Intra Smart Grid Management Frameworks for Control and Energy Saving in Buildings

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Abstract. In the context of Smart Grids and Internet of Things (IoT) Systems, distributed monitoring and actuation through Wireless Sensor and Actuator Networks (WSANs) is fundamental to control the energy usage in buildings. Moreover, the realization of algorithms for the optimization of the energy consumption is of paramount importance. This paper presents a loosely coupled integration between a flexible management framework for WSANs, namely the IGMF (Intra-Grid Management Framework), and a Dynamic Energy Scheduler with local control on sensors and actuators, namely the ITESS (IoTLAB Energy Scheduling System). The integrated system allows the users to manage whole buildings applying Dynamic Energy Schedulers for different environments.

Keywords: Smart Grid, Internet of Things, Wireless Sensor and Actuator Networks, Building Management, Energy Scheduler

1 Introduction

New technologies are creating novel opportunities in the monitoring and in the maintenance of buildings [1][2]. In this context, the continuous monitoring of buildings can lead to the realization of important services (e.g. energy utilization optimization) that can be merged with the so called "intra-grid" network [3] that controls and regulates the energy consumption in the part of the Smart Grid [4] that is located within the buildings. One of the best methods to monitor and control buildings is through the utilization of Wireless Sensor and Actuator Networks (WSANs) [5] that allow any arrangement of sensors/actuators inside a building. WSANs offer a more flexible solution to audit buildings and control equipment with respect to traditional systems, which require retrofitting the whole building and therefore are difficult to implement in existing structures. Solutions based on WSANs for the building monitoring and control can be installed in existing structures with minimal efforts. This enables an effective distributed monitoring of building structure condition, and building space and energy (electricity, gas, water) usage while facilitating the design of techniques for intelligent actuation of devices in buildings. In order to transparently and easily use WSANs, several frameworks have to date been implemented [6]. One of these is the IGMF (Intra-Grid Management Framework) [6] that is a domain-specific framework designed for the flexible and efficient management of WSANs deployed in buildings. The IGMF allows an effective management of (large) sets of cooperating networked WSAN nodes, a flexible node group organization to capture the floor plan of the buildings, tecniques for intelligent and distributed sensing and actuation, heterogeneous WSANs integration, system programming at low- and high-levels, quick deployment and update of applications to the WSAN through message exchange.

Through the use of WSANs in buildings, important considerations about the energy spent can be done. The optimization of the energy consumption in buildings is of paramount importance in the future smart grid. The rationale behind this optimization is twofold. On the one hand, the energy demand is growing at a faster pace than the grid capacity which has provoked blackouts as well as environmental concerns [7]. This leads the utilities to incentivize a more rational and efficient energy consumption. To do so, they implemented smart pricing tariffs which are based on a variable energy price [8]. On the other hand, from the user side, the optimization of the energy consumption in buildings leads to important savings, especially under the smart pricing tariff paradigm. Several works in literature have to date tackled the problem of energy profiling/energy optimization in buildings [9]. Within the context of smart pricing, energy scheduling is the state-of-the-art methodology to address this problem from an analytical point of view [8]. Regarding the power-shiftable loads, heating, ventilation and air conditioning (HVAC) modules are considered as the most energy demanding appliances in home buildings [10], [11]. According to studies, they represent the 43% of residential energy consumption in the U.S. and the 61% in U.K. and Canada. The significant energy consumption of the HVAC systems, along with their direct influence on the user's well-being, highlight the necessity for effective HVAC management algorithms that reduce the power consumption in the buildings, taking into account the end-user's comfort. In [12] IoTLAB Energy Scheduling System (ITESS) has been presented. Such system comprehends two HVAC energy scheduling methods in an IoT framework, where the users are able to interact remotely with the HVAC control system. In particular, the users may retrieve information about the temperature and the energy consumption at various spots of the building under control, while they are also able to remotely configure the desired temperature of comfort in given places.

