CN) proved as an optimal solution.

3.3.3. Policy distribution

The above cited Powerlink case is an example of a *coordinated* power management approach, i.e. where power policies are determined by one or more controller nodes and distributed to field devices for execution, or otherwise defined statically and executed through a time synchronization mechanism. As opposite to coordinated methods, several examples of *uncoordinated* techniques exist, where decision making takes place entirely within the single end device boundaries, with little or no coordination or shared knowledge with neighboring system parts.
Coordinated methods with controller nodes benefit from the fact that the power manager is able to collect a deeper knowledge of the whole system state, enabling more precise context awareness in the trade-off between power and QoS. The architecture of this kind of systems is given by the interaction between Power Managers (PMs) and Power Manageable Components (PMCs) [14]. These two elements do not necessarily have to reside on separated devices, neither does the PMC need to be unique and centralized, allowing for several possible distributed models.
The main objective of coordinated *Dynamic Power Management* (DPM) schemes is to enable the system to be reconfigured, enabling only the minimum set of resources to execute a specified task [14]. This concept shows great relevance with regard to KNX networks. Let's consider central functions, such as scenarios, for example. Most of them represent information on the (future) system state, which could be exploited to enable energy saving modes in all those devices that will be idle due to the specific context.
However, even though central coordinated analysis would surely provide great benefit to efficiency, it cannot be effectively implemented in distributed networks [14] such as KNX, both to avoid possible scalability issues and because data collecting cannot be optimized in terms of accuracy, speed and lightweight at the same time. The more reasonable approach in KNX, coherently with [14], is to rely on incomplete information on the global system and integrate it with autonomous, uncoordinated local decision making (hybrid approach).

3.3.4. Energy Budget

Whatever policy distribution model is chosen, it is critical to ensure that actual energy conservation is achieved. The overall objective is to let devices spend as much time as possible in low power, but a formal estimation method is required.
Therefore, since networking energy efficiency requires to introduce *power states* with differentiated consumption levels, a complete *Power State Machine* (PSM, [14]) has to be defined, reporting the different possible states and the allowed transitions among them. For each transition in the model it is then necessary to highlight the relevant energy costs and savings. Let's assume for example that we have a basic model with two states, HIGH and LOW, during which the device power requirements are, respectively, P_H and P_L. The transition between states implies a time T_{TR} and a power P_{TR}.
Starting from an initial condition in which the device is in its HIGH state, let's assume that the power management policy requires a transition to LOW and subsequently back to HIGH.
During this cycle, energy consumption is expressed as follows:

$$E_{CYCLE} = E_{TR(h-l)} + E_L + E_{TR(l-h)}$$

with

$$E_{TR(h-l)} = P_{TR(h-l)} \cdot T_{TR(h-l)}$$
$$E_{TR(l-h)} = P_{TR(l-h)} \cdot T_{TR(l-h)}$$
$$E_L = P_L \cdot \mathbf{T_{SLEEP}}^{*}$$ (* time spent in sleep mode)

while, without entering the cycle, the energy consumption would have been

$$E_{BASE} = P_H \cdot (T_{TR(h-l)} + T_{SLEEP} + T_{TR(l-h)})$$

The objective of the power management policy is to ensure that, in any given situation, $E_{CYCLE} < E_{BASE}$. Since in the previous expressions the only variable term is T_{SLEEP} (the others are fixed for a given technology or device) we have to impose that $T_{SLEEP} > T_{BE}$ where T_{BE} is defined as *break-even time*. In other terms, the device should be put in low power mode only if this can be expected to last for enough time to justify the additional transition costs. From the previous relations, T_{BE} can be directly expressed in terms of the other parameters, as in [14], therefore it is a fixed property of a 2-state PSM model (more complex models will have a number of similar break-even time parameters).

3.3.5. Policy implementation

The analysis proposed above provides a quantitative picture of the concept that main purpose of a DPM is to *maximize* T_{SLEEP}, i.e. the time spent in low power state(s). More in particular, an ideal power control would make it possible to achieve an accumulated sleep time exactly complementary to the activity time, so that no percentage of time is spent by devices in unproductive idle states. Real DPM systems are approximation of this ideal limit.
Maximization of T_{SLEEP} (or, equally, minimization of T_{IDLE}) can be accomplished through two alternative approaches: *predictive* schemes, which apply statistical

analysis in order to estimate probability of idleness in the upcoming time intervals, and *synchronized* architectures, that organize resources in appropriate pre-determined time schedules.
Approaches belonging to the latter category are more frequently found in wireless networks and in deterministic automation networks (e.g. industrial Powerlink). The underlying medium access is regulated mostly by Time Division Multiple Access (TDMA) and devices work with very low duty cycles, that is they spent most of the time in sleep state, wake up only during their reserved time slot, engage in communication procedures and then switch back to low power. In wireless protocols such as ZigBee, battery operated devices can work continuously without battery maintenance for years, by applying very low duty cycles.
This kind of technique cannot be easily deployed in non-deterministic or non-TDMA networks, and KNX, where Carrier Sense Multiple Access (CSMA) is used, is a relevant example. In these systems, predictive methods are the most feasible choice.
The base concept for predictive DPM is to exploit knowledge of the past system events to infer predictions regarding future idle periods [14]. In particular, for what stated above, DPM needs an estimation of the probability that the subsequent idle period will be longer than a given value (i.e. the break-even time, at least). These predictions are based on significant uncertainty and mainly rely on the self-correlation that the system behavior exhibits. The ideal predictor is not subject to wrong estimates, while real, good predictors can only aim at minimizing the rate of mispredictions. Predicted idle periods can be longer or shorter than the ones actually taking place: overprediction and underprediction are terms that can be used in these cases, respectively [14]. In the first case, we have an impact on QoS and performance, while in the second one, on energy efficiency. The trade-off between overpredictions and underpredictions is another way to examine the previously described trade-off between energy efficiency and QoS/performance: when the first parameter is more crucial than the second one, a predictive scheme that is less subject to underpredictions is necessary, and vice versa in the opposite case.
Depending on the nature of the underlying statistical analysis, predictive methods can be grouped into *static* and *adaptive* techniques.
Static prediction implies an offline analysis of the system behavior in order to highlight the most suitable regression model to correlate past and future events. Obviously, the underlying assumption is that the system has a stationary evolution, i.e. the offline collected knowledge can be considered a good representation of the system behavior in any given condition. Once the statistical parameters have been determined, the model can be exploited to estimate idle periods length, occurrence of active time intervals and so on.
The most simple example of static prediction is *fixed timeout*: when current idle time is longer than a given value, it is assumed that the device will remain idle for an additional time at least equal to the break-even (refer to ACPI policies in Desktop PCs for example). Choice of the timeout implies a statistical analysis in order to find the best fitting value. Short timeouts tend to overpredict (QoS degradation) while longer timeouts tend to underpredict (low efficiency).
Fixed timeout is a predictive approach that only examines a mono-dimensional history of the system (i.e. current idle time duration). More sophisticated methods

employ regression equations correlating *n* past events in order to reach better results (see [23] for an example).
Adaptive prediction methods are needed when no offline preliminary analysis is possible or when the system exhibits non-stationary evolution. In these methods, not only the prediction is based on the system history, but even the parameters used for the analysis are dynamically adjusted to the observed events. Adaptive timeout approaches, for example, may increase or decrease the timeout threshold in consequence of evolution of the system behavior, in order to avoid excessive impact on QoS (or enable higher efficiency, respectively). Other methods are based on a set of timeout values, each continuously weighed with regard to current observation and the best-fitting value is then dynamically picked and deployed [14].

3.4. Applying DPM to KNX

This section proposes a general discussion about the approaches described above, in the perspective of an introduction into the KNX standard. Feasibility and backwards compatibility are main factors in evaluating the various techniques.
It has already been observed that synchronized approaches are not feasible in KNX, given its asynchronous CSMA structure. Hence, predictive techniques are the most obvious option. The performance of these methods mainly depends on how predictable KNX networks are, and how strongly self-correlated events occur within it. Therefore a statistical characterization of KNX traffic is needed.

3.4.1. Statistical distribution of idle intervals

For the purpose of current analysis, results will be presented here from a network monitoring sessions executed in the previously described KNX environment. The traffic collecting was limited to a single day period and aimed at a preliminary assessment of the statistical distribution of idle periods in the given KNX network. This was done in the perspective of extending this analysis to other KNX systems also, in subsequent phases of the work.
The traffic monitoring shows that there actually is a great percentage of bus idle time. The following graph plots the cumulative distribution function of the idle time duration.
The indicated point shows that more than 70% of idle intervals were longer than 4 seconds (nearly 90% was above 1s). Whether this is a usable result or not depends on the break-even time for KNX devices, which has yet to be determined. As a term of comparison, we may consider that, in ZigBee networks, devices achieve very high energy efficiency by sleeping during beacon intervals, which can have comparable values (in some cases, beacon intervals can even be much shorter, down to tens of milliseconds). The actual break-even for KNX has to be specifically determined, especially once it is clearly estimated what components are most power-hungry in the hardware model; how many of them can be effectively put to sleep during low-power states; how fast a fully active state can be recovered and so on.
With this clarification in mind, we can anyway conclude that there actually is a sleeping potential in KNX networks, since a high percentage of time is spent by devices in idle mode and the previous graph suggests that this is true even for the whole system bus.

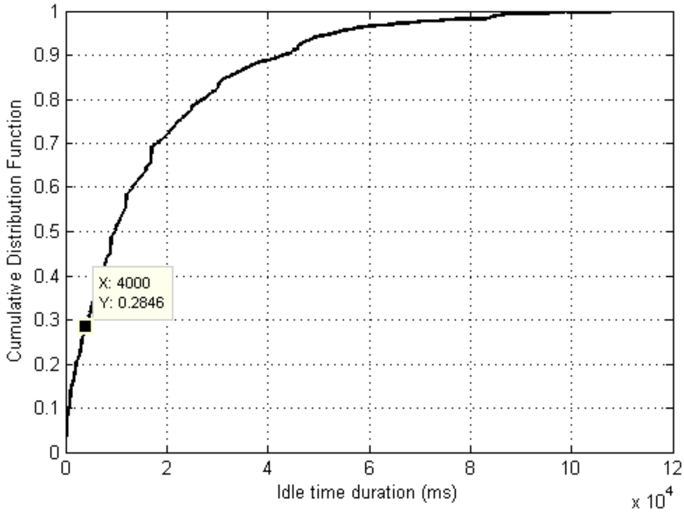


Fig. 3.4 – Idle time duration cumulative distribution

3.4.2. Uncoordinated DPM challenges

In order to exploit this finding for achieving energy efficiency, a predictive, uncoordinated DPM has to be introduced (refer to previous considerations). We may assume, for example to deploy a basic approach with a static predictive method (fixed timeout) and enable KNX devices to enter sleep mode after the given timeout has expired. The wake up event is the detection of a bus carrier (transceiver has to remain active during sleep mode) meaning there’s an incoming frame to be examined and eventually executed. In this case, as already observed, timeout length is critical for trade-off between power and QoS: short timeouts will provide more energy savings, at the cost of a QoS penalty since a higher percentage of packets will be targeted to a sleeping device, thus increasing the latency of the command execution. This basic approach has been simulated within Matlab in order to estimate the performance with a range of possible timeout values. Results are depicted in Fig. 3.5, which shows that this approach is not feasible, because there is no possible trade-off between power and QoS, with this method. Any increase in the energy efficiency is immediately paid back by QoS degradation. Even though it is necessary to estimate the actual increased latency due to a sleep to wake-up cycle in a KNX device, it can be stated that in the majority of cases, this method is not likely to be acceptable.

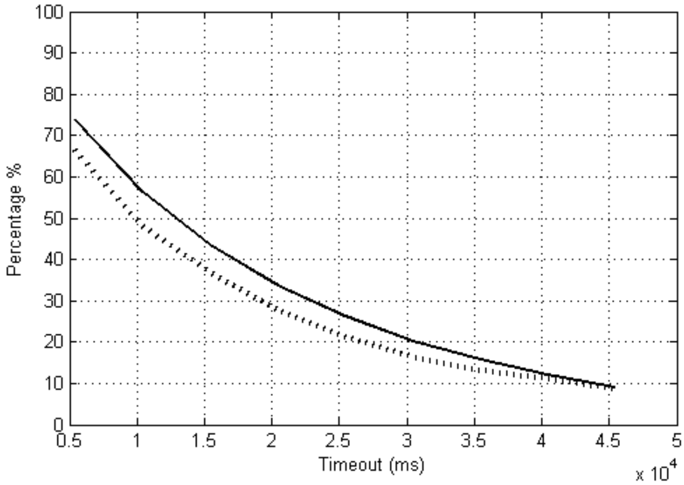


Fig. 3.5 – Fixed timeout DPM simulation results: accumulated sleep time (solid line) and total rate of wake-up events (dotted line) simulated with a range of timeout values

This finding is due to the statistical behavior of a KNX network. The following graph depicts the inter-packet times measured between bus frames for an excerpt of the traffic trace (for better readability).

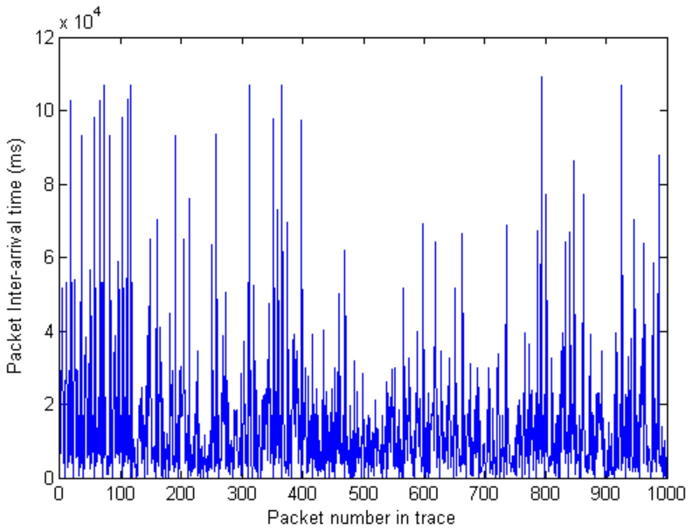


Fig. 3.6 – Packet inter-arrival times in KNX traffic

As the picture suggests, KNX traffic does not exhibit network flows (such as the ones found in TCP/IP data networks): a basically one-to-one relation exists between packets and automation requests. This is applicable to HBASs which are based on *network variables* and the concept of *process points*.
The consequence is that traffic predictability is very low. Packet occurrence represents an event-driven statistical process difficult to describe within a reliable model. Idle periods between packets, in the whole system, have a significant range, from milliseconds to minutes, on a busy day, which increases of 1-2 orders of magnitude during night or otherwise “off” periods. This fact, combined with a low predictability of packets, makes it hard to introduce an effective energy conservation mechanism to put devices to sleep during idle periods.
The following picture reports the results of the autocorrelation function applied to the whole trace with up to 1000 lags. With the sole exception of a few equally spaced peaks (due to periodic HVAC frames), the traffic self-correlation is fairly low, confirming the overall impression of low predictability.

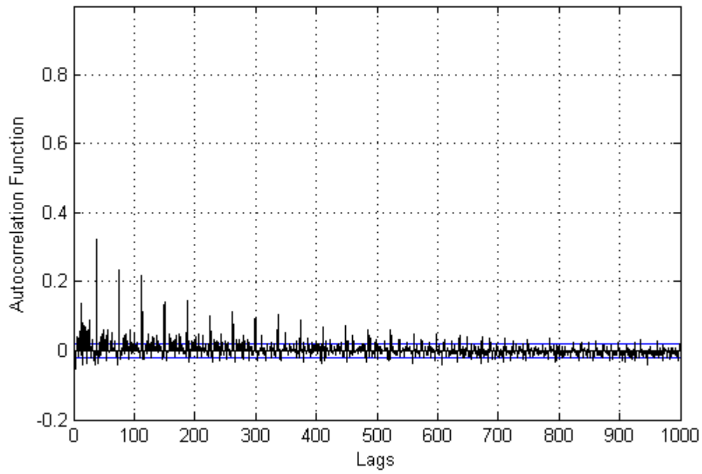


Fig. 3.7 – Autocorrelation of traffic trace

It is due to this very situation, that the approach described above proved to be ineffective. In order to be able to effectively exploit the amount of idle time that is indeed present in a KNX network, more sophisticated methods have to be considered. At this stage of research, only preliminary results are available, but it can be shown that better performances are achievable.
The limitation of the preceding technique was that devices had to wake up at every packet, even when the current frame was not targeted to them. This is of course necessary in order to avoid neglected packets in the system. However, only a small percentage of wake-ups were really necessary, since only few incoming frames had to be executed by a given node. If we focus on a single device, in fact, the number of frames actually relevant for it can drop to very small values. As an example, a specific device was chosen within the system, namely a room controller located in a central position in the house, and bound to several group addresses in

the system. In order to provide a rough indication of the device activity, the monitoring phase has been split up into hours and for each hour the number of frames relevant for the specific device has been counted. The Fig. 3.8 provides a graphical representation of the device activity.

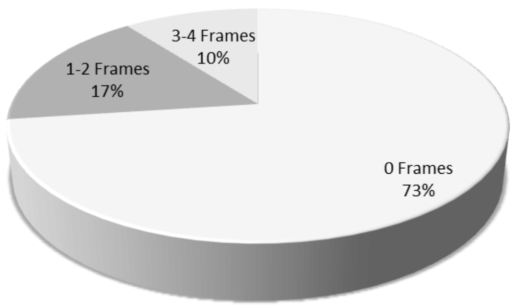


Fig. 3.8 – Device activity: percentage of hours with given number of sent/received frames

For nearly 75% of time the device was idle (not necessarily for consecutive hour intervals). During the remaining time portion the device was directly addressed by a maximum of 4 multicast frames per hour. This situation is similarly found in other devices within the system, with only some specific exception (e.g. cyclical messages).

3.4.3. Power proxying

This suggests that an alternative and more effective approach would be to introduce a mechanism, beyond simple carrier detection, to wake up the device only when a relevant packet is received. Unfortunately, current KNX hardware model would require the whole BCU to wake up to correctly classify incoming packets, thus effectively reducing the potential power saving. It is much likely, in fact, that the greatest percentage of device power consumption is due to the BCU itself, in the majority of cases (a deeper analysis on power distribution within KNX devices is a necessary step for further developments).

