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Towards a software infrastructure for district energy management

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Abstract— **Nowadays ICT is becoming a key factor to enhance the energy optimization in our cities. At district level, real-time information can be accessed to monitor and control the energy distribution network. Moreover, the fine grain monitoring and control done at building level can provide additional information to develop more efficient control policies for energy distribution in the district. In this paper we present a distributed software infrastructure for district energy management, which aims to provide a digital archive of the city in which energetic information is available. Such information is considered as the input for a decision system, which aims to increase the energy efficiency by promoting local balancing and shaving peak loads. As case study, we integrated in our proposed cloud the heating distribution network in Turin and we present exploitable options based on real-world environmental data to increase the energy efficiency and minimize the peak request.**

Keywords—Internet of Things; Ubiquitous Computing; Pervasive Computing; Middleware; Distribution Network

I. INTRODUCTION

One of the challenges in today's economy and research aims in converting our cities into *Smart Cities*. In this field one of the main topics is the reduction of energy waste and CO_2 footprint in the energy distribution network as well as single buildings and houses [1]. Nowadays, thanks to ICT it is possible to access real-time information about building environmental characteristics and energy consumption [2]. At district level, information about district heating/cooling and electricity grid can be also accessed. Hence, ICT is recognized as being a key player against the energy waste. Indeed pervasive devices can efficiently control the whole energy chain from the single apartment up to the whole distribution network. Moreover, middleware technologies enable common interfaces to monitor and control devices such that these heterogeneous sources of information can be put together in a common decision system. On the other side, ICT revolution in Building Information Modelling (BIM) [3] enables digital organization of building characteristics and parameters. Hence, putting together all this technologies and correlating the resulting information, it is possible to have a complete overview of the energy consumption in the whole city in order to design efficient energy policies.

Following this view, we propose a distributed software infrastructure, which targets to make a Cloud digital archive for energy management in the district. It aims to share environmental information coming from pervasive devices deployed in buildings and energy distribution networks across the district. To achieve it, the Cloud is based on a service-oriented middleware, which allows the interoperability between heterogeneous hardware and software technologies. In addition to environmental data, it shares structural characteristics and parameters about buildings (BIM) and energy distribution networks providing also their virtual models. This structural information, enriched with real time monitoring data, can be accessed and exploited to: i) profile the energy consumption from the district point of view down to the single building; ii) design more efficient control policies; iii) increase energy user awareness. Finally, as case study, we integrated in the proposed Cloud the information coming from the heating distribution network in Turin, and based on this real-world information, we present some solutions to increase the energy efficiency minimizing the peak request.

The rest of this paper is organized as follows. Section II reviews some background literature. Section III presents the proposed software infrastructure. Section IV analyses three exploitable options to increase the energy efficiency in the district heating networks. Finally Section V reports the concluding remarks.

II. BACKGROUND

In order to optimize the energy waste in the Smart City, a key challenge remains to achieve true interoperability between heterogeneous technologies and devices. Service Oriented Architectures seems to be promising along this direction [1], [4]. In the domain of Home Automation, Corno et al. have developed a *Dog home gateway* [5], built on the DogOnt *v1.0.3* ontology model [6], for the interoperation between various domotic devices. The ontology is designed to explicit representation of commands, accepted by domotic devices, and notifications, generated by suitable control devices.

Concerning the domain of Smart Building, the service-oriented middleware presented in [7], [8], [9], have treated the interoperability issue. *Socrades* [10], [11], [12] is a modular, adaptive and open infrastructure forming a complete Service-oriented Architecture ecosystem that will make use of the embedded capabilities. The infrastructure components are specified and it is shown how they can interact and be combined to adapt to current system specificity and requirements. In [13], Stavropoulos et al. present *aWESoME*, a web service middleware for Ambient Intelligent environment. It allows the interoperability between heterogeneous devices again to provide a system that enables automation and energy savings in large buildings. The event-driven user-centric middleware presented in [2], [20] aims to provide reusable distributed components to convert existing buildings into smart energy efficient buildings taking into account the user behaviour patterns. It also aims in integrating already deployed building automation technologies with new pervasive devices.

In Addition to research projects, OPC Unified Architecture [14] should be noted as an example of an integration effort for the most common wired standards, such as SCADA or BACnet. However in the Smart City context, this still is not enough, indeed it must be open to any kind of other commercial technologies both wireless and wired.

We propose a distributed software infrastructure based on a service-oriented middleware for district monitoring and management. It aims to enable the interoperability across heterogeneous devices, both wireless and wired, in order to access and share heterogeneous information related to energy distribution systems, buildings and apartments in the district. In addition to environmental data, the Cloud also stores information about the virtual models of buildings and district systems. The purpose is to provide a digital archive of the city in which energetic information is available. This information can be exploited to characterize the energy consumption profile from the single building to the whole district in order to design more efficient control policies. In addition the software infrastructure provides a set of API to develop application to increase user awareness.

III. DESCRIPTION OF THE SOFTWARE INFRASTRUCTURE

The proposed solution, exploiting a distributed approach, aims to make a digital archive of energetic information, structural characteristics parameters about buildings and district systems. The resulting Cloud for the district energy management enables the communication across the different actors and components exploiting a distributed service-oriented middleware.