This paper proposes the integration of the IGMF with the ITESS. Such integration leads to a whole system that allows the users to manage buildings applying Dynamic Energy Schedulers for different rooms. Thereby, IGMF permits a more flexible and scalable deployment of the HVAC energy scheduling approach.

The rest of the paper is organized as follows: Section 2 introduces some related work about the integrations of systems; Section 3 presents the IGMF, the

ITESS, and the characteristics that their integration can have; Section 4 shows an example of loosly coupled integration applied to the systems introduced in the previous Section. Finally, in Section 5 some conclusions are drawn.

2 Related Work

The integration of heterogeneous systems is a notable issue, widely addressed both in academia and industry. Different integration solutions have been developed leading to different levels of coupling, that is the degree of direct knowledge that one element (or even, one system) has of another one. On the basis of the direct knowledge degree, in literature the integrated systems are usually divided into:

- **loosely coupled systems**, in which multiple components can cooperate and interoperate regardless of hardware, software, incompatible technologies and other functional features. Moreover, to work properly they do not need to be dependent on each other.
- **tightly coupled systems**, in which hardware and software are not only linked together, but are also inter-dependent, so that the slightest variation from the original status of one of the composing elements implies adverse effects;

These approaches may be applied at different levels [13]:

- at physical level, a tightly coupling implies a direct link between the components while a loosely coupling usually relies on physical intermediary devices;
- at communication level, tightly coupled systems usually exploits a synchronous communication style while loosely coupled systems an asynchronous one;
- at management level, the tightly coupling approach usually exploits a centralized control of process logic. On the contrary, the loosely coupling exploits a distributed control;
- at service level, services are discovered and bound statically in tightly coupled systems, while in loosely coupled systems it is done dynamically.

It is worth noting that both the approaches are not good or bad per-se, because everything depends on the benefits to be obtained after the integration process.

Such paper will mainly focus on loosely coupled architectures. Loose coupling occurs when the interconnected systems elements are highly inter-operable but at the same time minimally inter-dependent. In this case, the integrated system testing, maintenance and recovery costs are reduced, while system flexibility, modularity, robustness and agility increase. To realize a loose coupling, virtualization-based and gateway-based solutions are commonly exploited at different levels of the system architecture. Virtualization allows the creation of a digital artefact of a single device or of a whole system, with the aim of hiding the underlying complexity and reducing at same time the overall interdependency. Gateway-based solutions, instead, aim at increasing the interoperability, establishing shared standards and protocols to facilitate the integration of heterogeneous components/systems. Both these approaches realize loose coupling mainly by exploiting the Software Agent and the Web Service paradigms. In literature have been proposed several examples of loosely coupled integration. iCore [14] is a cognitive management framework for the IoT, in which every real world object (RWO) is virtualized into a digital always-on alter ego, called virtual object (VO), reflecting RWOs status and capabilities. The interactions between RWOs and related VOs happen through gateways, using the REST interface over various wireless or wired access technologies. The ITEA3 project [15] provides a network and services infrastructure for autonomic cooperating smart objects, with the goal of simplifying the development and the deployment of the distributed applications. Similarly to iCore, in ITEA3 heterogeneous components are concretely connected through gateways which exploit a REST interface. Vital framework [16] aims at federating heterogeneous IoT architectures and platforms in the context of the Smart Cities, loosely coupling them by means of different PPIs (Platform Provider Interfaces), which are specified and implemented as a set of RESTful web services and represent a uniform way for accessing the services and data sources regardless of the underlying platforms or providers. Butler [17] and Santander[18] frameworks present a unified, open and horizontal platform to provide services in the context of the Smart Cities. They both exploit a gateway, (defined SmartObject Gateway for Butler, SmartSantanderGateway for Santander) which relies on the REST paradigm and allows the interconnection of different networks to achieve access and communication among embedded devices, servers and mobile terminals.

3 The IGMF / IoTLAB Energy Scheduling System Integration

This section introduces the IGMF, the ITESS, and their system integration.