However, several approaches may be evaluated to modify the hardware model and introduce a small-footprint bus front-end module, inside BCUs, capable of executing a run-time filtering of packets (packet classifier). Architectures such as the one described in [4] succesfully deploy packet classification modules onboard the so called *Smart-NICs,* that is smart network interfaces for ethernet based devices and systems, for energy efficiency (wake up power-hungry devices only when it is strictly required). This approach is commonly called *Power Proxying* (see also [5]). Packet classifiers can be effectively realized with reasonable cost and power overhead [24] and therefore provide benefits for energy conservation.

Within current work, we are interested in simulating the potential energy saving achievable by introducing such power proxying feature in the predicitve DPM

already described, leaving impementation cost details to possible future research efforts or manufacturer analysis.
A second simulation routine has been executed on the collected traffic trace, modified so as to include the described packet filtering technique. Results are shown in the following picture.

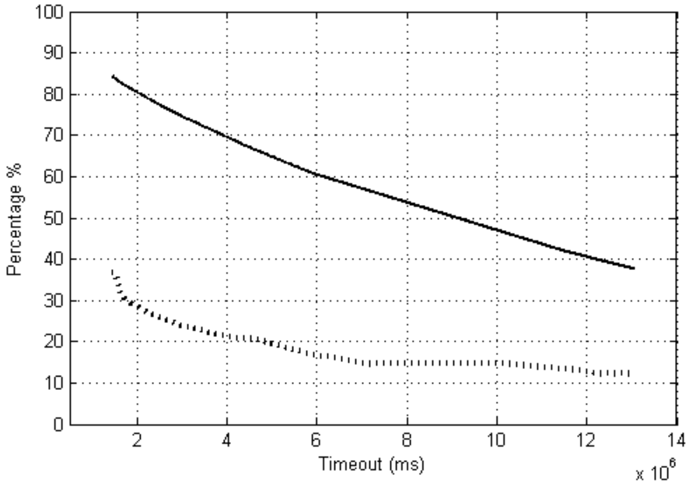


Fig. 3.9 – Results of fixed timeout DPM simulation with power proxying: accumulated sleep time (solid line) and total rate of wake-up events (dotted line) simulated with a range of timeout values

The simulation suggests that the introduction of packet filtering provides great benefit, if compared toprevious results. The two curves, sleeptime and wake-up rate (related respectively to energy efficiency and QoS degradation) are now allowing possible trade-off choices. The method described is capable of providing high percentages of sleeptime, with smaller impact on QoS than in the previous case. Even though it is apparently difficult to reach a 10% threshold for QoS degradation and achieve 40% energy saving at the same time, this result suggests that packet filtering techniques are effective in the KNX case.

3.5. Towards a power state switching hardware model in HBAS networks

In the second simulated case above, filtering was limited to identifying packets targeting the specific device. More sophisticated packet classification could instead take into account also other network events and infer a better knowledge of current context and therefore a more precise prediction of future activity. The research question that this work intends to address is to what extent network traffic in HBAS is a source of information about the environment and, more importantly, how manageable the complexity of such analysis is. Un-doubtfully, extensive data mining would prove beneficial to extract knowledge based on network traffic but the

challenge at stake here is whether this information can be extracted in real-time by the embedded devices themselves, and in this case, whether the degree of approximation is acceptable.
Towards this objective, the experimental setup described above was further specialized in order to gather network data along with network energy consumption. Collected data then fed a simulation environment where a few possible approaches were experimented.

3.5.1. Experimental setup

System setup for this second stage of the work is depicted in Fig. 3.10 which also proposes a visualization of the analysis workflow for the work described here.

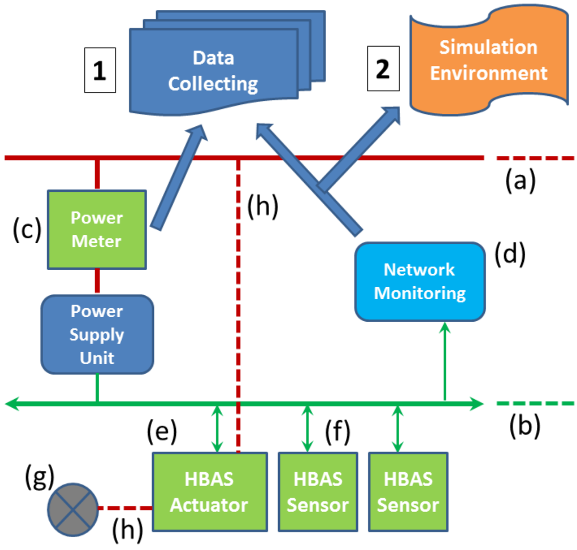


Fig. 3.10 – Schematic diagram of the experimental setup and workflow of analysis

The electric distribution line (a) and HBAS data line (b) are represented. Power is supplied to HBAS devices by the PSU, and the corresponding energy consumption is measured by the energy meter (c). HBAS nodes comprise actuators (e) and sensors (f): the formers control and deliver power to actual loads and appliances (g) in the house, the latter comprise wall switches, temperature sensors, etc. Energy consumption due to electric appliances (h – dotted line) is excluded by the data collecting represented here (1), and measured, instead, by the central energy meter installed by the service provider. A network monitoring device (d) feeds the simulation environment (2) with actual traffic trace collected from the HBAS bus, for subsequent analysis.
The network trace was collected in a completely transparent way, so as to actually manage the data flow taking place on the communication infrastructure. Below an excerpt of the collected raw trace, in Table 3.1.

14:49:58.046	2B 00 F9 EA BC 11 01 09 0C E3 00 80 00 83 B6
14:49:58.046	2B 01 00 00 CC
14:50:04.437	2B 02 B4 82 BC 11 12 03 00 E3 00 80 15 C3 F6
14:50:04.437	2B 03 00 00 CC
14:50:11.687	2B 04 11 7D BC 11 16 30 07 E1 00 80 12
14:50:11.687	2B 05 00 00 CC
14:51:03.343	2B 06 20 9A BC 11 0F 10 04 E3 00 80 0C C1 E7
14:51:03.343	2B 07 00 00 CC
14:51:47.062	2B 00 BC EB BC 11 01 09 07 E3 00 80 00 00 3E
14:51:47.062	2B 01 00 00 CC
14:51:51.062	2B 02 37 6A BC 11 01 09 0A E3 00 80 00 00 33
14:51:51.062	2B 03 00 00 CC
14:52:01.000	2B 04 19 58 BC 11 20 10 03 E2 00 80 00 03
14:52:01.000	2B 05 00 00 CC
14:52:08.078	2B 06 1E B5 BC 11 01 09 09 E3 00 80 00 00 30
14:52:08.078	2B 07 00 00 CC
14:52:25.046	2B 00 9E FF BC 11 01 11 05 E3 00 80 00 00 24
14:52:25.046	2B 01 00 00 CC
14:52:25.093	2B 02 F1 D1 BC 11 01 09 0F E3 00 80 00 00 36
14:52:25.093	2B 03 00 00 CC
14:53:18.046	2B 04 F5 F5 BC 11 01 09 08 E3 00 80 00 00 31
14:53:18.046	2B 05 00 00 CC

Table 3.1 – Raw HBAS traffic excerpt

The network monitor reported timestamps with millisecond granularity and network frames are recorded in hexadecimal format, including preamble bits and checksum. Frames come in pairs for the presence of confirmation mechanisms required by the standard. The shorter frames are relevant for reliability and congestion analysis, but are mostly irrelevant for the purpose of current work, hence they were used, within the scope of this work exclusively to sanitize the dataset prior to analysis (discarding possible anomalous network conditions that would have affected the validity of results).

Human readable network data (not usable fir the analysis conducted below) is nevertheless useful to understand the typical natures of HBAS based on network variables. In these systems, frames are not structured into network flows. Rather, each frame represents a mostly isolated piece of information. This implies, as already anticipated above, the observed unpredictability and low correlation between packets, taken exclusively as network events. The hypothesis here is that, since environment events are un-doubtfully correlated among them, it is reasonable to expect that this correlation can be detected also at network level by means of a meaningful restructuring of the raw traffic.

Table 4.2 reports a human-readable traffic excerpt. Note that, due to page space constraints, not all frame fields are present in the table (namely, routing priority, as well as checksum and other fields have been stripped out). The last column in the table is not a frame field. It represents the inter-arrival times exploited for the analysis above when depicting the statistical distribution of packets.

Time	Source	Dest.	Desc.	DPT	Type	Data	Interval
20:15:01.609	1.01.15	2/0/4	Area1 temp value	2 byte	Write	0C B0 | 24	
20:15:03.421	1.01.23	2/0/5	Room1 temp value	2 byte	Write	0C AE | 23,96	00:00:01.812
20:15:09.406	1.01.26	2/0/6	Room2 temp value	2 byte	Write	0C BD | 24,26	00:00:05.985
20:15:11.187	1.01.22	6/0/7	Presence sensor	1 bit	Write	$01	00:00:01.781
20:15:12.500	1.01.32	2/0/7	Room3 temp value	2 byte	Write	0C E9 | 25,14	00:00:01.313
20:15:24.109	1.01.20	6/0/1	"TV" scenario	1 byte	Write	$01 | 0 %	00:00:11.609
20:15:26.703	1.01.20	6/0/1	"TV" scenario	1 byte	Write	$01 | 0 %	00:00:02.594
20:15:43.781	1.01.22	6/0/8	Light dimmer	4 bit	Write	$00	00:00:17.078
20:16:22.656	1.01.23	2/0/8	-	1 byte	Write	$00 | 0 %	00:00:38.875
20:16:28.765	1.01.22	6/0/7	Presence sensor	1 bit	Write	$00	00:00:06.109

Table 3.2 – Human readable traffic excerpt from the experimental setup with the indication of inter-arrival times between packets

3.5.2. Requirements for the target green networking solution

Before going further with analyzing the collected data, it is worth mentioning here the underlying requirements that were taken into account during the effort of reaching an effective solution able to reduce energy consumption due to HBAS networking equipment. Below you find a brief explanation of each of the objectives.

3.5.2.1. Close-to-market/pre-market solution

Green functionalities should be designed so as to make it as easy as possible to integrate it into existing commercial devices, exploiting widely accepted concepts and components.

3.5.2.2. Backwards compatibility with current standard

Green functionalities should not interfere with standard functionalities provided by the device. More in particular, definition of frames should not be modified so as to accommodate the novel functionalities.

3.5.2.3. Co-existence of green and non-green devices

Awareness about the existence of green devices within the network must not be necessary by any of the network elements. Network stability and coherence have to be regarded as priority compared to energy efficiency. This means, for example, that network presence should not be affected by devices in stand-by mode.

3.5.2.4. Absence of central elements

No introduction of central decision making nodes should be expected. These nodes may severely impact network stability in case of failure to execute timely green functionalities.

3.5.2.5. Zero impact on network load

Exchange of green-specific frames, repetitions or other types of network overhead should not be permitted. More in particular, it should be impossible, for a network monitoring element, to determine whether green devices are present or not.

3.5.2.6. Low impact on QoS

Reasonable levels of QoS should be preserved for end users. Since this is a primary element of trade-off, it will not be possible to avoid any impact completely. However, careful assessment has to be performed about user acceptance.

3.5.2.7. Transparency with regard to integration middleware

Integration middleware should not be affected by the presence of green devices within the network. Operation of supervisory systems, as well as other kind of central middleware, such as interoperability frameworks, should not be disrupted and should be considered as priority over energy efficiency, within the scope of this work.

3.5.2.8. Disabling command

In the perspective of a better user acceptance, and, especially, to introduce adequate support for network diagnostic and maintenance procedures, green features must be designed so as to provide the capability to disable them completely through central or specific commands.

Other objectives that will be considered in perspective of future works, but will not be strictly addressed during current effort, are the following.

3.5.2.9. Robustness against external middleware

External systems cannot be affected by the presence of green devices (see above). Nevertheless, the inverse should also be guaranteed. In fact, energy-unaware design of supervisory, integration or interoperability systems, might force green devices into activity levels (for example through polling) inducing unwanted power switching from low power modes.

3.5.2.10. Auto-configuration

Green functionalities should be designed so as to enable straightforward system commissioning by personnel with reasonable expertise. More in particular, deploying green devices should not disrupt common technical practices and design guidelines.

3.5.3. Experimental approach

Towards multiple power state switching and Dynamic Power Management (DPM), possible approaches may be grouped into *coordinated* and *uncoordinated* ones [9]. This work focuses on the second case and intends to validate the feasibility of an *uncoordinated sleeping* approach, which basically consists in making devices autonomously enter low-power sleep modes during idle periods. The effectiveness of such mechanism mainly depends on three elements: the *total amount of idle*

time available for any single device, the *fragmentation* and the *predictability of the idle intervals*.
In order to obtain an estimation of these three factors, the main parameter measured during the data collecting phase was the duration of intervals between subsequent packets (during which the HBAS bus is idle), i.e. the packet inter-arrival times.
With respect to the overall amount of idle time available, the collected packet inter-arrival times show that a great amount of time is spent by devices in idle states. This is both true at device level and system-wide: percentages roughly around 70-80% of the total test time are spent by single devices, and by the whole system, being idle [24].
Moreover, regarding the fragmentation of the idle time, it can be observed that most of the idle intervals are long enough to be actually exploited for an effective power switching. Short intervals, in fact, may prove useless if the additional power cost for state switching is not at least counter-balanced by a corresponding energy saving during the achieved sleep time. Fig. 4 in the previous chapter depicts the cumulative distribution function for the inter-arrival times, showing that more than 70% of them are longer than 4s, and nearly 90% above 1s).
ZigBee networks deploy an energy efficiency power state switching by sleeping during beacon intervals, that have values comparable to, and often much shorter than the ones measured in this case. However, actual break-even time [24] for HBAS devices has to be estimated in order to clearly validate the usability of the previous results.
As to the third parameter, the *predictability* of idle intervals, it has to be noticed that, even though the traffic monitoring shows that we have a great amount of idle time available to switch devices into sleep mode, it also demonstrates that the predictability of these idle intervals is fairly low. This is mainly due to the fact that HBAS traffic does not exhibit network flows or other typical patterns (unlike TCP/IP data networks): a 1:1 relation exists between packets and request sessions (especially true for HBASs based on *network variables*, such as KNX). Fig. 7 in the previous chapter depicts the autocorrelation function, plotted with 1000 lags, for the inter-arrival times within the whole trace.
Except for a few values above zero (due to cyclical groups of frames belonging to heating control) the autocorrelation function shows that packet occurrences, and idle periods between them, represent environment-driven stochastic processes difficult to describe within a generally usable model. In order to deploy an effective Dynamic Power Management (DPM) scheme, instead, it is necessary to rely on a statistical model for idle periods and to develop a suitable prediction algorithm, according to that model.
Moreover, this prediction algorithm should be compact enough to be successfully and effectively executed by end nodes, within their constrained computing resources (and without negatively affecting energy consumption). Therefore it would not be reasonable to introduce complex statistical processing routines, that would surely be resource and power consuming for HBAS low foot-print devices (that could not handle historic data, neither effectively perform complex calculation without increasing latency). Hence, an offline analysis of the traffic trace is required, in order to highlight recurring patterns and eventually enable devices to detect them by means of fast, ad-hoc algorithms.

3.5.4. Patterns in HBAS network trace

An empirical approach to this kind of analysis would be to take into account the very nature of HBAS packets. Each one, in fact, is the consequence of an environment event, be it caused by humans or by other factors. The idea is that it could be possible to leverage any knowledge about these environment events in order to extract the corresponding patterns within the traffic trace. For instance, events due to humans (entering rooms, switching lights on, etc.) surely have properties that can be exploited. It is reasonable to expect, for example that human actions will exhibit a certain degree of *spatial correlation*, since users do not continuously move around the environment (especially true in a residential house). Moreover, human actions will certainly show several *logical correlations* between them: most of the commands will be grouped into functional groups within which self-correlation values may be much higher (consider, for instance, lighting control: commands belonging to this category will certainly happen within specific and repeatable sequences). These correlations are likely to introduce patterns within the HBAS trace, which could be exploited to perform traffic prediction and energy performance optimization [28].

In order to deploy the concept and validate this assumption, the collected traffic trace has been searched for possible patterns by isolating packets belonging to specific HBAS functions or applications (e.g. “heating” or “lighting”), on one hand, and those belonging to a specific spatial domain (e.g. “living room”) on the other.

What could be immediately verified is that the resulting specialized traces exhibit interesting propertied, depicted in Fig. 3.11, where packet inter-arrival times are plotted for a filtered trace obtained by isolating the subsystem devoted to lighting control (the X-axis reports the packet sequence numbers within the filtered trace). The graph shows a very clear pattern, with a few very long idle periods (order of hours in this case) interleaved by higher load periods (in the plotted graph, duration of idle periods is given by the peaks, while duration of busy periods is not represented directly in this kind of diagram).

This behavior is similarly found for other functions of the system (except for the automatic or periodic ones or, at the other end, for the emergency or safety devices) as well as for various spatial domains. Therefore, it is possible to conclude that, within one specialized subset, packets are organized in sessions, that is busy periods (with frequent transmissions of frames), separated by idle periods, whose length may vary depending on the nature of the subset itself.

3.5.5. Adjacency Sets

We may therefore introduce the concept of adjacency sets: we have an adjacency set when packets belonging to it are organized in subsequent sessions separated by neat discontinuities on the inter-arrival time diagram.

In this research work, two distinct categories of adjacency sets have been preliminarily investigated, according to the hypothesis introduced above: a functional and a spatial one. Other adjacency sets may be considered also, but were not addressed within the scope of current work.

The observed properties of adjacency sets could be exploited in several ways in order to enhance network energy efficiency through the introduction of DPM schemes. They, in fact, enable a more reliable predictability of packet occurrence and idle periods: occurrence of a packet within a certain adjacency set increases the likelihood of an upcoming transmission of another packet within the same set, until the point of discontinuity (idle interval) that can be detected, for example, by a basic timeout algorithm.

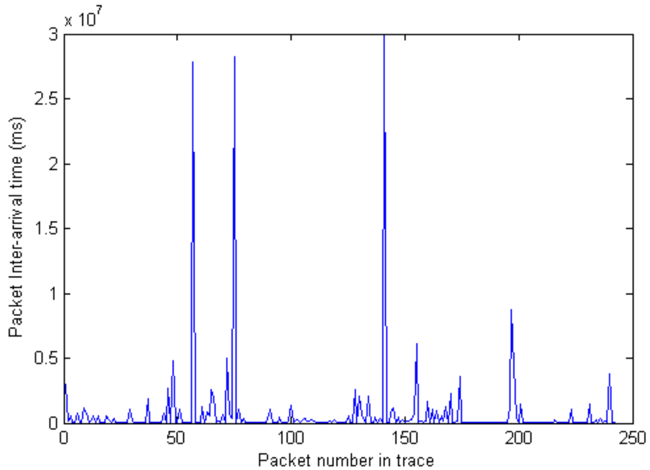


Fig. 3.11 – Packet inter-arrival times within the filtered trace

Since “adjacent” packets are all merged into the overall trace, a packet filtering feature has to be deployed on field devices, in order to detect relevant packets and engage in the proper decision making process regarding DPM accordingly. The packet classification could be executed in software (with performance issues) or in hardware (by introducing packet filtering modules, as in [24]). However, since implementation issues are likely to be mostly dependent on the specific technology and particular vendor, no further details on this subject have been explored within this work.

3.5.6. Leveraging identified patterns to maximize PoQoS trade-off

In order to introduce power state switching by exploiting the concept of adjacency sets, the key is to determine the correct sets and make end nodes perform packet classification algorithms correspondingly. Given a basic “sleep after timeout” mechanism, for example, a device should reset its timer after detection of a packet belonging to its own adjacency set (even though not directed to itself), because this event implies that we still are in the busy interval. When no packets have been detected for $T_{timeout}$, all adjacent devices can safely turn into sleeping mode. The first packet of the following session will wake up every adjacent device again. The very first command issued in the session will be subject to an increase in execution latency, due to the added waiting time for the device state switching sequence to complete.

Therefore, the trade-off is between two crucial (and conflicting) parameters that have to be both optimized: *total accumulated sleep time*, providing energy saving, and *rate of wake-up events*, negatively affecting latency and hence the Quality of Service (QoS) perceived by users of the system. The length of $T_{timeout}$ is the key for this optimization: short values of the threshold would result in higher amounts of sleep time (thus increasing energy savings) at the cost of a negative impact on QoS (since it is more likely that devices will enter sleep states too early, before adjacent packet sessions expire), while longer thresholds would help avoid the latter, at the cost of a reduced overall sleep time. The optimization and trade-off between energy savings and user experience is an important aspect of any contribution towards energy efficiency in wired or wireless automation protocol [27]. In order to perform an assessment of the best matching timeout value, and evaluate the effectiveness of the described approach, a Matlab™ simulation routine has been set up.

3.5.7. Simulation results

The simulation has been run using a wide range of values for the length of the timeout, and by feeding the system with the real traffic trace. Two adjacency sets have been chosen for the simulated packet filtering: the functional set (grouping devices devoted to lighting control) and the spatial one (grouping devices physically located in the living room).

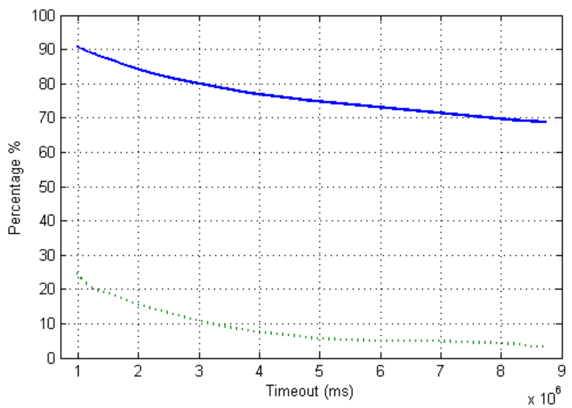


Fig. 3.12 – Simulation results obtained exploiting the spatial adjacency set: sleep time (blue, solid curve) and rate of wake-ups (green, dotted curve)

In both cases, results show that the approach based on adjacency sets introduces significant opportunity for higher energy efficiency and energy proportionality. Fig. 3.12 depicts the achieved performance for the spatial classification case, where an accumulated sleep time of 74,98% was reached with a fairly acceptable 4,9% of QoS degradation (due to latency). Fig. 3.13 reports the simulation results for the functional case, showing worse trade-off conditions.

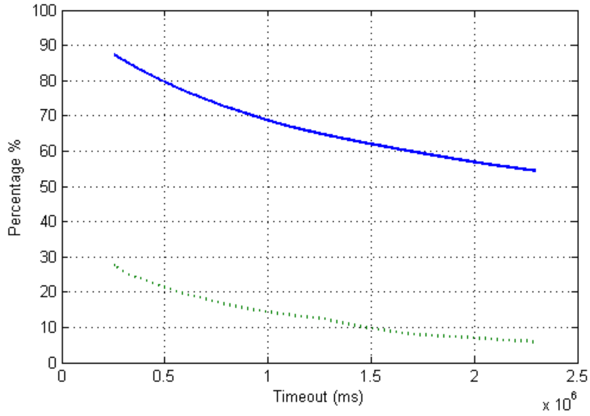


Fig. 3.13 - Simulation results obtained with the functional adjacency set: sleep time (blue, solid curve) and rate of wake-ups (green, dotted curve)

In this specific example, the weak performance of the functional packet filtering indicates that the chosen adjacency set does not effectively reflect a homogenous event pattern within the environment, and could, therefore be more carefully defined.
In order to estimate the actual benefit of the introduction of adjacency sets, a third simulation has been run, executing the same static timeout algorithm, but without the packet filtering. Fig. 3.14 shows the performance obtained in this case.

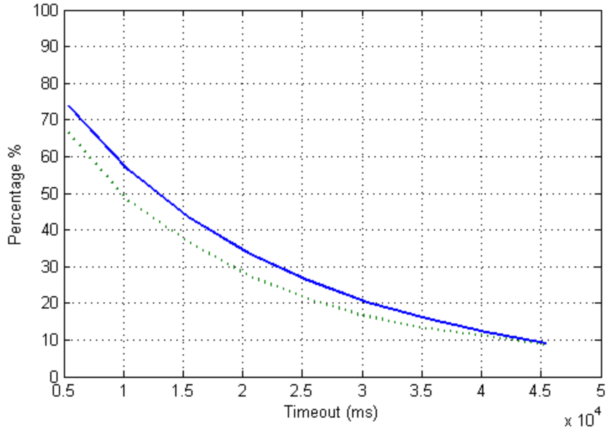


Fig. 3.14 – Simulation results without packet filtering: sleep time (blue, solid curve) and rate of wake-ups (green, dotted curve)

Results suggest that adjacency sets enable significant improvements. As the picture clearly indicates, without packet filtering, the two curves are very near to each other, meaning that in order to reach a suitable energy performance, an excessive degradation of service has to be accepted. This confirms that the adoption of the adjacency set concept dramatically increases the energy savings that can be achieved at any given QoS requirement.

4. N.A.S.A. SUSTAINABILITY BASE: DESIGN AND ASSESSMENT OF A PLUG LOAD MANAGEMENT SYSTEM

Green technologies and sustainable approaches in the building sector have been receiving increasing attention for several years up to present time. This growing interest is due to the major impact that buildings have on the economy, environment and human quality of life and, ultimately, health. Residential housing units were approximately 130 million in the United States of America in 2009 [44] and about 5 million commercial buildings as of 2003 [45]. In terms of economic impact, more than 8% of the U.S. gross domestic product was allocated, in 2007, to residential and commercial building construction and renovation (1.2 trillion dollars). In terms of environmental impact, residential and commercial buildings were responsible for 40% of total U.S. primary energy consumption and 72% of electricity consumption [46].

Fig. 4.1 – Rendering of Sustainability Base (photo courtesy of NASA)

Given this scenario, worldwide government efforts have been directed toward the objective of promoting beneficial effects on sustainability, energy efficiency, and the environment. In the U.S., NASA's Renovation by Replacement (RbR) is an example of such government initiatives. NASA's RbR aims at replacing outdated and inefficient buildings at NASA centers with renovated, energy-efficient, new concept buildings. "Sustainability Base" is the result of an RbR competition won by NASA Ames Research Center to design and build a 50,000 square foot high-performance office building, with the target to acquire a LEED Platinum rating. Commercially available technologies have been adopted in Sustainability Base, along with innovations and technologies originally developed for aerospace missions to monitor and control building systems and optimize energy and water consumption.

The overall objective of Sustainability Base is to represent a research test-bed in order to implement, test and demonstrate innovative sustainable technologies, approaches and concepts.

4.1. Motivation for a Plug Load Management system

Focus of the work presented in this chapter is to monitor, measure and control electrical plug loads. This definition includes every electrical appliance or device which does not belong to building plants (such as HVAC, lighting or others) and is therefore commonly found beyond the scope and action of the BAS. These devices, instead, are usually under direct control of building inhabitants. Thus they are subject to possible misuse, un-careful (if at all) planning, overlook of energy consumption and underestimation of anomalies. In traditional, inefficient, minimally code-compliant office buildings, plug loads may account for 25% or less of total energy usage, and that's why these loads have been mostly disregarded in various energy saving approaches found in literature. As technology enables high efficiency buildings to become widespread, it is estimated that plug loads may account for more than 50% of the total energy usage [48] and therefore need closer attention.

4.2. Pilot Study

In order to conduct a preliminary assessment in the perspective of deploying a plug load management system in Sustainability Base, a pilot study was set up at NASA Ames Research Center and conducted in a conventional building, available on campus, between February and August 2011. This pilot study went through three phases: first, data from a variety of plug loads was passively collected, then a preliminary assessment was made as to estimate the effectiveness of introducing a control mechanism for specific plug loads, finally, an evaluation was performed about the overall effectiveness and limitations of the plug load management system chosen for the study. The building that houses Intelligent Systems Division was selected for this experimental activity simply for reasons of convenience. The mentioned building hosts mixed office and laboratory spaces. Sustainability Base is planned as an office building with no laboratories, therefore the pilot study was restricted to office space.

4.2.1. Testing equipment

For this experimental study, both for the monitoring and for the controlling parts planned within the work, an infrastructure of smart power strips was deployed with the implicit requirement to minimize impact on the existing environment and working habits and reduce deployment costs. The mentioned infrastructure is developed by Enmetric Systems, Inc. and is designed to enable both metering and control of individual plug loads. The Enmetric system is conceived as infrastructure in that it includes *Power Ports* and *Bridges.* The former, reported in Fig. 4.2, is equipped with 4 channels (receptacles) each providing individual monitoring and control. The second infrastructure element is a wireless 802.15.4 bridge allowing communication with the Power Ports (sending and receiving monitoring data and commands, respectively, to and from the bridges). Networking capacity of the bridges allows up 50 Power Ports to be connected to a single bridge. Bridges communicate with the higher hierarchical level, represented by a Cloud based service, to which energy data is relayed, through connection to the Local Area Network (LAN).

Fig. 4.2 – Smart power strip deployed for the study (photo by Enmetric, Inc.)

The uplink from the Power Ports to the bridges allowed for transmission at one second intervals of energy data. The Power Ports deployed for the study were a pre-production version and only allowed transmitting power values, whereas current version also provides voltage, amperage, frequency and power factor).
The Cloud stores data at one minute intervals recording, for each minute, minimum, mean and maximum power values. This data is then retrieved either interactively through a web based Graphical User Interface (GUI) or through Application Programming Interfaces (APIs).

Fig. 4.3 – 802.15.4 Bridge interfacing with the Power Ports (photo by Enmetric, Inc.)

The deployed plug load metering infrastructure for this work comprised 15 Power Ports and 3 Bridges.

4.2.2. Physical locations for the test environment

The experimentation setting was spread over two floors with the following subdivision: 2 Bridges and 11 Power Ports for the second floor and 1 Bridge and 4 Power Ports for the first floor. Fig. 4.4 depicts the distribution of said devices.
In order to resemble the future Sustainability Base subdivision of spaces, the composition of locations for this experimental study was made as follows: 7 workstation locations, 1 break room and 1 copy room (with ratios roughly

corresponding to the expected 210 workstations, 4 copy rooms and 6 break rooms in the final Sustainability Base building).

4.2.3. Appliances population

Among the 60 available channels, only 50 were actually connected to appliances subject to monitoring, due to practical considerations (lack of devices at specific workstations and need to avoid overloads when connecting power consuming appliances to the same power strip).
In order to address a variety of devices within the study, as close as possible to the future Sustainability Base, workstations of administrative, financial, project management and technical divisions were included in the test. It should be noted, however, that statistical significance of the chosen sample was not a priority objective for this work. Sample composition is reported in Table 4.1 below.

Device	**Individual**	**Shared**		**Total**
		Break room	Copy room	
Desktop PC	6			6
Monitors	7			7
Laptops	3			3
Printers	5	2		7
Copiers		1		1
Phones	2			2
Shredders	2	1		3
Speakers	3			3
Scanners	3			3
Other workstation electronics (lamps, hubs, HDDs, chargers, etc.)	10			10
Refrigerator			1	1
Vending machines			2	2
Microwave			1	1
Coffee maker			1	1

Table 4.1 – Plug load device breakdown

4.2.4. Methodology

Work plan for the study included two phases: a first, passive, monitoring campaign, without any control in place, in order to establish a baseline of energy consumption to determine optimal policy definition and allow for subsequent comparative analyses (this phase spanned five weeks); during a second phase, schedule-based rules were employed through the PLMS infrastructure. Default schedule was set to turn devices off during non-business hours, enforcing a power down time between 10pm and 6am. Basically, the adopted policy was very conservative and aiming at a homogenous treatment of appliances, without further sophistication as to optimizing rules based on individual work schedules (except for a couple of cases, after consultation with the occupants) or load sensing or other similar techniques. Indicated timings were adopted for both week days and weekends. This second testing phase comprised both monitoring and controlling.

First floor

Second floor

Fig. 4.4 - Pilot Study Power Ports (green) and Bridge Locations (red)

4.3. Results

Before reporting about overall performance of the energy conservation policies under test, it is important to go through some important aspects of the analysis that constitute the main focus of the experimental study at Sustainability Base within the scope of current work. More in particular, the collected data was investigated so as to extract relevant consumption patterns of the various kind of appliances and whether these patterns were influenced by the adoption of the energy efficiency mechanisms (beyond the obvious overall reduction of power draw).
In the Green Networking section it was stressed that, given the narrow power range exhibited by the network globally, it was possible to conclude that the HBAS under test offered room for improvement in terms of energy conservation. Below we will identify this tendency within Sustainability Base appliances' energy curves.

Also, in anticipation to concepts pertaining to the final section on Smart Grid Demand Side Management strategies, it can be observed here that some specific appliance behavior, as induced by the PLMS policies performed in this study, may imply undesired side effects on the global infrastructure efficiency (which instead relies significantly on grid stability and demand predictability).
In the upcoming paragraphs, appliances and devices at Sustainability Base will be grouped based on their relevant traits (i.e. regarding their consumption profile) for the objectives of the analysis conducted throughout this document.
Other, more general considerations about the outcome of Sustainability Base PLMS experiment, will be also proposed further on within this chapter.

4.3.1. Workload dependent appliances

Some of the appliances within the study exhibited a typical behavior that, following the outcome of the Green Networking approach, it is to be recognized as efficient in terms of energy consumption. That is, they showed a close relationship between energy demand and current workload in most conditions. We have already observed that this is visually detectable on the energy curve where a high degree of variability is noticeable, characterized by: a wide range of power draw values (ideally from a zero power idle state, up to the working maximum, through the various intermediate states, either discrete or continuous, if any) and a quick shifting between power states, upwards, strictly as needed, and downwards, as soon as possible (ideal behavior).

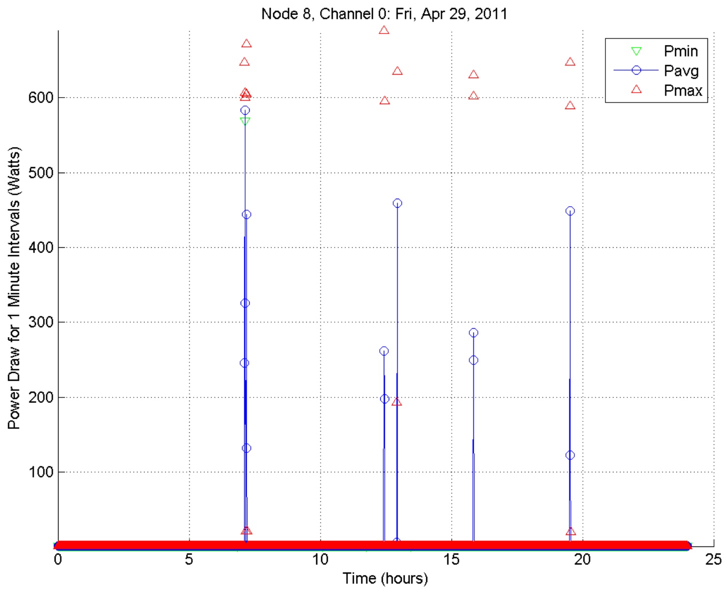


Fig. 4.5 – Use-dependent power draw pattern

Assessing adherence to this heuristic model requires a correspondent characterization of what has to be intended as “workload” in each specific case.

For the Green Networking prototype that was relatively straightforward (workload was made coincident with the network load targeting the single device and requiring its action or acknowledge). For other types of appliances, that might prove more difficult, especially for complex devices, such as computer systems (see below) where both energy consumption and workload may vary within a continuous range and the latter, in particular, requires extensive modeling pertaining to Computer Science research.
Workload modeling, however, was relatively easy for at least two types of appliances under test for the Sustainability Base PLMS, namely two appliances located in the break room: the microwave oven and the coffee maker. For these two, energy curves were found to be almost entirely use-dependent, with particular regard to the former (confirming intuitive anticipation).
Fig. 4.5 depicts the described circumstance: the power peaks are relatively narrow along the time axis and during idle periods energy consumption is consistently low and limited, in this case, to the range between 1.2W and 1.4W (Fig. 4.6 depicts the corresponding stand-by power draw curve). For this device, as expected, PLMS policies were practically ineffective. Enacting rules allowed to save 0.08kWh per week, which is a very low performance compared to that obtained for other devices and for the overall system (refer to subsequent paragraphs).

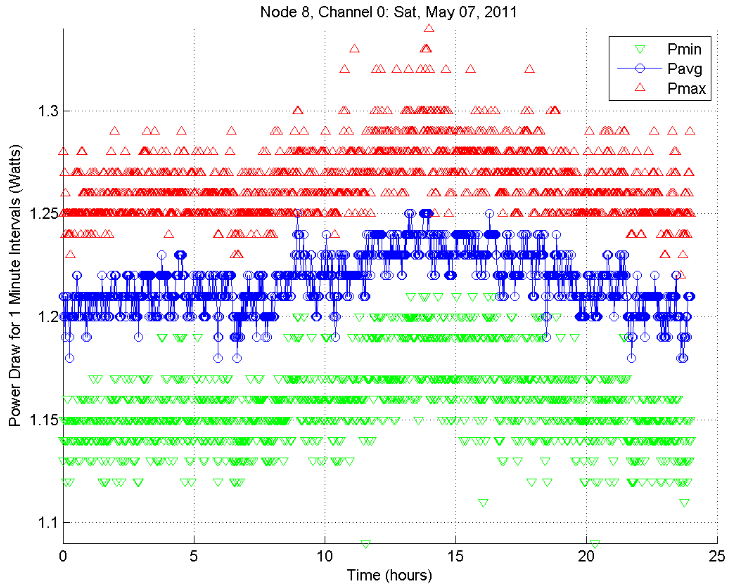


Fig. 4.6 – Stand-by power draw (microwave oven)

Similar conditions apply for the coffee maker, which, however, presents warm up cycles that account for longer active periods, and a baseline stand-by power of 5W. In this case, the energy saving potential through the deployed PLMS is 0.31kWh per week. Fig. 4.7 represents active power cycles for the coffee maker (stand-by power graphs are identical to the previous case and not reported here).