3.1 The IGMF

The IGMF (Intra-Grid Management Framework) [6] is a domain-specific framework based on WSANs that allows both a proactive monitoring of spaces and a flexible control of devices. The IGMF has the aim to overcome the limits of the frameworks already presented in literature by providing: (i) an effective management of (large) sets of cooperating networked WSAN nodes; (ii) flexible node group organization to capture the floor plan of the buildings; (iii) tecniques for intelligent and distributed sensing and actuation; (iv) heterogeneous WSANs integration; (v) system programming at low- and high-levels; (vi) quick deployment and update of applications to the WSAN through message exchange. Figure 1 shows a component layered based representation of the IGMF. It is worth to be noted that the layers are divided in BS-Side (basestation-side) and Node-Side depending on the place where they are deployed. BS-Side and Node-Side communicate through the IGMF Communication Protocol. The Node-Side components are:

- the *Hardware Sensor Platform* which allows the interaction with platform specific sensors/actuators and radios;
- the *WSAN Management* which allows the communication according to the IGMF Communication Protocol;
- the *Sensing and Actuation Management* which provides a platform-independent access to all the sensors/actuators in the node;
- the *Node Management* which coordinates all the components for the task execution;
- the *Local Group Management* which enables the nodes to manage their groups. A node can be configured according to its group membership;
- the *In-node Signal Processing* which allows the nodes to calculate synthetic data on the samples collected from sensors;
- the *Multi Request Scheduling* which manages periodic requests for sensing/actuation.

The BS-Side layers are:

- the *Heterogeneous Platform Support* which allows the upper layers of the BS-side part to communicate with different platforms;
- the *WSAN Management* which allows the communication with the BS and the other nodes according to the IGMF Communication Protocol;
- the *Group Management* which manages the organizations of the nodes in the WSAN in groups. Groups are designed to represent physical or logical characteristics of the nodes;
- the *Request Scheduling* which allows high-level applications to use the WSAN.

On top of the Request Scheduling Layer an *IGMF Manager & GUI*, an IGMF manager providing a graphical interface that permits the local control of the IGMF WSAN, has been implemented. It allows to manage nodes and groups, to schedule requests for sensing/actuation, to visualize the nodes on the floor plan of a building, and to print charts of data from sensors.

3.2 The ITESS

In this section a description of the IoTLAB Energy Scheduling System (ITESS) is provided. Figure 2 presents a block diagram of the overall architecture. It consists of the following elements:

i) A set of HVAC modules.
ii) A set of actuators that control the HVAC modules.
iii) A WSN, which sends measurements of temperature and energy consumption to a gateway.

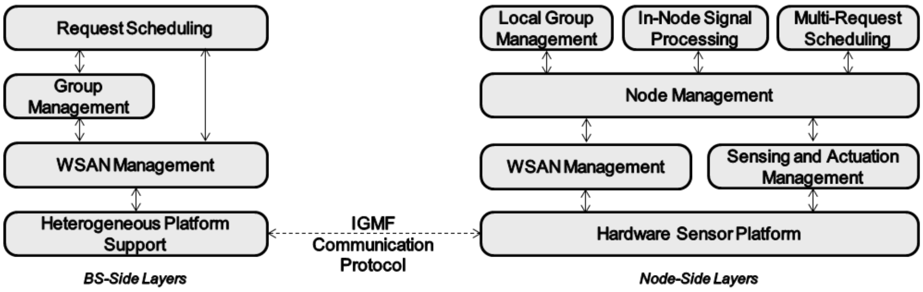

Fig. 1. The IGMF architecture.

iv) A gateway (GW) that incorporates the proposed energy scheduling methods and connects the local network to the Internet. That is, it contains a web server and a database to store data received at the GW from the WSN or the internet.

v) An embedded IP device (e.g., tablet or smartphone) with an interface to interact with the HVAC energy scheduler. It also displays both the temperature and the energy consumption in the building measured by the WSN.