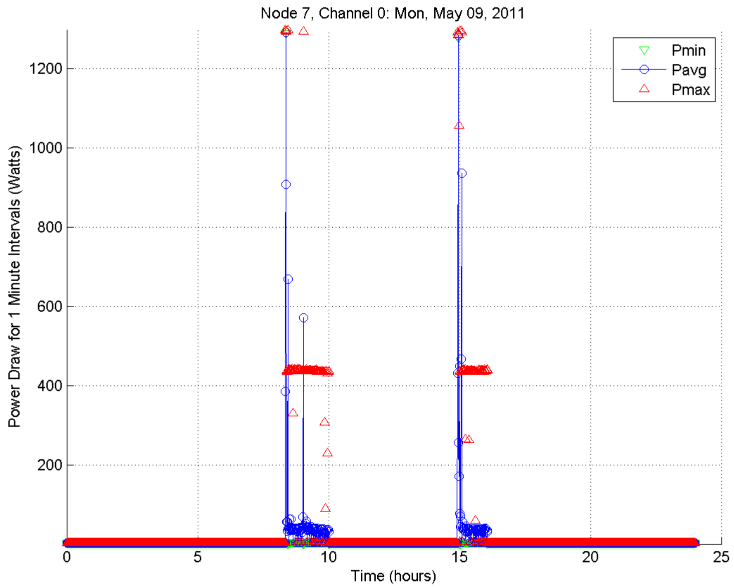


Fig. 4.7 – Use-dependent appliance with warm up cycles

4.3.2. Appliances affected by start-up issues

In some cases, monitored loads went through high energy demand phases when transitioning from off to active states compared to corresponding transitions starting from a stand-by base condition, instead. This implies negative effects when enacting PLMS rules that will be briefly examined here.

One of such appliances, namely a drink vending machine in the break room, normally performs refrigeration cycles as in the picture below. Overall energy consumption in this case was indeed reduced through the PLMS system (in particular, the usual 10pm-6am switch-off rule allowed to reach reductions up to 5.1kWh per week). However, the internal refrigerating system required a significant amount of energy to cool down to its operating temperature, when turned back on after policy enforcement. Fig. 4.9 reports one of the worst cases recorded during the test.

The graph shows that the internal refrigerator brings the power draw up to its maximum peak for long periods of time before entering usual cycling as soon as the regime thermal condition is reached again. This long peak would have been avoided without energy efficiency measures in place. As anticipated, despite this behavior, overall consumption is reduced, thus applying PLMS appears convenient.

However, in this case, local optimization potentially overlaps negatively with global (grid) optimization. We will discuss in further chapters within this document how a crucial requirement for the electrical grid is the overall stability, which, in turn, is negatively affected by demand peaks. The electrical grid is typically over-

provisioned, in terms of costly energy production facilities, in order to deal with peak conditions occurring for only very small percentages of time. Part of the Smart Grid vision revolves around the concept of shaping users' energy demand in order to avoid global peaks. Peak shifting, for example, is one of Smart Grid approaches, aiming at a more efficient energy delivery. It implies the deployment of various techniques, ranging from technical to economic measures (e.g. time-based tariffs), in order to foster a better distribution of loads, globally, over time, thus avoiding peaks, difficult and anyway costly for the grid to deal with.
Therefore, for cases such as the one represented by the appliance under consideration here, load scheduling practices should be discouraged, since local (building level) energy saving opportunities conflict with global (grid level) ones. Local scheduling in fact might easily turn into a synchronization effect globally, yielding to unsustainable conditions for energy productions, transmission and distribution. Not surprisingly, in fact, it can be observed that, with time-based tariffs, now common practice for an increasing number of utilities, the mentioned local energy conservation (occurring during low-tariffs portions of the day) would likely be counter-balanced in terms of final costs for the user.
This can be regarded as a general concept, involving appliances and systems where the relationship between energy use and expected functionality is affected by non-linear effects within the underlying physical process. For these systems, the correct strategy is to exploit, rather than ignore, the typical energy storage effects (see [101] for further insight).

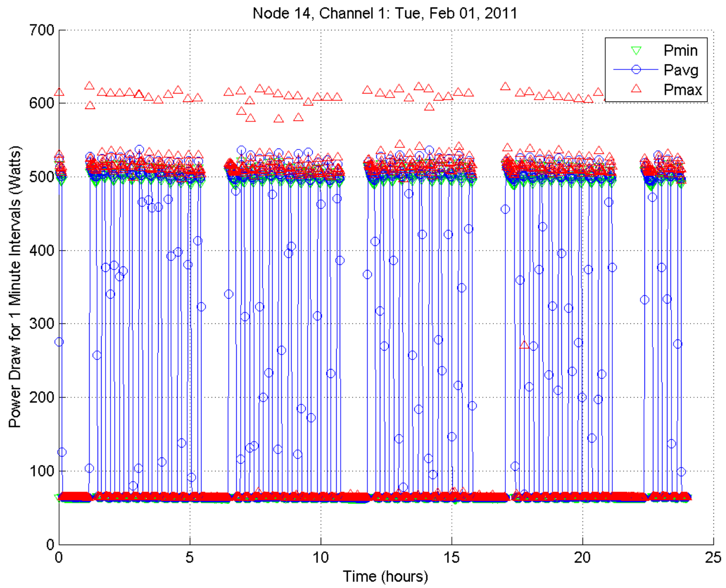


Fig. 4.8 – Refrigeration cycles for the drink vending machine

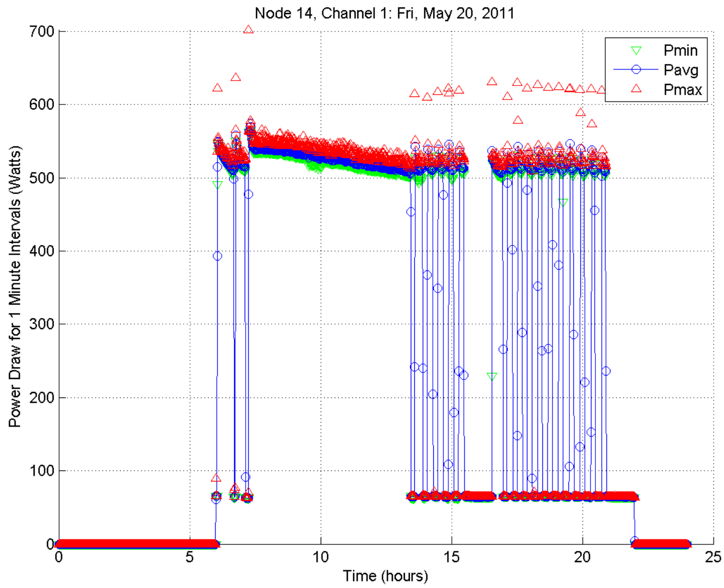


Fig. 4.9 – Start-up cycle for the refrigerator to reach operating temperature

4.3.3. Complex devices and built-in power management policies

Complex devices are those exhibiting a wide range of internal operating states, raging within a continuum that is difficult to model or assess from outside the device itself. Basic plug load control, as the one experimented in this work, is mostly unable to deal with the internal device complexity and therefore mostly ineffective if not dangerous. Computers are an example of this category. Due to their typical shut down requirements, enacting PLMS policies on these devices, might result in asset degradation or damage and possibly cause data loss or disruption of the workflow.

Moreover, performance of PLMS for complex devices is generally lower than the one achievable with built-in power management policies, when applied correctly and consistently. During the PLMS experimental study, power saving settings for workstations under test were modified to enable machines to enter low power state after 3 hours of inactivity. Occupancy sensors could be deployed also so as to force computers into sleep mode upon leaving the workstation area (however, occupancy sensors usually have parasitic power draw and require careful configuration to avoid false detections).

Fig. 4.10 exemplifies the higher effectiveness of internal energy management policies over external PLMS. It represents the energy consumption measured for a 30 inch monitor (separately from the connected computer). The graph is dived in 4 zones: during zone 1 (days 1 and 2) the monitor was not subject to either PLMS or internal energy saving mechanisms; during zone 2 (days 3 and 4) PLMS rules were enacted as for other examples; in zone 3 (days 5 to 18) PLMS policies were turned off and internal energy management was activated instead; zone 4 (days 19 to 33) saw both actions in place.

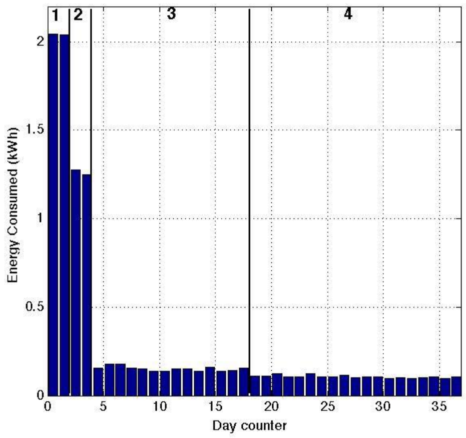


Fig. 4.10 – 30" monitor energy consumption (see also [95])

As it appears clear, internal energy management policies have twice as much effectiveness over external PLMS.

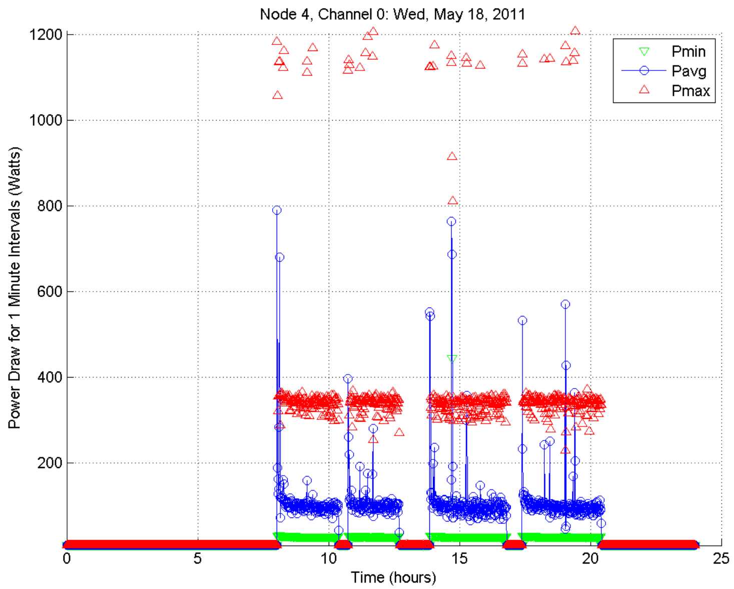


Fig. 4.11 – Black and white printer power draw

Similar behavior was reported for other appliances as well. Most notably, the black and white printer located in the copy room. For this device, the typical power draw is depicted in Fig. 4.11. This printer is equipped with energy management putting it to stand-by mode after an inactivity timeout (initially set to 4 hours and then decreased to 1) and is characterized by a relatively low stand-by power consumption (see Fig. 4.12) and a high start-up peak demand (reaching 1200W, see Fig. 4.11). For the combination of these factors, PLMS proved to be ineffective for this appliance, and even counter-productive: the printer energy consumption was higher while controlled by the PLMS and the internal stand-by mechanisms compared to being managed by the latter alone.

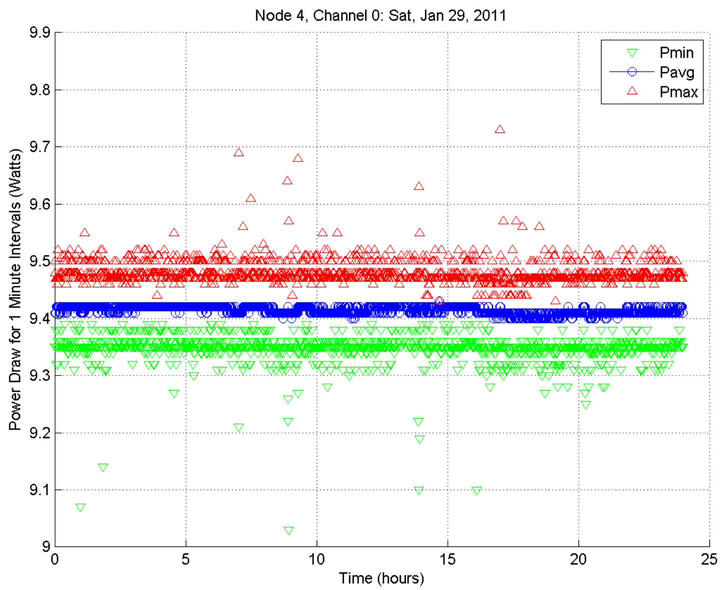
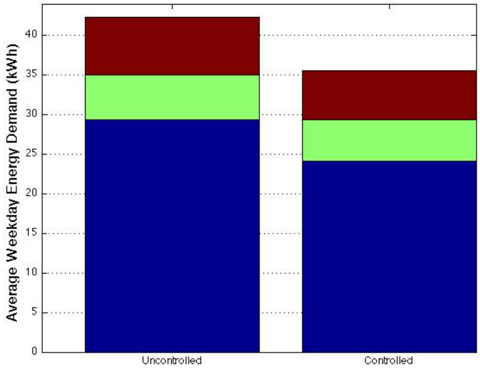


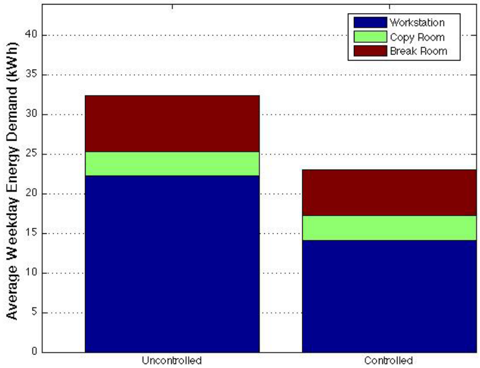
Fig. 4.12 – Black and white power draw in stand-by mode

4.4. Global outcome of the experimental PLMS

The overall performance of the PLMS under experimentation is depicted in Fig. 4.13 where the information is split between weekdays (Fig. 4.13a) and weekend days (Fig. 4.13b). In both graphs, uncontrolled (left bar) and controlled (right bar) average daily energy consumption are shown. Energy saving performance introduced by the PLMS policies reached 6,8kWh/day (16%) for weekdays and 9,6kWh/day (30%) on weekends. Due to some of the considerations reported above, only 39 of the 50 channels were subject to the PLMS rules. More in detail: 6 channels (workstation computers) were left out due to the need to avoid potential damage or data loss; 1 channel (refrigerator) was left out for food preservation reasons; 2 channels (see above) were found to consume more energy with rules in place; 1 channel supplied power to a PLMS bridge; 1 channel did not return to a ready-to-use state once reenergized. The bars in Fig. 4.13 also report values pertaining to workstations, break room and copy room portions in different colors. The different portions will be briefly described in more details below.



(a) weekdays



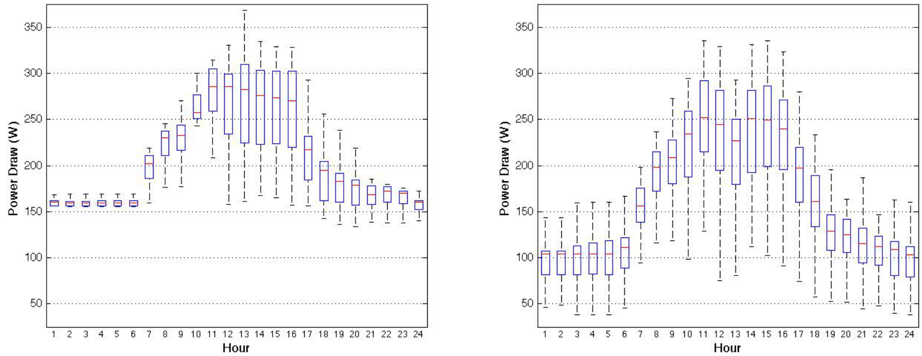
(b) weekends

Fig. 4.13 – Uncontrolled and controlled average daily energy usage [95]

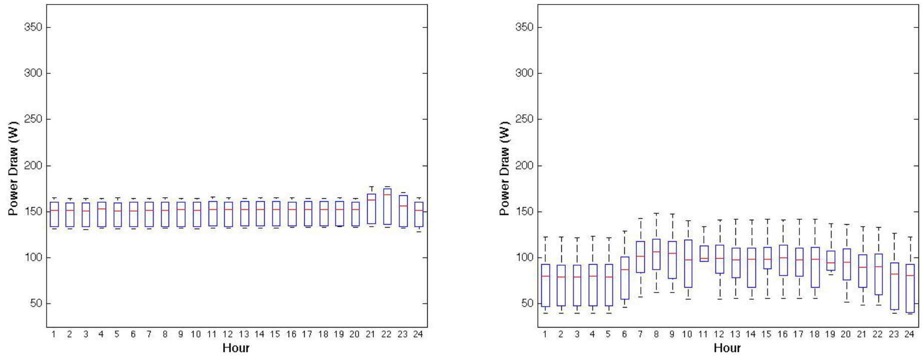
4.4.1 Workstations

A large portion (40 out of 50) of the monitored channels included workstation loads, hence the large portion of the corresponding energy usage. Each workstation is comprised of a computer machine (either desktop or laptop), a monitor and other electrical loads such as speakers, printers, external hard drives, electronic paper shredders, networking devices (such as hubs), USB hubs and additional monitors or computers.

Weekly baseline energy consumption for the average workstation was 27kWh. Adopting schedule based PLMS rules as described above, allowed for a weekly energy consumption of 21kWh. This reduction was both due to scheduled control and to optimization of internal energy saver settings. PLMS policies were deployed so as to adopt a conservative approach, avoiding negative impact on workers' habits and allowing occasional variations in work hours.



Weekdays: uncontrolled case (left) and controlled case (right)



Weekends: uncontrolled case (left) and controlled case (right)

Fig. 4.14 – Boxplots for average workstation power draw [95]

As we'll discuss later, granularity of schedule based PLMS was limited by the actual capabilities of the deployed PLMS infrastructure, therefore, the energy saving potential was not exploited to its full extent. Higher performances could be reached by adopting different policies defined at user level, for instance, or even better, dynamic sensing of environment conditions in order to allow for more timely action by the PLMS. Both these aspects depend on the underlying infrastructure on which the PLMS is based on: the first concept (policy definition ad user level) is

related to commands distribution and sophistication of the actual controllers (the Power Ports in this case), whereas the latter refers to the need of sensing equipment as well as an information-sharing and decision-making infrastructure.
Fig. 4.14 depicts energy usage by workstations over weekdays/weekends during both controlled and uncontrolled phases. The graphs were generated through clustering daily data on an hourly base and calculating average workstation power draw for each hour. This process was then iterated for each day within the set. Distribution of mean hourly power draw was then represented by means of a boxplot graph (red line is the median of the average workstation power draw, the box indicates 25th and 75th percentiles, the whiskers indicate minimum and maximum values).

4.4.2. Break Room

Break room loads included some of the appliances already discussed above for their significant energy behavior, such as the microwave, the coffee maker, the vending machines, as well as a refrigerator (excluded from the PLMS due to food conservation concerns). Vending machines accounted for 84% of the overall break room energy consumption. PLMS rules enacting within the break room allowed for a total of 9.0 kWh of energy saving every week.

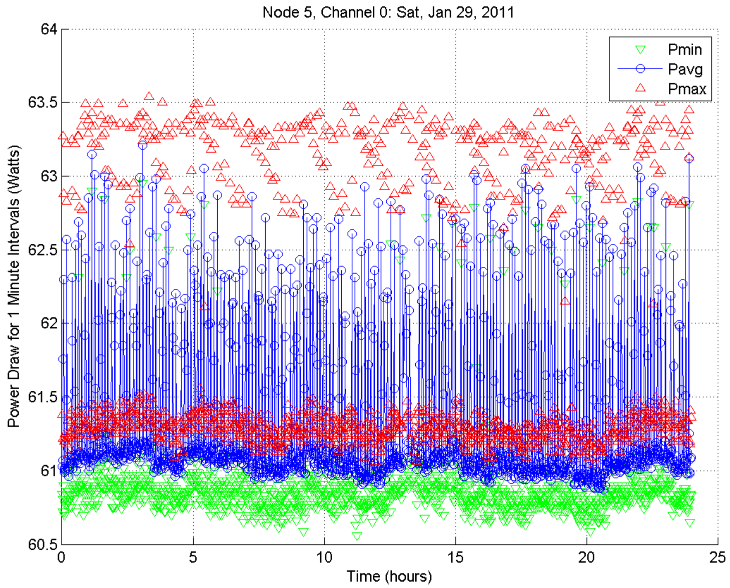


Fig. 4.15 – Copier stand-by power draw

6.3.2 Copy Room
PLMS performance dropped significantly for loads located within the copy room. More in particular, schedule based control rules tended to interfere negatively with built-in power management features of the shared copiers and printers. We already discussed the example of the black and white printer above. Also for the copier,

though, PLMS was not reasonably applicable due to undesired (yet contingent) appliance behavior when subject to external switching cycles, such as failure to automatically power on when re-energized and to enter stand-by mode consistently for part of the study. Stand-by power consumption is reported in Fig. 4.15, whereas Fig. 4.16 reports power consumption when idle (note that during that day no transition to stand-by occurred). Even though the high stand-by power (60W) and idle state consumption (over 250W) would have allowed for great saving opportunities, PLMS rules were suspended for this appliance.

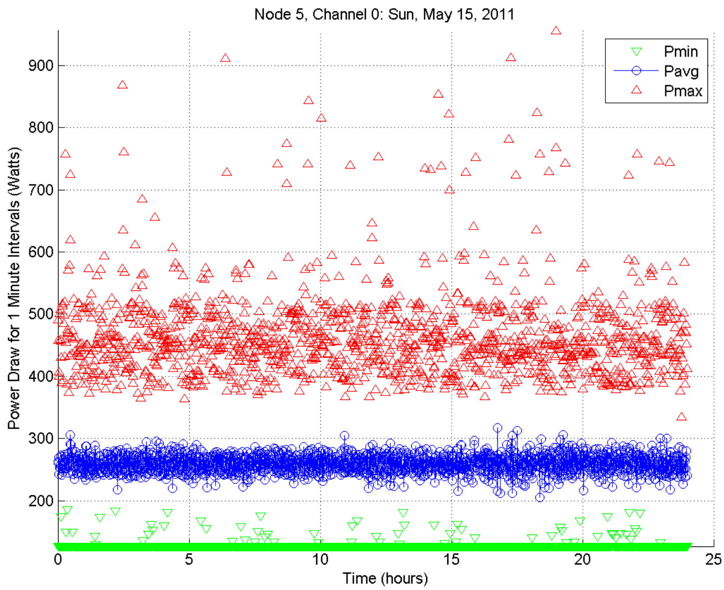


Fig. 4.16 – Copier idle state power consumption

A more comprehensive taxonomy of appliances and devices and the corresponding performance of the PLMS is outside the scope of this work. More details about the outcome of the plug load metering trial for other devices not mentioned here can be found in [95].

4.5. Limitations of the approach

The PLMS deployment described above represents an effective method to asses energy usage by office appliances in order to determine guidelines and recommended good practices. There are a few issues, however, to take into account in the perspective of deploying similar systems on a wider scale or submitting the described PLMS design for standardization. In the Sustainability Base project, given the objective to produce a thorough assessment of appliance behavior and provide guidelines for green practices, optimal solutions to design issues regarding the PLMS itself were not strictly a primary expected research outcome. Nevertheless, part of the research effort was also driven by this

perspective and the upcoming paragraphs will discuss relevant conclusions and results obtained on this matter.
On a first note, it appears obvious, for example, that monitoring systems targeting plug loads should be considered exclusively as part of larger scope monitoring infrastructures, including other building plants, in order to integrate as many information flows as possible. This would provide a more reliable picture of the energy consumption within the building, but also it would open up several opportunities to define complex policies acting across the various subsystems, able, for instance, to leverage information extracted from one realm to enforce relevant adjustments on another, or to combine data from more than one realm to achieve a more globally informed decision making.
Moreover, it is paramount that future models for commercial PLMS will be based on a logical separation between monitoring and actuation. The smart power strips deployed at Sustainability Base also provided onboard channel switching capabilities, which allowed, during the experimental study, an easier definition and deployment of policies. However, this would represent a severe limitation on a more general point of view. First of all, in fact, this circumstance jeopardizes the modularity and flexibility of the overall system, which could be hard to adapt to new requirements emerged after the initial investment. Secondly, future green buildings will be likely equipped with automation technologies, which should be exploited for actuation, for overall design coherence and for run-time consistence of any supervisory control in place (to avoid information misalignments due to lack of communication between the independent PLMS and building automation).
Therefore, on a wider perspective, monolithic design of PLMS should be discouraged and consistent design paths, heading to a system integration view, be explored and proposed, instead, which is objective of the upcoming sections. Before going into the details of integrated PLMS design approaches, we will examine the limitations relevant for the PLMS as discusses so far, in order to better inform the reader about the objectives of the proposed restructuring.

4.5.1. Definition of contexts and policies

In the described PLMS, both monitoring and rules enacting were structured taking into account a context definition, which was mainly based on a statically defined time schedule. This followed a common practice in Energy Management Systems EMS, where, typically, operation is preliminarily organized taking into account common sense considerations, such as splitting the time domain between office and non-office hours when deploying for commercial buildings. This straightforward approach, yet effective in experimental setups, limits the applicability of the designed systems into other scenarios, without ad hoc adjustments that, in some cases, might adversely affect the effectiveness of the PLMS as originally intended. Below we will go through some of the implications of this design choice that have to be addressed in the restructuring.

4.5.1.1. Coarse grained definition of contexts

In order to guarantee a satisfactory level of homogeneity of relevant parameters within a given context, statically defined time-based intervals tend to be configured to last for relatively long periods of time. This is due to the fact that statically defined contexts repeat daily and therefore the shorter the time interval, the higher the probability that distinct days would exhibit very different conditions on small time scales. Longer time intervals guarantee that contingent daily variations would be eliminated averaging them over a longer time interval. In other terms, we can safely assume that energy consumption over a whole workday for a specific workstation would not vary significantly when comparing different days within a dataset. The same would not apply for shorter intervals (conditions between, for instance, 3pm and 3.30pm, are very likely to be extremely variable from day to day).

Longer time intervals masquerade the environment complexity by means of an implicit averaging operating. Unfortunately this stripes out a great amount of valuable information, and makes it nearly unfeasible to adopt tailor made energy policies. This was experienced clearly during the PLMS pilot described above.

4.5.1.2. Mutual exclusivity

Typically, statically defined contexts are mutually exclusive in that their definition can rely mostly on one parameter, that is time. Therefore, any given operating condition falls exclusively within one of the predefined contexts. Slightly more sophisticated models might include more than one set (the overlapping of day/night and week/weekend above is an example) but that would simply multiply the available options over a matrix of possibilities (in the PLMS above, the available slots came in a number of 4, not all equally significant).

When more parameters are considered (including, for instance, presence detection, number of people, recent history of events), context definition is no more conceivable in terms of a matrix. Rather it is a tuple of micro-contexts occurring simultaneously and providing a clearer picture of what is actually happening within the environment. This concept will be better explained and exploited in the last chapter of this document.

4.5.2. Granularity of actions

The PLMS system described above, based on an infrastructure of smart power strips, for easier deployment, showed its main limitations in the limited capability of possible control actions. More in particular, this appeared more evident when dealing with devices with inner complexity (in terms of number or even continuity of operating states) or with internal energy management features.

The former category of devices was not safely manageable by the PLMS, to avoid asset degradation (or data loss, in the case of computer), whereas the latter experienced negative interference by the PLMS onto the internal power saving mechanisms (coexistence of the two proved to be ineffective or even counter-productive).

A different approach would more beneficial to the extent that the control mechanisms employed by the PLMS can effectively leverage existing device functionalities (whether energy-related or not), beyond strict turn-on/turn-off policies. This possibility also requires that the appliances provide interfaces for external control of their internal states. Several white-goods appliance producers are starting to equip their products with HBAS-related modules able to inform external controllers of current internal state and allow more fine-grained manageability.

5. RESTRUCTURING SUSTAINABILITY BASE PLUG LOAD MANAGEMENT SYSTEM EXPLOITING SMART BUILDING TECHNOLOGIES

This chapter aims at assessing design alternatives in the perspective of providing an extension to the energy management system experimented at Sustainability Base. The objective is twofold: first, the architecture examined here aims at achieving a higher level of integration between the Plug Load Management System (PLMS) and the Building Automation System (BAS); second, it extends the monitoring and management features onto the indoor lighting subsystem. The first objective is due to the need to explore ways to overcome some of the drawbacks and limitations of the PLMS approach described earlier, with the intention to possibly introduce novel functionalities, otherwise not feasible at a lower level of PLMS-BAS integration. The inclusion of the lighting subsystem within the scope of energy management (obviously desirable step forward toward a more reliable and complete picture of the overall building energy performance) offers several opportunities as to cross-relate data for decision-making (refer to the concept of "implicit sensing" [97]) and to apply enforcement of energy conservation policies to a wider set of sinks. Estimating and measuring energy consumption due to the lighting system separately (respectively during design and building operational phases), possibly on a room by room basis, is of crucial interest since an accurate knowledge would guide energy managers and designers towards the most appropriate lighting systems and management policies, effectively complementing the estimates and measurements regarding MELs.

It should be noted that the choice of the indoor lighting, as the elected subsystem targeted by this extension, is grounded on the empirical observation that it can be considered as "closer" to inhabitants (i.e. more directly controlled and/or influenced by users' presence and activity) than other building management plants, such as Heating Ventilation and Air Conditioning (HVAC), thus more likely to be affected by similar patterns as the ones found in plug-in devices. Not surprisingly, in fact, some of the metering devices (i.e. smart power strips) designed for PLMS are equipped by presence sensors to enable or disable power supply, similarly to several lighting controllers commonly found in various commercial light controllers. Nevertheless, this assumption will not be subject to further validation here, since the overall objective of the study is to encapsulate PLMS into more general purpose BAS features and the design principles introduced below are not adversely affected by this specific choice.

5.1. Contribution to technical knowledge and practices

As of the time of writing, the most recent efforts in characterizing energy patterns regarding Miscellaneous Electrical Loads (MELs) are still executed at an experimental level, with no specific guidance with regard to the opportunity and feasibility of a deployment of such practices within common, non-research scenarios. Referring to scientific literature to be published concurrently to (and independently of) this document [96], it appears clear how energy monitoring of plug loads still requires a more stabilized body of knowledge with regard to methodological aspects. Moreover, while measurements campaigns up to now (see for example [98] and [99]) have demonstrated the energy saving potential

inherent with MELs monitoring, it is still an open question whether these benefits will counterbalance the infrastructure costs in commercial or residential buildings, outside laboratory conditions. Many, if not all, of the cited works deal with setting up independent, dedicated architectures devoted exclusively to MELs monitoring, with costs that are safely assumed to be prohibitive in regular scenarios.
Therefore, main contributions of this chapter are: to demonstrate an existing path towards performing MELs monitoring through re-using BAS infrastructure; to show the inherent trade-offs as to the degree of analysis that can thus be reached, rather than deploying a dedicated subsystem; finally, to provide building designers with a methodological framework to equip buildings under their own supervision with reasonable MELs energy monitoring features, without disrupting common design, commissioning and maintenance practices as well as typical BAS contracting cost estimates.

5.2. Applicable norms and regulations

Given the perspective described above, it is certainly advisable to engage in a technical approach guided by adherence to current building automation standards and regulations, with special regard to lighting equipment and pluggable devices, where applicable.
As to the latter, it should be noted, however, that MELs have not reached a thorough degree of standardization as to recommended architectures, practices and tools for energy monitoring and management purposes. The same is not true for indoor lighting systems, which, instead, have been the target of several worldwide standardization efforts. Beside norms regulating required lighting performance and visual comfort levels, such as UNI EN12464-1 [73], we will refer here more specifically to regulations regarding energy measurement and energy optimization within indoor lighting systems. Relevant standards in this specific field are UNI EN15232 [71] and UNI EN15193 [72], that will be both taken into account and discussed below. The latter is specific to lighting systems with regard to energy measurement, while the former deals with building automation features at large, providing classification criteria as to impact on energy conservation due to the introduction of individual BAS features. All of these regulations cover almost every detail regarding how to distinguish a comfortable place or condition from a not acceptable environment, describing specific requirements, pertaining to indoor lighting, to obtain acceptable levels of visual comfort. Standards suggest a division of the environment into separate working areas within which there’s a homogeneous set of requirements for lighting levels, depending on the prospected use.
These levels are mainly expressed in terms of lux, although it is worth mentioning, that there’s a tendency (refer to UNI EN15193 for example) to characterize indoor lighting also by means of other values such as color temperature (conventionally measured in units of absolute temperature, Kelvin) suggesting a range of possibilities from cool white to warm (i.e. yellowish) light, directly related to biological effects onto the people subject to the light stimulus. This biological effect is only partly dependent on the actual light performance for pure vision but has an impact on the overall comfort achieved, due to its influence on the regulation of hormones in humans. Standards define as “algorithmic lighting” the process by means of which lighting levels, direction and color temperature are automatically

controlled. Within the scope of current work, however, the crucial parameters, object of measurement, will be the overall energy consumption and power profile.
In terms of classification of systems based on their energy conservation performances, the two cited norms, EN15232 and 15193, describe quantitative and qualitative approaches. The former proposes a classification of buildings into a hierarchy of levels depending on the automation features that have been implemented. In this specific case, the focus is strongly directed toward HVAC features, while the description level regarding indoor lighting is more coarse-grained. The latter norms, on the contrary, focuses exclusively on lighting systems indicating a few alternative techniques to reach a quantitative estimation of energy footprint. Among this methods, we will discuss the most relevant one for HBAS, showing how it can be effectively leveraged to coordinate PLMS and more traditional EMS into an integrated system.

5.3. Exploiting building automation systems for energy auditing: concepts and methods

EN15193 proposes some approaches for a direct measurement of the energy consumption part due to lighting subsystem. The concept of structured electrical design, with dedicated circuits for lighting on one side and everything else on the other, is depicted in the picture below (refer to the standard).

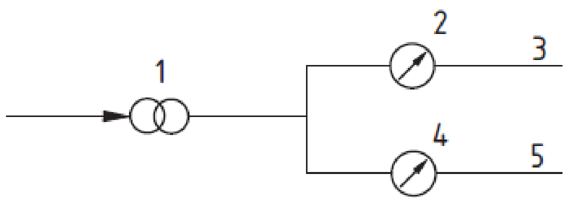


Fig. 5.1 – Power metering with dedicated circuits (EN-15193)

In Fig. 5.1, the primary electric power (1) is separated into two distinct circuits (3 and 5) with separate measurement equipment (respectively 2 and 4). By correctly allocating luminaries exclusively within one circuit, it would be possible to have specific real-time information regarding lighting energy consumption, for online or offline decision-making or accounting.
This kind of approach can then be further extended to an architecture where segregation of circuits is applied, for example to a floor by floor basis, or other equivalent policies.
In Fig. 5.2, power meters 5 and 6 handle two lighting environments, whereas meter 2 reports the whole consumption (including lighting and non-lighting subsystems). This scheme can be surely considered during design and extended according to planned requirements.

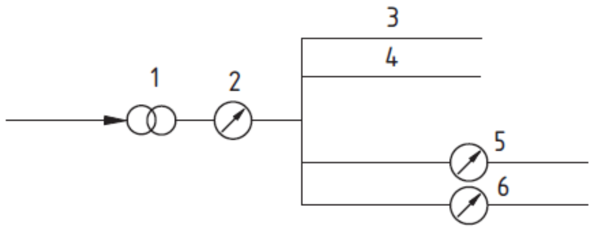


Fig. 5.2 – Multiple circuits segregation (EN-15193)

However, direct measurement schemes would not be always reasonable if one or more of the following cases apply:

- Renovation of existing buildings
- Requirements cannot be planned during design
- Requirements are subject to (frequent) change
- Cost and/or time for wiring is a concern

The underlying logic beneath a segregated circuit design is hard-wired and static, therefore re-planning or fine-tuning would require costs comparable to the installation costs.
Therefore, the norm also describes a third alternative, based on a general concept of bus technologies, without referring to any commercially available technology.