The functionality and flow of information of the proposed architecture is explained as follows. The temperature is measured at several locations by means of the WSN. Then, the measurements are periodically sent to the gateway, where the energy scheduling algorithm is implemented. This algorithm selects the combination of the active HVAC modules that minimize the energy cost for given comfort constraints and energy price during a particular time period. These decisions are sent, through shell commands, to programmable surge protectors (actuators), which actuate on the HVAC modules. The HVAC modules modify the room temperature according to the decisions taken by the energy scheduler. In [12], two energy schedulers are proposed: the Dynamic Energy Scheduler with Comfort Constraints (DES-CC) and the Dynamic Energy Scheduler with Comfort Constraints Relaxation (DES-CCR), see [12] for further details.

Moreover, the gateway hosts a database to store the measurements of temperature and energy consumption. These measurements can be accessed by a remote Internet user. More specifically, they are displayed at the user's IP device, as the gateway implements a web server which manages the communication between the remote user and the local database. This is illustrated in more detail in Figure 2, where the connections between the most relevant blocks are shown. Furthermore, users are allowed to interact with the energy scheduler through their IP devices, by setting the upper and lower bounds of the temperature of comfort.

To get more insights, let us shed light on the temporal behavior of the energy schedulers and the role of the temperature constraints on it. Note that the energy scheduler works in a time interval basis. At the end of each time interval ("current

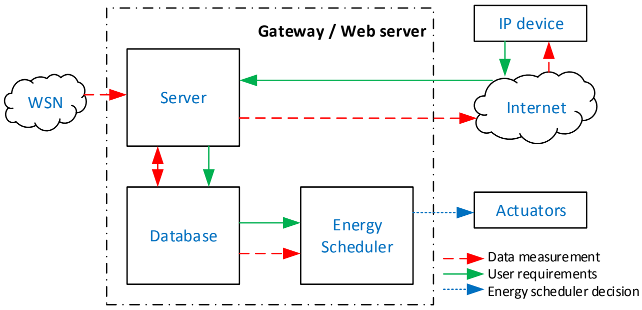

Fig. 2. Block diagram of the energy scheduler with comfort constraints system.

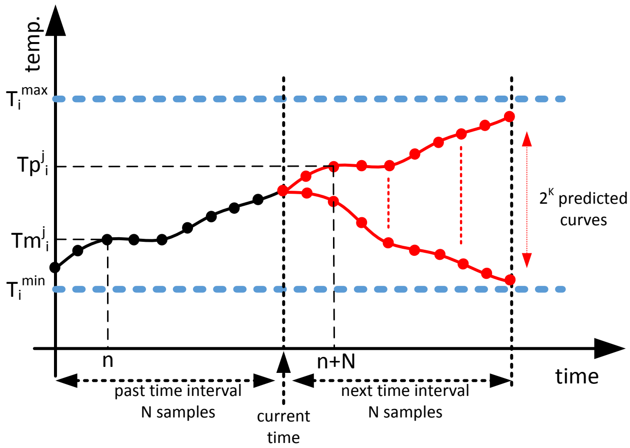

Fig. 3. Prediction of temperature, a fundamental step of the energy scheduler to assess comfort in the future time interval.

time" in Figure 3), the energy scheduler must make a new decision. That is, it must decide which HVAC modules will be active during the next time interval. In order to make this decision, the energy scheduler should predict which would be the temperature provoked by each configuration of HVACs. As there are K HVAC modules and we assume that they are either turned on or off, this corresponds to predict 2^K curves of temperature, as it is illustrated in Figure 3. These predicted temperatures are denoted by $Tp_i^j(n)$, where $1 \leqslant i \leqslant M$ denotes the i-th node and $1 \leqslant j \leqslant 2^K$ is the j-th combination of HVACs turned on or off. Finally, on one hand, the DES-CC selects the configuration of HVACs that minimizes the energy consumption cost within the bounds of comfort, i.e., $T_i^{\min} \leqslant Tp_i^j(n) \leqslant T_i^{\max}$, while the DES-CCR selects the HVAC configuration that optimizes the tradeoff between being closer to the comfort temperatures $T_{u,i}$ and saving energy. This selection is executed by the actuators that control the HVAC modules. It is worth to remark that the higher the number of sensors, the more accurate is the temperature measurement and thus the comfort assessment, though the overall computational cost increases. Also, the temperature dynamics do not change very fast, thereby the sampling rate can be rather slow, in practice it has been observed that 30 seconds is enough for a proper behavior of the system. Last but not least, the higher the time window for taking decision the least accurate the predictions. The interested reader is referred to [12] for further details.