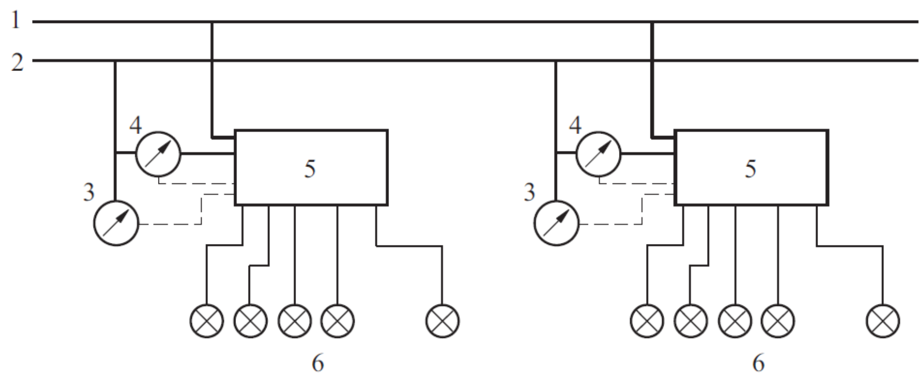


Fig. 5.3 – Energy metering by means of bus based lighting controllers (EN-15193)

In this case, loads are driven by dedicated controllers (5) connected to a communication and control infrastructure (bus line, 1). Energy draw from the power line (2) is measured in terms of voltage (3) and current (4) collected by controllers to drive the luminaries (6).
HBAS could therefore be exploited to circumvent the limitations of traditional monitoring and reach higher amount and quality of data extraction from the field. Rather than centralizing power measurement at circuit level, this action could be distributed at device level, and in some cases (depending on the automation

protocol used for design and the specific set of luminaries adopted in the system), even at channel (single local lighting point) level. Within fieldbus systems, the concept of channel is generally associated to that of a process point (in terms of process automation terminology) that aggregates hardware resources (i.e. power switches to drive loads) and software resources (procedures and data objects that encapsulate the physical resources for handling commands, events and status). Very often, a single channel is associated to a single switching load. Since handling of channels happens separately, it could be reasonable to perform power measurement at channel level, and several commercial systems have followed this approach.

5.3.1. Technology choice

In order to specialize the general scheme reported above from EN15193 (which is applicable to almost any commercially available automation technology), further analysis and design guidelines will be based on the already introduced ISO/IEC 14543-3 (known under the brand name KNX™). This choice will not imply significant loss of generality for the upcoming discussion, which will be approached in the perspective of an extensibility to several other building automation protocols and device models.

The underlying objective of adopting ISO/IEC 14543-3 for this restructuring should appear clear in that the overall intention is to move beyond the limitations indicated for the Sustainability Base PLMS, with special regard to the static definition of contexts. It has been discussed in previous sections regarding the Green Networking prototype (which is based on an experimental study conducted on an ISO/IEC 14543-3 HBAS network) how the concept of *adjacency sets* proved to be an interesting opportunity to enable basic context detection. Following chapters dealing with Smart Grid load forecasting features will further explore this concept, but within the scope of the current discussion it is worth anticipating that integrating the PLMS into the HBAS allows for exploiting context awareness techniques, enabled by the HBAS through the introduction of adjacency sets, in order to orchestrate the monitoring and policy enforcement provided by the PLMS under a more flexible structure of time intervals. The latters could be thus based upon a runtime evaluation of current environment conditions, rather than a one-time configuration of fixed time slots that would not reflect the inevitable dynamicity found in real environments.

Moreover, the distributed application logic of ISO/IEC 14543-3 represents a strong asset for the purpose of the EMS system under analysis. As already summarized in the survey chapter describing HBAS technologies, the concept of process point is referred to as *group object* in ISO/IEC 14543-3, namely a physical resource that can be handled independently of others, both locally and remotely (via the network). Associated to the physical resource, passively (sensor) or actively (actuator) connected to the physical environment, several data structures belong to the group object for communication and computing purposes. Several group objects can be gathered at a higher level of abstraction into a *channel* (i.e. a collection of group objects logically related to a same resource or function). Several process points are then bound to each other into what is commonly addressed to as a *network variable*. That is process points associated to sensors and actuators are logically bound to each other in order to set up a distributed function or application (following this process, for instance, load switching devices are put under command of a wall button or other type of sensors). Since *process points* or *network variables* are data structures modeling a physical phenomenon, the information they carry can be exploited in order to collect energy information related to the physical processes and therefore produce energy metering values as required by the objective of this work. Moreover, the degree of flexibility provided the concept of channel allows for an extremely fine-grained energy monitoring, beyond the capabilities of the scheme published in EN-15193 (where the represented schematic depicts controllers that appear to act as single channel devices, at least for the energy measurement part).

We will now discuss architectural choices regarding the planned design, with a particular focus on the relevant trade-offs. Given the flexibility mentioned above, it is clear how energy metering through HBAS can be executed with various cost-benefit approaches, depending on overall requirements and criticality of the auditing procedures for the building owners, managers or maintainers. In the following sections, some use case scenarios will be described, able to accomplish current objectives, depending on the available equipment and the planned requirements. There might be cases, in fact, where features such as detection of anomalous energy consumption is not a focus, or where past investments cannot be lost and cost trade-offs suggest approximate methods. Both cases will be covered here. The concept to be demonstrated is how BACS may offer metering possibilities regardless of whether this requirement was planned during design or not. First method below makes use of a direct metering approach, exploiting special actuators with onboard metering equipment. A second scheme obtains similar objectives but with smaller requirements on the HBAS devices that have to be deployed on the field. This second method is thought to be possible also on existing systems without any device replacement or network re-planning, yet offers basic PLMS and EMS functionalities, provided that an initial measurement campaign is conducted, similarly to the one executed for Sustainability Base.

5.3.2. Energy metering by adopting special purpose actuators

This direct method exploits actuators with onboard metering possibilities. Such kind of actuators usually have a structure as the one depicted below. Green connections represent data lines (bus cables outside the device, board tracks in the inner part) whereas red lines stand for power cables. “Switch” and “Power Meter” are physical resources manageable through the encapsulation of the two group objects (respectively, Switch Obj and Metering Obj). In this very simplified scheme, this two objects are logically grouped within a device channel. Adjacent channels share the same structure and refer to distinct resources. Each channel manages a single physical load.

By looking further into this model, it appears clear that in building automation systems similar to ISO/IEC 14543-3, the concept of device is secondary to that of group object or channel. From this point of view, a physical device is a sort of enclosure for channels. It is not surprising, therefore that addressing in such systems is object-driven (of course there is a device-driven addressing but its use is mainly limited to commissioning or maintenance).

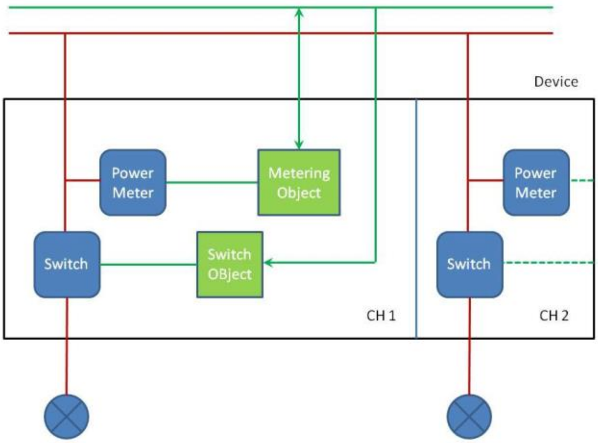


Fig. 5.4 – ISO/IEC 14543-3 multichannel actuator with power metering

The model above is neither compulsory nor convenient in a general sense. Depending on the application, also other situations are possible. Refer to picture below.

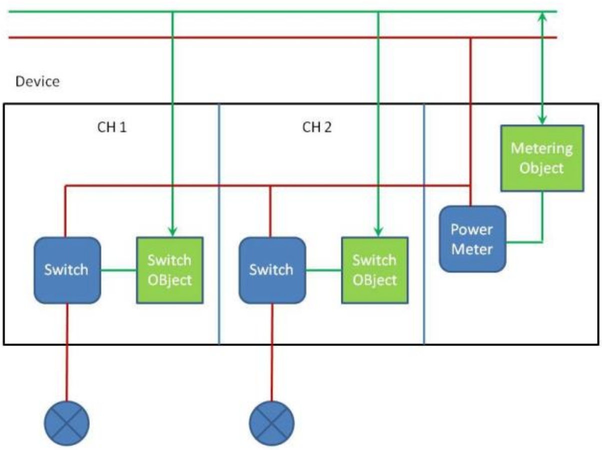


Fig. 5.5 – ISO/IEC 14543-3 multichannel actuator with single power meter

In this case, only a cumulative (per device) information is made available to the network. This actuator would not be strictly considered a three- channel but a two-

channel one, where the metering object is a device level resource. Channels are usually meant to be independent of each other.
Depending on the specific actuator, metering objects can be able to provide

- Real-time instantaneous power
- Energy measurement over a predefined time windows
- Overall energy measurement since commissioning (or since last overflow)
- Reach of specified power levels (for diagnostics or accounting)

The most convenient design would require to use actuators able to provide relevant information natively. When this is not possible (especially within existing systems) a supervision system will have to account for the associated information processing (refer to the paragraph about the overall system architecture, below).
The choice between the two example schemes is only driven by cost concerns and application requirements. It is worth mentioning that even the number of channels available, for example in Fig. 5.4, is a cost-related choice. From a logical point of view, there would be no downside in considering single-channel devices. Channels are grouped within one device only for product price motivations so that fixed costs (e.g. shipping, ordering, packaging costs) are spread over several channels (sometimes the “cost per channel” parameter is considered by designers).
First model (Fig. 5.4) offers the greatest flexibility as to fine-grained power metering. Actually, every single load is measured separately.

5.3.3. Indirect energy metering by exploiting database knowledge

A second method is suggested here to achieve energy metering based on building automation systems. Requirements are the same as above, that is, fine grain measurements, possibly on a load by load basis.
This second method, however, doesn’t rely on the existence of onboard measuring equipment within actuators. Instead it exploits information collected by historical data or obtained through extensive measurement campaigns. Referring to the Sustainability Base plug load monitoring executed in order to establish a baseline of energy-related data, that effort could easily have been directed toward building a database of appliances, devices and loads, containing relevant information about average energy consumption, peaks, confidence intervals. This information, or at least the most statistically reliable portion, could then be used as input for a central indirect estimation algorithm combining loads operating conditions and times with the corresponding energy parameters. Overall consumption would then simply be obtained, for simple visualization or accounting purposes, by straightforward power*time calculations executed at central supervisory machines. Hence it is applicable to existing systems or to systems where costs associated to measurement have to be as low as possible or with minimal modifications to existing infrastructure.
HBAS technologies are able to deliver precise knowledge about load operating times, by means of dedicated device features, commonly found in low cost, off the shelf devices. Several ISO/IEC 14543-3 actuators are, in fact, based on a model such the one depicted below. In this typical kind of ISO/IEC 14543-3 device, the switch/dimmer is driven by a switch object (command) and a feedback informational path reporting its current status via a status object is given in parallel. Given the concept of process point it could be argued that this second object may be unnecessary (since the process point models a physical process, there is no need for a duplicated object associated to the same phenomenon). The presence

of the feedback object enables to model the same physical process by means of a distinct data structure, other than the switch/dimming object, making it possible to provide a more readable information in cases where the switch/dimming object itself may not be self- explanatory. This is especially true when dimming is involved, and the dimming objects may contain a step value, which doesn't provide enough information on the current status of the load. Another example could be when timing is involved (staircase light) when the load status is not driven by the status object alone (light turns off after timeout, without requiring or implying a toggle on the switch object). When this kind of actuators is available, the system provides a reliable information on the on/off/dimming status of each load attached to feedback enabled actuators. Therefore, an indirect measurement of energy consumption is possible.

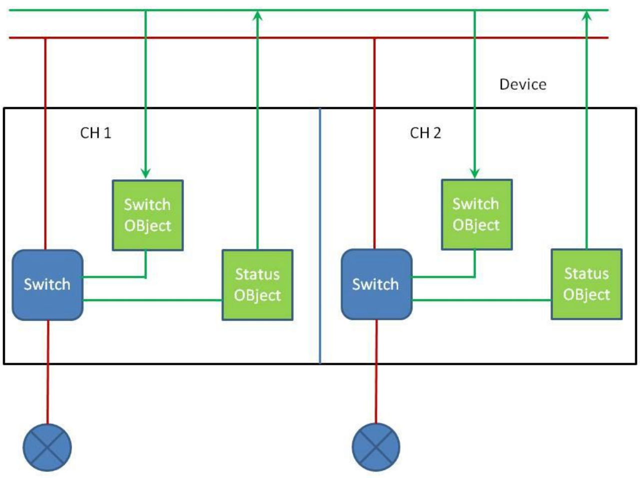


Fig. 5.6 – ISO/IEC 14543-3 multichannel actuator with feedback objects

Refer to the case shown below as possible example scenario. A typical building setting is depicted in Fig. 5.7, where one actuator drives switching loads belonging to two office rooms and a bathroom.

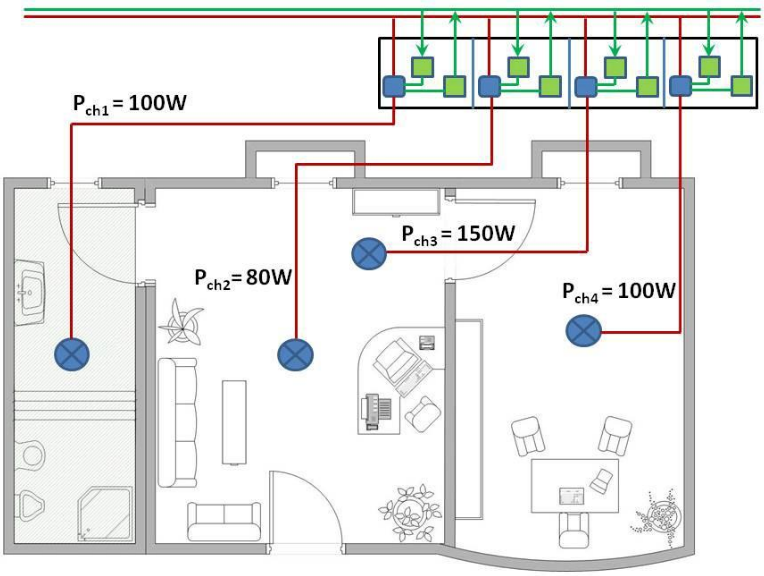


Fig. 5.7 – Example BACS scenario

The BACS supervision system acquires status information regarding loads via the communication feedback objects and associates it to the internal time tracking of operating intervals, and to the power attached to each channel (offline database knowledge).

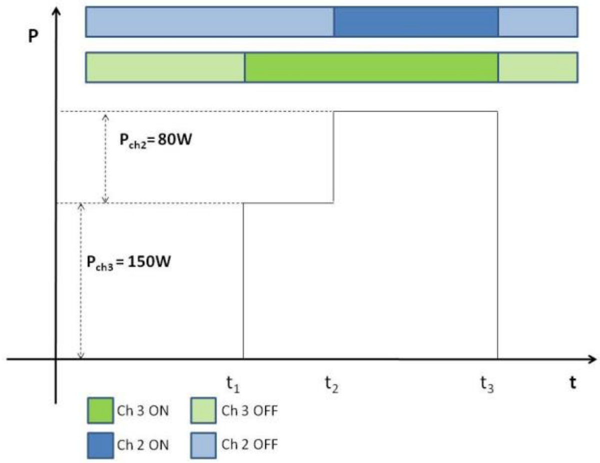


Fig. 5.8 – Feedback Objects in the example case

Fig. 5.8 graphically describes this concept in an example situation. The graph reports instantaneous power supplied by channel 2 and 3 on board of the actuator in Fig. 5.7. These two channels drive known loads which, in this example, are switched on independently at separate times and finally switched off by a central timed command. In the graph, t1 is the switching instant for Pch3, t2 for Pch2 and t3 for the central command. In the given example, energy consumption would be given by $E=Pch3*(t3-t1) + Pch2*(t3-t2)$. This calculation can be performed within the central supervision system without difficulties and additional costs, by a plug in software if a supervision machine is already present or by a special dedicated host machine or embedded device. Estimations have to be made, in this case, whether the supervision system has enough resources to handle the entire BACS (with regard to the number of independent timers necessary to be kept simultaneously active). Especially in those scenarios where supervision is co-located with several other unrelated services (web or other) scalability limitations could arise. In most cases, though, the calculations above should not be an issue.
Network load, instead, has to be carefully considered. Reception of the status via feedback objects cannot be polled by the supervision system, otherwise the trade-off between time-precision and network load induced by the measurement would prove unfeasible (i.e. the supervision would have to poll actuators quickly enough to reach sufficient time granularity, making it more likely to cause network congestion). Therefore, status updates have to be pushed (by the actuators) rather than polled (by the supervision). Network congestion due to the overall BACS is an issue here also, since a delay on a specific status update would result in an imprecise time measurement (underestimation of the resulting energy consumption).
Another even less invasive indirect approach, could be based on the switching object itself. Given the nature of a network variable binding related process points, it is, in principle, possible to infer energy consumption through the time-based method above, but without relying on the status objects, and without introducing network traffic (see above). Already existing network variables associated to switching loads (i.e. group addresses, in ISO/IEC 14543-3) could be simply shared by the supervision system and the sensors/actuators directly (this is also very likely to happen anyway, for the very purpose of the supervision itself). Information about the current power demand is then provided by the switching objects themselves and no additional traffic is induced in the system. However the unreliable coincidence between switching objects and actual status of the actuators output, already discussed above, mandates the introduction of suitable measures to avoid misalignments due to typical HBAS features such as the presence of timers, logical triggering, step value dimming and the PLMS policies themselves. Another relevant example of misalignments between switching objects and load status maybe that of “out of band switching”, that is switching taking place without the ISO/IEC 14543-3 bus being involved). This can be caused, for instance, by local switching (directly in the actuator itself) or from within external BACS networks, integrated into ISO/IEC 14543-3. Say, for example, the lighting system integrates ISO/IEC 14543-3 segments and Dali segments. Without a feedback object, it would not be easy to determine if a switching load belonging to a Dali segment has changed its status when direct commands are issued within the external network. This can be taken care of at design time, but can affect the measuring system over subsequent re-commissioning, in large projects where coherence may not be always maintained.

5.4. Data collection system architecture

All methods described above rely on the standard ISO/IEC 14543-3 data infrastructure in order to deliver energy monitoring and measurement features, without introducing any ad-hoc approach or non-standard device. ISO/IEC 14543-3 bus is used to convey energy related information and, for the indirect methods, to infer load statuses, as well. In order to perform energy monitoring within ISO/IEC 14543-3 systems following the described methods, a suitable system architecture has to be designed. In particular, a specific module dedicated to data collecting and/or treatment has to be introduced. At this stage, this energy module is considered as a logical entity. Objective of this paragraph is to provide some implementation hints about the energy module within real systems. As anticipated, this could be an element of a general purpose system (i.e. the supervisory server) or a dedicated embedded system. While in the former case the resulting architecture is typically centralized, in the latter case both centralized and distributed design are feasible. In the following sections, further details are provided on the two options.

5.4.1. Centralized energy monitoring at the supervisory system

The most obvious approach is to delegate energy measurement and monitoring tasks to the supervisory host machine. This is commonly located at the backbone level, at a (topologically) central location within the network. Supervisory or visualization (state monitoring and reporting) systems are general purpose platforms with high end GUIs. Common scenario is to deploy this crucial network function by means of a desktop/workstation machine running specific management software. Supervisory machines are equipped with physical bus interfaces enabling communication with BACS devices via polling mechanisms (especially at system start-up when an updated image of the network is required) or device push. Transparent capture of network traffic is also possible. Purpose of supervision is related to system maintenance, diagnostic, safety and security. Energy monitoring and measurement could thus be successfully executed by this kind of central node.
A possible scheme of how this could be accomplished involves an energy module running as a dedicated task on the supervisory system (depending on the specific case, this software module could be a daemon, a plug-in or other) collecting and processing fieldbus data. This approach can be applied to any of the methods mentioned above. However, processing performance and network load have to be carefully analyzed, in order not to introduce negative effects.
With regard to the first method (direct measurement by onboard equipment within field devices) a centralized module could provide a central repository for measurement values. In this scenario, network load is not an issue, as long as actuators are carefully programmed so as to only send periodic updates or even only allow polling as needed (depending on their internal logging capabilities). Computing requirements are quite low for the supervisory system and mainly limited to possible accounting features. Also, in case the supervisory system is periodically turned off for not negligible periods of time, no data loss can occur as to energy measures, since the base counters are distributed over the actuators.
The indirect methods (relying on a continuous monitoring of network variables), instead, impose tighter requirements on the supervisory system. In fact, this has to be online at all times, to avoid misalignments and data loss for energy measures

(more specifically, a down time of the supervisory system would result in an unrecoverable underestimation of energy consumption, since every load switching occurred during offline periods would be permanently lost). Moreover, the supervision machine must receive or capture every single frame pertaining to the lighting system. This can result in an increased network load, since the network planning will have to take care of a suitable routing of every frame onto the backbone, even when sender and receiver are located within the same network segment. Also, enough computing resources have to be allocated within the supervisory machine, since every incoming ISO/IEC 14543-3 frame regarding the lighting system will typically start an onboard timer and a subsequent calculations (with prior database value fetching) plus update of energy counters. Depending on the specific supervisory machine this can be negligible or not. Therefore, when indirect methods have to be used, careful design is required. Scalability is an issue and an increased system dimension could result in a supervisory machine replacement.
In order to avoid these negative effects and maintain scalability, another possible approach is presented here.

5.4.2. Centralized or distributed energy monitoring by means of embedded systems

Especially when indirect methods are preferred, a more sensible option would be to adopt an embedded monitoring device dedicated to energy measurements. That could be a bus-coupled device able to execute the prescribed data collecting and processing procedures. Such simple approach would require very limited or no interference with the central supervisory system. For example, in cases where the supervisory machine is periodically offline, this approach would provide measuring continuity.
Moreover, in order to address processing and network load issues, a distributed design could be explored, with several monitoring devices active over the network and dedicated to system subparts. This would indeed result in an increased scalability: as to network load, in fact, a smaller number of frames would have to be routed over the backbone link (distributed monitoring devices could be located directly on the monitored segments) resulting in a reduced probability of congestion; with regard to processing resources, each monitoring device would have to deal with a limited number of devices, if compared to a centralized approach. Also, an increased system dimension could be addressed by simply adding one or more monitoring devices, as needed (in some cases, a re-distribution of tasks over the several devices could be possible or advisable, at commissioning time). Each of these devices would then periodically report and update energy values to the supervisory system, for proper accounting and visualization. The distributed monitoring devices represent, therefore, an intermediate layer between fieldbus devices and the supervisory system, providing greater flexibility and scalability for systems where direct or (especially) indirect calculations methods, such the ones presented above, are deployed.

6. SMART GRID DEMAND SIDE MANAGEMENT EXPLOITING ADJACENCY SETS

This chapter describes an ongoing research effort aiming at exploiting previous original results regarding green networking in HBAS in the field of Smart Grid, with particular focus on Demand Side Management (DSM) strategies. Previous sections highlighted the fact that the introduction of adjacency sets as a data clustering technique to enable a lightweight, heuristic real time pattern detection, provides pieces of knowledge about the overall context that were only partly planned within the initial objectives of the main power state switching approach. It is un-doubtful that this context awareness information could help higher abstraction layers to foster the delivery of more sophisticated features into the smart environment, related to both Ambient Intelligence (i.e. responsiveness, adaptability) and to energy efficiency. Regarding the latter, main focus of this research, we could expect that a certain degree of context awareness may, for instance, help to: identify anomalous sources of energy consumption (active loads which are unrelated to current context); correlate energy consumption patterns to user habits and environment conditions to point out unexploited opportunities for energy conservation; identify specific context scenarios which are more energy consuming or less responsive to energy efficiency strategies than others; finally, predict upcoming energy usage based on the recent history of user/system contexts.
More in abstract terms, the examples above suggest a conceptual switch of energy conservation strategies from a more traditional approach based on *sinks* (i.e. appliances, devices) to one based on *contexts*. Typically, state of the art energy management schemes, such as the ones discussed and used in previous chapters, assume, as their base element of analysis, single appliances or subsystems. According to this paradigm, monitoring equipment outlines energy curves for the single appliance or cluster of appliances (i.e. subsystems, such as for the case of indoor lighting), with not specific regard as to the various working contexts that the monitored objects go through during operation. Usually, *contexts* are introduced indirectly and approximately by defining coarse grained time intervals (such as the distinction between weekdays and weekends, or nights and days). These time intervals are defined assuming homogeneous conditions within them and are suggested by common sense. Surely, these examples represent a straightforward method to organize data collection and specialize policy enforcement rules, and, indeed, they represent a reasonable, though rudimental and static, definition of *contexts.* However, this paradigm fails to capture the existence of underlying structures in energy consumption profiles, which have to be modeled and detected in order not to approach collected data as a flat, mono-dimensional realm.
Further insight on this matter will be provided in the following paragraphs, where the concept of *adjacency sets*, described earlier in this document, will be explored as a possible heuristic method to deliver reasonable context detection. It will then be discussed whether this approach can be successfully exploited in energy management systems, with a particular focus on DSM.

6.1. Building automation as a key enabler for the Smart Grid

It is recognized [94] that the most efficient approach toward developing an effective demand-side load management scheme is to exploit the functionalities offered by a

building automation system on the local side, in order to successfully achieve the global optimization targets envisioned for the Smart Grid.
At policy enforcement level, Smart Buildings can effectively be exposed onto the grid by providing various mechanisms to higher level controllers (refer to demand response architectures described earlier) enabling them to implement load shifting, peak clipping, and other demand side management actions. Through building automation, all of these actions can be performed in a more structured way than with other traditional approaches, such as direct control and ripple control, delegating the final actuation to the local HBAS. With the mediation of HBAS, user preferences and a number of other local parameters could be taken into account within the control loop, without unnecessary burden onto the grid side, which cannot reasonably manage a very large number of nodes with reliability and flexibility.
Similarly, monitoring and decision making processes can as well be assisted by the presence of a local HBAS, representing a crucial source of information to implement load forecasting techniques and to reach a more detailed picture of the local context. Gaining such information is a necessary step, before grid policies can be enforced, in order to limit any impact on the user experience and quality of service as much as possible. Again, such kind of data collection and interpretation would be unfeasible if performed at grid level, whereas the local HBAS has a more natural access, for instance, to sensing functionalities provided by field devices, as well as logging or visualization features implemented by higher level processing elements.
Therefore, Smart Buildings can in principle support the Smart Grid both for policy enforcement and decision making processes. However, it must be noticed that the former type of support (local actuation) is primarily subject to standardization and interoperability issues (i.e. defining external interfaces provided to higher level controllers within the Grid), whereas the latter (local sensing/forecasting), instead, is currently an open research challenge and it cannot be immediately and easily provided by any commercially available BA technology. Hence the need for a contribution to the knowledge in this field, which is objective of the research effort described in the following paragraphs.

6.2. Local context detection and load forecasting exploiting adjacency sets

The present research plan stems from the observation that the concept of adjacency sets, introduced earlier, has the capability to potentially provide a wide range of real-time information about the environment and therefore it may be exploited as a basic context awareness tool. This instrument has to be regarded as basic to the extent that, intuitively, the level of sophistication that could reasonably be reached in terms of context awareness may not be sufficient to support complex Ambient Intelligence approaches, but might be effectively leveraged into a demand side management local support system for load forecasting purposes.
Previous sections have discussed how the process of defining adjacency sets is a knowledge-consuming task, meaning it requires details about the environment, system configuration, people habits, and so on. Once deployed, though, it provides real-time knowledge, since it is able to assess, depending on the currently active sets, what specific situation or context is in progress at the moment. This has to be

regarded as an advantage over more static systems, such as the plug load management architecture deployed in Sustainability Base, where knowledge about real-world processes (office schedule, building and room usage, etc.) had to be leveraged anyway during system design, for instance to define policies and rule schedules, but, after deployment, due to the static definition of contexts (basically by means of fixed time intervals), the system was not able to extract any real-time information about the environment processes while unfolding.
The very nature of adjacency sets, instead, enables a more flexible definition of contexts, which by design are determined at run-time, and therefore a more precise action and a more reliable data collection. In particular, sets could be associated with specific situations that could then be detected at run-time and put in relation to the overall energy consumption, the instantaneous energy peaks and device prioritization relevant in each specific situation. It is therefore possible to assume that adjacency sets might provide prediction capabilities about the current or upcoming energy demand with a level of detail suitable to be leveraged by Smart Grid procedures and controllers devoted to DSM strategies.

6.3. Limitations of the proposed approach

Before discussing the methodological details of this research effort, we will briefly examine here the main technical issue that will not be subject to immediate analysis, but rather left to future works, although it presents a not negligible impact on the applicability of the final result, that is worth mentioning.
It has to be noted, in fact, that the quality and preciseness of the context information extracted leveraging adjacency sets, is likely to depend on the overall number of the sets that are going to be defined within the system, the dimension of each set and the diversity of devices included in each set. Therefore effectiveness of the system relies on a fine tuning procedure aiming at limiting false detections and late detections of contexts. This would require either an extensive human commissioning and testing or a self-configuring system-wide routine. As anticipated, it will be left beyond the scope of current work to define this whole process. Instead, the pursued objective will be to determine whether properly configured adjacency sets are actually able to provide context detection and forecasting capabilities as expected and to what extent these capabilities degrade by using less than optimal adjacency sets configurations. In case of a positive outcome for both of these research questions, adjacency sets would then prove itself as a foundational concept, relatively lightweight to implement in hardware (even though possibly non-trivial to commission before further studies) but with the capability to determine environmental context information without introducing substantial overhead, both in terms of computation, equipment and network energy consumption.

6.4. Overall research method

Assessing the existing relationship between context detection through adjacency sets and energy demand variations involves a thorough measurement of both information flows (energy curve and detected context sequences) within a given environment, simultaneously and with a suitable degree of granularity and flexibility, so as to adapt the analysis and monitoring strategies as the work phases progress. Implicitly, it is required that the environment subject to analysis be equipped by an HBAS controlling a substantial percentage of appliances and functionalities within the target residential unit. More details regarding the testing location will be provided later. The following two paragraphs, instead, will discuss more preliminary details regarding each of the two aspects subject to measurement.

6.4.1. Continuous energy curve estimation

Since the objective of this part of the work is to determine how context analysis performed by adjacency sets is able to provide Smart Grid related features including, but not limited to, load forecasting, the other information flow to be collected is the global energy behavior of the residential unit under test, as seen externally by the electric utility. Depending on the specific user profile, this would include active and reactive power as well as local generation through renewable sources. Therefore, it would be advisable to exploit the functionalities already at disposable of the electric utility itself. Namely, a Smart Metering appliance installed by the energy provider is a requirement (which is commonly fulfilled, at least in Italy) for the experimental environment.

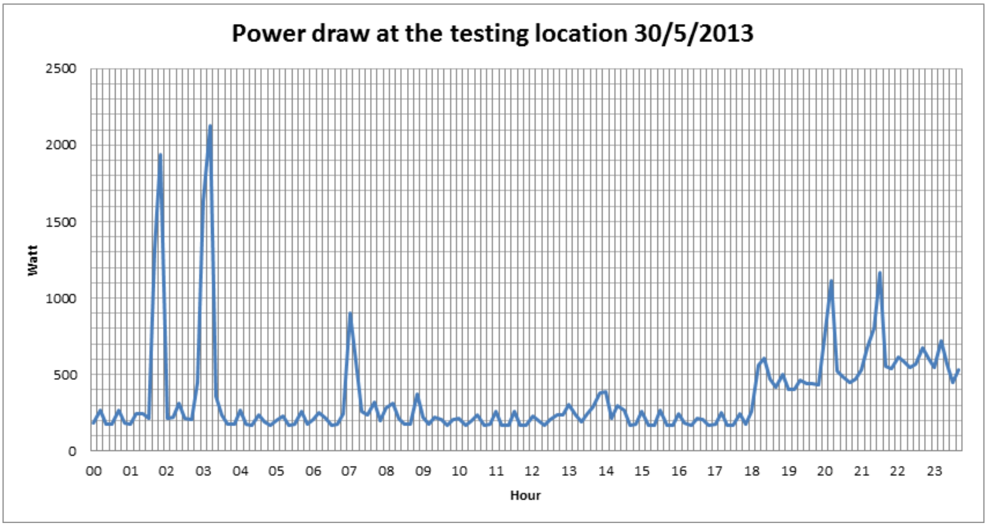


Fig. 6.1 – Daily power draw within the monitored location (smart meter data)

Also, the frequency of energy data collection should not be lower than a reasonable threshold, even though, for the planned analysis, real time data is not necessary. In fact, since the energy curve has to be correlated with the adjacency set sequence, it is assumed as sufficient that the time intervals between subsequent energy measurements provided by the Smart Meter are significantly smaller than the average duration of an adjacency set, so as to be able to collect a relevant energy curve contained within any single adjacency set. It will be assumed here, as a starting hypothesis to be reviewed in later stages of the work, that a number of energy samples close to or exceeding a hundred should be more than enough to allow significant conclusions as to the influence of adjacency sets and contexts over energy demand. Therefore, time intervals between energy samples smaller than adjacency sets duration by two orders of magnitude can be considered a very reasonable, if not excessive, target. Limited degradation of the ratio between the two time parameters will likely be allowed, even though with careful further revision. Specific portions of the information flows where this ratio will result dramatically penalized may, instead, be entirely discarded from the analysis. Fig. 6.1 represents a portion of the collected data as provided by the utility Smart Meter.

6.4.2. Context detection through HBAS network monitoring and adjacency sets packet classification

The HBAS system will be subject to a continuous monitoring aiming at basically two network data collecting activities to be performed in parallel.
On one side, the whole network trace will be gathered throughout the test period, by means of the lowest level mechanisms provided by the interfacing equipment, in order to obtain an unfiltered dump of the communication frames forward through the HBAS network infrastructure, including error messages, acks, nacks, status notifications and protocol handling frames. As of the time of writing, this data collecting (along with the one above) is in place.
On the other hand, a distinct yet simultaneous network monitoring will be put in place, targeting a higher level data collection. More in particular, this second information flow will only regard messages exchange that are relevant for adjacency sets detection. This includes command requests and status notifications falling within at least one of the defined active adjacency sets within the system (as determined before the testing routine starts).

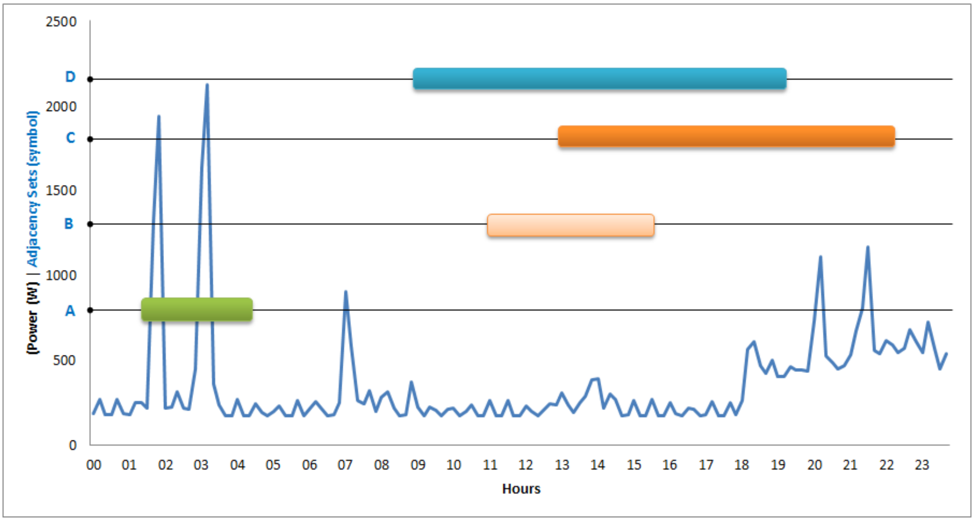


Fig. 6.2 – Example scenario of the combined datasets

Referring to the architecture described for the green networking prototype discussed in previous sections, the network monitor to be deployed here acts as a meta-device belonging to all the active adjacency sets and therefore triggered indifferently by any of them. At any given moment, this network monitoring strategy will be able to enlist the active sets and log their occurrence, duration and sequence accordingly. By means of subsequent refinements, the filtered network monitoring will be repeated with different configurations in place in order to: a) identify the best performance achievable by the method and b) assess the impact of various misconfiguration scenarios. Fig. 6.2 depicts the prospected target output of the combined datasets. The power curve is based on actual data (see also Fig. 6.1) whereas adjacency sets are represented for exemplification purposes (their detection requires the filtered data collecting, which, as anticipated, is not in place at the time of writing). Upcoming paragraphs will further detail the depicted scenario to illustrate the followed methodology for this research.