3.3 IGMF / ITESS

The IGMF and the ITESS are two complementary systems that can present several advantages when used together. In particular, they both use WSANs to sample the real world but, while ITESS is configured to use only wireless nodes that sample temperature, the IGMF provides (and can complete the ITESS with) a flexible framework that can be used both to collect data from heterogeneous sensor nodes and to wirelessly control actuators. On the other side, the ITESS can complete the IGMF with mechanisms to control ethernet actuators. Moreover, the ITESS provides a remote interface to control its system that can be used to control the integrated IGMF/ITESS. Finally, the IGMF can have access to the energy schedulers from the ITESS so applying its own energy schedulers.

In particular, the integrated system main features will comprehend:

– the management of a range of cooperating networked wireless nodes in the different parts of the structure;
– the capture of the morphology of any building so to correlate sensed data to a specific portion of the building;
– the adaptive management of sensing and actuation techniques;
– the management of network communication to allow different duty cycles for different wireless nodes;
– the low and high level programmability of the network;
– the fast deployment of concurrent applications at runtime;
– the energy consumption optimization of HVAC systems taking into account the user's comfort constraints and smart pricing tariffs in smart grids;
– the integration with Internet of Things (IoT). Remote users can oversee the energy consumption and the temperature of the building under control;
– remote users can interact with the HVAC control system by setting the desired temperature of comfort.

4 A Loosely Coupled Integration between the IGMF and the ITESS

A loosely coupled integration between the IGMF and the ITESS and based on Web Services has been designed. In particular, Figure 4 shows a high level view of the IGMF and the ITESS where:

- the *IGMF Wireless Sensor and Actuator Network* layer represents all the WSAN nodes on which the IGMF is deployed;
- the *IGMF* layer represents the framework presented in Section 3.1;
- the *IGMF Manager & GUI* layer represents the access point to use the IGMF compliant WSAN;
- the *ITESS Gateway* is the one described in section 3.2, i.e. it contains the energy scheduler, the server and the database that permit the interaction with external systems;
- *ITESS WSAN* is the WSAN taking temperature measurements;
- *ITESS Ethernet Actuators* are a set of actuators that control the HVAC modules.

Both the *IGMF Manager & GUI* and the *ITESS Gateway* expose a REST interface and stream sensor data. The following subsections will show the main designed high level functions that both the IGMF and the ITESS expose.

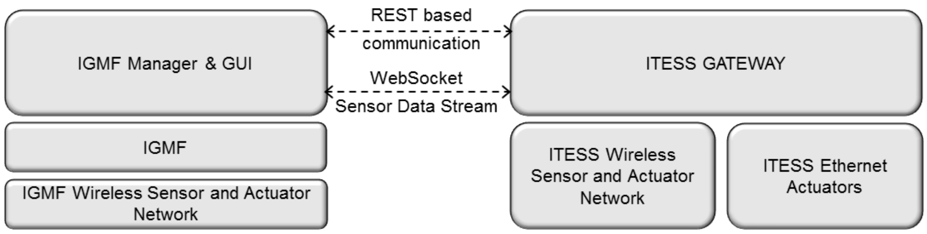

Fig. 4. Loosely Coupled Integration design between IGMF and ITESS.