6.5. Target system requirements

As already anticipated, load forecasting will not be the only objective pursued by this experimental study. A few other features relevant for the Smart Grid will be assessed as to their feasibility through the given approach. Below we will briefly introduce the objectives under investigation in the upcoming activities.

6.5.1. Local peak occurrence forecasting

The study aims at assessing to what extent it can be possible to determine, based on current (and, possibly, recently occurred) context(s), future potential contexts and the related expected occurrence of local peaks. In Fig. 6.2, for instance, occurrence of adjacency set A might provide information about the upcoming two local peaks. Correct definition of set A (in this example) has to ensure that the probability of peak occurrence exceeds a reasonable threshold.

6.5.2. Load forecasting

Beyond local peaks, this analysis also aims at assessing to what extent it can be possible to determine the expected energy consumption (rather than strictly peak occurrence) based on current (and, possibly, recently occurred) context(s). This implies the underlying assumption that energy demand is closely connected to the active context(s). In Fig. 6.2, for instance, energy demand between 6pm and 10pm might be forecasted by the occurrence of set C, or by a logical combination of the occurrences or sequences of occurrence of set B, C and D.

6.5.3. Estimation of the curtailment potential

Within any given context, energy demand can be structured in *interruptible* and *uninterruptible* portions, based on user preferences and other considerations. For example, at any given moment, the amount of energy consumption due to lighting might be curtailed (through dimming or switching). Within an adjacency set, active loads as well as loads about to be activated and deactivated are known in probabilistic terms. Therefore, the system can in principle be structured so as to provide a rough estimate of the amount of energy demand that could be curtailed by the utility in extreme grid conditions.

6.5.4. Introduction of an interruptible virtual electric sub-system

Curtailment mechanisms cited above are likely to interfere (in case they are exploited by the grid) with user habits. Therefore it could be reasonable to introduce logically distinct circuits, to which the user has direct visibility, in order to leave them the opportunity to define a priori when a device is interruptible or not, and possibly change their mind in case curtailment is enacted. This could be executed by the HBAS itself, providing smart plugs easily identifiable by the user as interruptible or not.

6.5.5. Introduction of a general enabling command for Demand Response operated by the user

To further enhance user acceptance, a general command could be provided by design within the system, to completely disable any monitoring or controlling activity by the utility. This could be a part of a Demand Response program, where the actual time spent in grid-friendly mode or outside of it, would be accounted for when calculating incentives and billing.

Future objectives that the system might aim at, but will not be covered during this first experimental assessment, have also been identified. These aspects will not be covered immediately, because they rely entirely on the hypothesis under investigation here, i.e. that adjacency sets can be exploited to effectively determine complex contexts taking place within the environment, with a satisfactory degree of precision to enable features such the ones described above. In case this hypothesis is verified, it is perfectly reasonable to pursue further objectives as follows.

6.5.6. Managing grid policies at local or neighborhood level against renewable production

Knowledge about upcoming peaks and demand, could be exploited directly at local level, in cases where renewable sources (such as photovoltaic panels, wind turbines or others) are deployed. The local system, would auto-assess its own stability, trying to match demand and supply at local level, with the aim to reduce as much as possible (or avoid entirely) the intervention of the utility. Thus, the local micro-grid (which could be at individual or at community level) could be optimized by running user-defined policies, possibly more aggressive than then ones likely to be deployable by the utility. In fact, end users might feel more willing to accept drastic curtailment knowing that not an external entity is imposing it. At HBAS and forecasting level, it is indifferent whether the system is acting in behalf of the global or the local grid. The only exception is that supply from renewables has to be estimated and possibly forecasted, which is why this specific activity falls beyond current effort.

6.5.7. Energy efficiency features

It has been anticipated, above, that the underlying assumption for load forecasting features is that energy demand within a given context assumes typical values over time (that is, distinct occurrences of the same context exhibit statistically similar energy demand). If this assumption is verified, not only load forecasting could be allowed with reasonable reliability, but also, the paradigm shift for traditional energy monitoring, anticipated in the introduction to this chapter, will be possible.

6.5.7.1. Context-based energy monitoring

Referring to Fig. 6.2, we could define as context-based energy consumption, the one occurring within a given adjacency set validity (or within a combination of sets into more complex scenarios, as discussed more in detail below). This will constitute a much more significant information than simple average over long predefined periods of time. Data collected under a context-based structuring, could enable the analysis to be referred to the amount of energy spent for categories of activity (cooking/eating meals, evening entertainment and so forth) based on the level of granularity of adjacency set definition. This could help owners, managers, maintenance personnel and other professionals to conduct more sophisticated assessment energy consumption and feasible conservation strategies, focusing on behavior, rather than strictly appliances.

6.5.7.2. Indirect NILM with estimation of the structure of energy consumption

When dealing with context-based monitoring such as described above, energy demand would be undifferentiated among its single contributions. This would imply that also contribution due to appliances or devices not involved within the context would be included in the monitored consumption. In order to further specialize energy assessment, knowledge about single consumption contributions would be beneficial. According to Non-Intrusive Load Management NILM techniques, this kind of knowledge can be obtained by a specialized signal processing acted upon the power supply line, to detect specific *signatures* induced by active loads. However, since this type of analysis might prove costly to be performed with enough reliability (see for instance [106] for discussion about limitations of NILM), a more approximate (yet reasonable) method could be allowed by context-based monitoring. Within each context, in fact, the active (and upcoming) set of appliances is known within a specific (though yet to be assessed by this study) confidentiality range. Therefore, basic knowledge about average consumption of appliances could be extracted by historical data. For instance, if set S_i is comprised of devices $\{ d_1,d_2,d_3,\ldots d_j \}$ and implies an average consumption of E_i, by combining data across the ensemble of defined sets (with i ranging from 1 to N, where N is the overall number of configured adjacency sets), it is reasonable to expect that single appliances could be determined with regard to average consumption.
There are several experimental analysis to be performed in order to determine the feasibility of such an indirect NILM technique. For example, it could be questioned what would the required precision be for the global, instantaneous power consumption capable to identify also small contributions (due to low power devices, that could simply be stripped out by the implicit statistical averaging operation). Moreover, discussion about the relationship between appliances to be detected and number N, as well as average number of j devices per set. Say N_{APP} the number of appliances available within the environment. When N is small and j is large with respect to N_{APP}, the adjacency sets would not offer enough resolution to determine single appliances. In these cases, however, initial training phases (also common in direct NILM systems) could determine seed knowledge for a number of appliances depending on the actual values of N,j and N_{APP}.

6.5.7.3. Progress monitoring and gamification

Relating energy consumption with actual contexts and hence people behavior would surely help in increasing user involvement in the process of assessing improvements and introducing visualization as well as gamification opportunities. When only overall consumption is considered, part of the people active within the environment would easily become un-interested about the user-driven efficiency measures. If energy demand is split among activities, instead, individuals more interested in one of them specifically, will likely become more engaged in appreciating the related energy parameters and progress over time.

6.6. Testing equipment and methodology

The research activity here described is based on an experimentation agreement with the Italian DSO, Enel Distribuzione, signed on the 22nd of April, 2013. Enel provides equipment and support to assess the instantaneous power consumption within the chosen location, as measured by the utility's smart meter (see Fig. 6.3, depicting the smart meter widely deployed into Italian households).

Fig. 6.3 – Enel's smart meter

With the partner's staff, two approaches were considered in order to collect energy and power curves: namely the provision of historical data about the final customer and the deployment of an experimental client device interfacing with the smart meter. The latter was preferred for a few reasons: in this case, the interval between measures can be configured in order to accommodate for various experimental approaches; the data is available in near real time, rather than at the end of an agreed period of time; more complex intervention on the smart meter is feasible this was, provided that the master-slave relationship between the smart meter and the client device (respectively) can be reverted and more complex assessments can be explored in perspective. Fig. 6.4 and Fig. 6.5 depict, respectively, the "Smart Info" (SI) client device provided by the partner and employed in this study, and how this relates to the overall infrastructure, in Enel's vision. The SI is able to communicate with the Smart Meter through power-line, by directly plugging it into an available wall socket. The Smart Meter has to informed by the utility operator about authorization to communicate energy measures to the SI. In the environment chosen for this experimentation, this authorization was granted at the end of May 2013.

When the SI is authorized, it is able to request and receive a subset of available energy data stored in the Smart Meter, ranging from energy metering throughout the current or previous billing period, maximum power draw in current or previous billing period and so on. Within the scope of this study, the interesting data is the (near) real time power values, as well as the energy curve obtained through the SI.

Fig. 6.4 – Enel's Smart Info (courtesy of Enel Distribuzione)

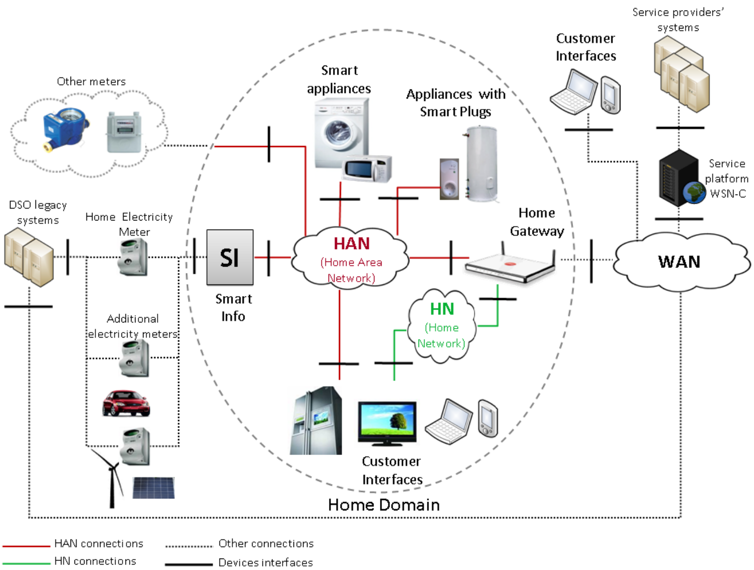


Fig. 6.5 – Enel Smart Info reference architecture (courtesy of Enel Distribuzione)

As in the picture, Enel Smart Info is fully integrated in Enel's Automated Meter Management (AMM) infrastructure (also known as "Telegestore") therefore it can provide access to a Grid-level knowledge about the local environment, useful to be matched against the HBAS-level information given by the adjacency sets. Thus the SI immediately appeared as the perfect solution to achieve the combined data collection discussed above. Table 6.1 reports an excerpt of the raw dataflow provided by the SI.


```
{"timestamp":1369865179,"value":568,"type":2}
{"timestamp":1369865186,"value":7785677,"type":7}
{"timestamp":1369865186,"value":7785677,"type":7}
{"timestamp":1369865186,"value":7785677,"type":7}
{"timestamp":1369865780,"value":517,"type":2}
{"timestamp":1369865160,"value":7785677,"type":6}
{"timestamp":1369865787,"value":7785763,"type":7}
{"timestamp":1369864800,"value":93,"type":0}
{"timestamp":1369865160,"value":7785677,"type":6}
{"timestamp":1369865787,"value":7785763,"type":7}
{"timestamp":1369864800,"value":93,"type":0}
{"timestamp":1369865160,"value":7785677,"type":6}
{"timestamp":1369865787,"value":7785763,"type":7}
{"timestamp":1369864800,"value":93,"type":0}
{"timestamp":1369865160,"value":7785677,"type":6}
{"timestamp":1369865787,"value":7785763,"type":7}
{"timestamp":1369866380,"value":164,"type":2}
{"timestamp":1369864800,"value":93,"type":0}
```


Table 6.1 – Smart Info dataflow

Timestamps are in POSIX format (number of seconds starting from January 1st 1970) and various value types are provided, check Table 6.2 for various available "type" codes (values are W or Wh, depending on type)

Energy consumed	0
Energia produced	1
Power drawn	2
Power generated	3
Power released to the grid	4
Energy released to the grid	5
Total energy consumption (log type 4)	6
Total energy consumption (E(t))	7
Total energy produced (E(t))	8

Table 6.2 – Available type tags for recorded values

6.7. Testing methodology

When the prospected combined dataflow is available, the experimental strategy that will be employed will be better clarified. However, it is expected that an analysis such as the one anticipated in Fig. 6.6 will be feasible.

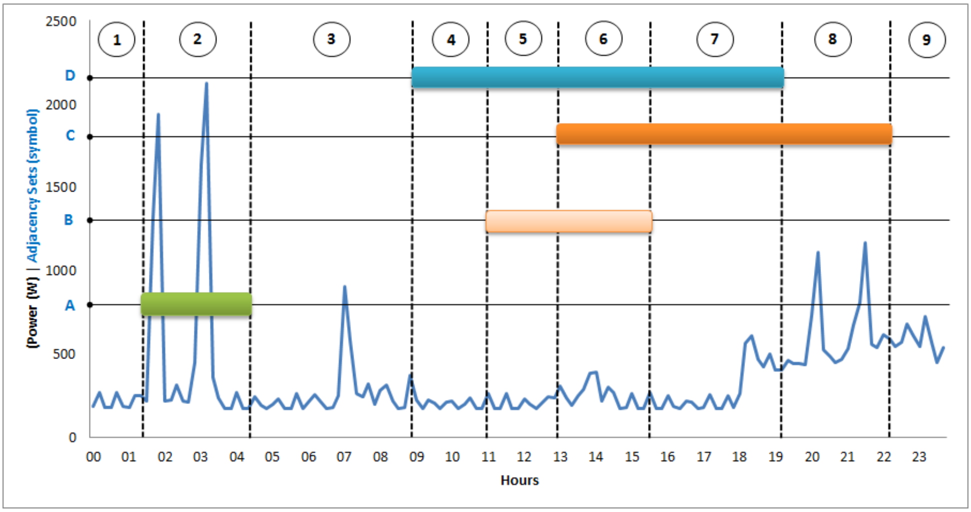


Fig. 6.6 – Prospected methodology of data analysis

In the picture, occurrence of the various adjacency sets subdivides the scenario in subsequent intervals. Each of these intervals will be defined as "context" within this study. That means that each adjacency set represent a sort of micro-context, which then combine into more complex structure. This is due to the intuition that adjacency sets proved effective in the green networking approach. However, in that case, context awareness was not a primary objective. Therefore it is questionable how a single set might safely define an environment context. Therefore, during the study, both individual sets and combinations of them will be regarded as potential context defining tools.

Following the example, context number 5 is defined by {B,D}. If all occurrences of {B,D} within the datasets exhibit a similar energy pattern (in terms of load and peaks), then the {B,D} combination would be considered as significant. Mapping between adjacency sets combinations and environment contexts might involve direct survey of user habits (possibly thorough explicit activity logging). However, the objective here is load/peak forecasting, therefore, should single combinations not correspond to human-level activities, they could nevertheless be significant for energy predictions, anyway.

Other statistical inference that will likely be explored regards the sequence of combinations. For example, it could be verified that, in the picture above, context 5 implies context 6 ({B,D} implies {B,C,D}) within a given time frame or immediately. Also, energy parameters might be influenced by the most recent sequence of combinations.

A circumstance that will be carefully considered will regard time intervals without any adjacency set in the active state (in the picture, this is true for time intervals 3 and 9). In case the percentage of time spent in these intervals remains high with any given choice of the realm of adjacency sets, this might imply the method cannot be applied consistently.
Following the described approach, in conclusion, the concept of context will be modeled, in this work, as a multi-dimensional space, with adjacency sets as base vectors. This implies that the choice of the adjacency sets is crucial to allow for a complete and efficient coverage of the available space of contexts.
Also, optimal adjacency set choices might also take into account minimization techniques for the inter-dependence between them (such as non-orthogonal base vectors).

6.8. Testing location

The location where the testing is taking place is the same as for the green networking study. As already described, it is a 140m^2, two-floor apartment, with two usual inhabitants. The HBAS controlling the house is of medium complexity and includes several advanced features. Below some pictures depicting a few details of the user interfaces and the HBAS devices, typically distributed among electrical closets throughout the house.

Fig. 6.7 – Room controller (second floor), above, and touch screen panel with logic functions and scenarios (living room), below

Fig. 6.8 – Two electrical closets with HBAS devices distribution (first floor, above, and second floor, below)

CONCLUSIONS

ICT systems offer great opportunities for energy management and optimization, but at the same time, they represent an overlooked cause of energy waste, due to a low energy awareness both at protocol design level and at device design level. In HBAS, this issue is confirmed, despite the fact that HBAS are developed and deployed as enabling technologies to enhance the energy performance of houses and buildings. The main reason for this has to be found in the combined effect of over-provisioning and flat power characteristic of HBAS devices and systems, because of which HBAS nodes consume high-peak energy also during low-duty intervals. Energy proportional operation would require the introduction of multiple power state switching approaches, namely through a Dynamic Power Management scheme. In order to effectively introduce DPM, a preliminary assessment is needed to actually verify its feasibility and impact in HBAS technologies.

Data collected during a study case has shown that, while a great amount of accumulated time is spent by devices in idle state, at the same time the network predictability is very low. This implies the need for a statistical model capable to characterize the occurrence of the idle intervals.

The dependence between environment events and network traffic may suggest that existing correlations among the formers may result in specific patterns within the latter. As a first step, some spatial and logical correlations have been explored, confirming that those patterns actually apply. This brought to the introduction of the concept of *adjacency sets* to identify subsets of the traffic trace where packets are organized in sessions. These sessions can be exploited to introduce energy saving (at the networking level) by a basic uncoordinated sleep after timeout approach. The effectiveness of this approach has been validated by means of a Matlab simulation that has shown how energy savings up to 75% can be achieved with limited impact on user experience (latency increase for as low as 5% of commands).

Energy efficiency of the controlled environment was also subject to analysis, within this work. Most notably, the experimental setup of a plug load management system (PLMS) at Nasa Sustainability Base showed that plug loads, which represent a crucial contribution of consumption in future net zero energy buildings, impose thorough analysis to introduce their management by means of automated systems. PLMS will typically be most beneficial when integrated into more general energy management systems, rather than left as standalone systems, due to difficulties to cover a wide range of appliances with homogeneous performance.

Finally, an ongoing smart grid effort, based on the assessment of the concept of adjacency sets, was presented, in the perspective of its deployment in demand side strategies. Since this part is still in progress, it is not possible to provide solid conclusions at the moment. Enel, the Italian electric utility, has been involved in order to provide real-time utility-side energy monitoring of the lab setup for a period of at least two months. The research strategy plans to analyze the combined data-flows, i.e. the energy curve and the detected adjacency sets, in order to identify possible correlations between the two, enabling forecasting abilities for local load and peak values.

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