4.1 IGMF exposed functions

The main designed high level functions that have been exposed by the IGMF to be integrated with the ITESS are shown in this section (see Figure 5). In particular, this functions have been partially introduced in [3]. In the functions the concept of *group* has been highlighted. Every node belongs to one or more groups. A group is a set of nodes sharing logical (e.g. a sensor on its board) or physical (e.g. the place where a node is placed) characteristics. Using group composition/intersection flexible set of nodes can be addressed all at once. This possibility is important in a complex environment such as the building one.

It is worth to be noted that most of the functions (except 4,5,9) return an acknowledgment if the message has been successfully sent to the WSAN. The functions are explained in the following:

1. Creates a new group starting from a list of groups and a set theory operator to combine them;

```
1)  GroupAck addGroup(GroupList, Operator)
2)  GroupAck modGroup(Group, ModifyMethod, GroupList, Operator)
3)  GroupAck delGroup(Group)
4)  GroupList getGroups()
5)  NodeList getNodes(Group)
6)  RequestAck scheduleSensorRequest(Group, SensorParams)
7)  RequestAck scheduleActuatorRequest(Group, ActuatorParams)
8)  RequestAck unscheduleRequest(Request)
9)  RequestList getRequests()
10) ResetAck resetNode(Group)
11) LoginAck login(User)
```

Fig. 5. The IGMF exposed functions.

```
1)  [EnergySchedulerAck,EnergySchedulerID]=setEnergyScheduler(GroupList, EnergySchedulerParams)
2)  EnergySchedulerList getEnergyScheduler()
3)  EnergySchedulerAck modEnergyScheduler(EnergySchedulerID, EnergySchedulerParams)
4)  EnergySchedulerAck delEnergyScheduler(EnergySchedulerID)
5)  IoTPlotID=newIoTPlot(data,FigParams)
6)  IoTPlotAck=delIoTPlot(IoTPlotID)
7)  LoginAck=login(User)
```

Fig. 6. The ITESS exposed functions.

2. Modifies a group according to a ModifyMethod (add/remove/update) and to a list of groups and a set theory operator to combine them;
3. Removes the group received;
4. Returns all the groups already created by the IGMF;
5. Returns all the nodes in a specific group;
6. Schedules a specific sensing task, configured according to the passed SensorParams, on a group;
7. Schedules a specific actuation task, configured according to the passed ActuatorParams, on a group;
8. Unschedule the received request;
9. Returns all the requests already running in the IGMF;
10. Resets the nodes belonging to the passed group;
11. Provides a login operation for the loosely coupled system.

It must be noted that the commands 1-10 can only be invoked by the coupled system (that owns specific rights).

4.2 ITESS exposed functions

In this section a list of high level functions, provided by ITESS, are presented. They allow the interaction of IGMF with ITESS. In figure 6 the complete list of the functions that permit the interaction is shown. In the following, the functions are explained in more detail.

1. Permits to define a new energy scheduler with comfort constraints for the set of nodes defined by "GroupList". The variable, "EnergySchedulerParams"

contains the parameters that characterize the energy scheduler, such as the temperature of comfort bounds, the energy cost definition or the energy scheduling interval.
2. Obtains a list of the energy schedulers that are currently active.
3. Modifies the parameters of the energy scheduler (specified by the "EnergySchedulerID" identifier).
4. Deletes, i.e. it stops, the activity of the energy scheduler (specified by the "EnergySchedulerID" identifier).
5. Creates a new IoT plot service. This will permit to plot the data measured by a group of WSAN nodes (managed within IGMF) into the device of a remote user (connected through ITESS).
6. Removes the plot associated to IoTPlotID.
7. Permits to login in a user. This allows him or her to use the previous described functions.

5 Conclusion

This paper has introduced a loosely coupled integration of the IGMF and the ITESS. The loosely coupled integration allows the systems to cooperate and interoperate without hardware or software dependencies. In particular, the systems have been integrated through sets of functions that have been exposed through REST interfaces.

Future work will be devoted to the real implementation of the presented loosely coupled integration and on the definition of a tightly coupled integration between the IGMF and the ITESS.

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