The rest of this section describes in more detail both the middleware infrastructure and the Cloud for district energy management.

A. Middleware infrastructure

The design of the proposed middleware has its roots in the LinkSmart middleware, whose basics are presented in [15]. LinkSmart is a generic service-oriented middleware for ubiquitous computing, which allows an easy integration of heterogeneous technologies and enables a hardware independent interoperability between them. Figure 1 schematizes the proposed middleware, which consists of three layers: i) *Integration Layer*, ii) *Middleware Layer* and iii) *Application Layer*.

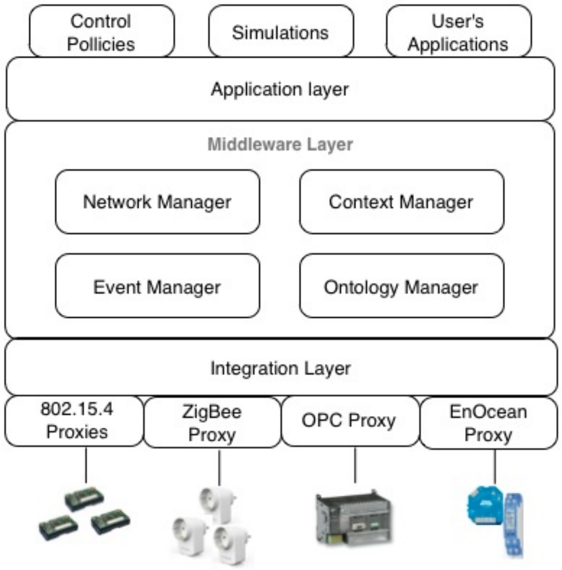

Figure 1. Middleware Infrastructure

The *Integration Layer*, which is the lower layer, is in charge to enable the interoperability across heterogeneous sources, both hardware and software. To achieve it, we started from the concept of LinkSmart's proxy, which describes the integration of a specific technology into LinkSmart. It abstracts a certain technology, device, network, or subsystem to web services. A proxy acts as a bridge between the middleware network and the underlying technology. It translates whatever kind of language the low-level technology speaks into LinkSmart web services; thus, the low-level technology can be used transparently by any other LinkSmart component. In particular we developed proxies to integrate wireless technologies [16], such as IEEE 802.15.4, ZigBee and EnOcean. Moreover, about wired technologies, it has been developed a specific proxy to allow the interoperability with the OPC Unified Architecture [14], which incorporates all the functionalities provided by different standards, such as SCADA or BACnet. It is worth noting that, thanks to the service-oriented approach, the proxy can also integrate into the middleware third-party software. So it should not be considered only as a bridge for hardware technologies but also for other software.

The *Middleware Layer* is in charge to enable a peer-to-peer communication across the different entities in the middleaware network. Web Service calls are routed through the Network Manager, which creates a SOAP tunnel to the requested service endpoint [17], and making a direct communication between the entities, regardless of firewall or NAT (Network Address Translator). In addition, the middleware exploits also a publish/subscribe approach [19] implemented in the Event Manager. It allows the development of loosely-coupled event-based systems removing all the explicit dependencies between the interacting entities. The Context and Ontology Managers are two complementary components, which together manage semantic knowledge about the application domain and the implemented system. This includes meta-data about sensors

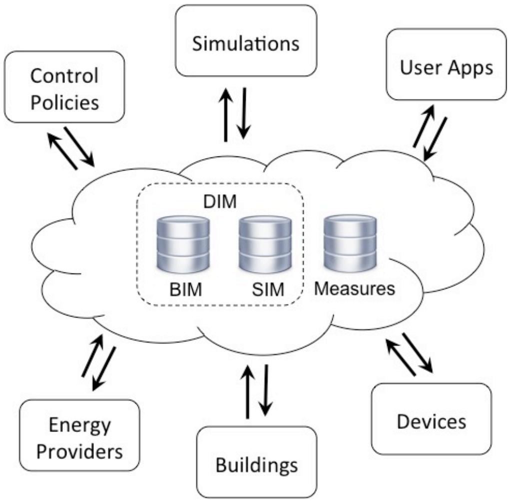

Figure 2. Cloud for District Energy Management

and actuators but also their relation to domain model objects such as appliances, grid's substation or buildings.

Finally, the *Application Layer*, which is the higher layer, provides a set of tool and API (Application Programmable Interfaces) to develop remote application:

- for simulating the energy consumption from the whole district to the single building, which can have as inputs both virtual models of the district and real-time information from the pervasive sensors.
- for implementing control policies to enhance the energy demand and to optimize the energy consumption from the whole district to the single building or apartment;
- for energy suppliers and facility managers to monitor and maintenance of the distribution network;
- to make district habitants aware about the energy consumption and promote green and energy-friendly behaviours.

B. *Cloud for District Energy Management*

The middleware presented in Section III-A has been exploited to make a Cloud infrastructure to share heterogeneous information about the district. It can also be considered as a distributed "smart" digital archive unique for the district to give support for the strategic plan of the city and to improve user awareness. Figure 2 summarizes the schema of the proposed Cloud, highlighting also the information flow from the devices (sensors and/or actuators) to the applications and vice versa.

Thanks to the middleware approach based on proxies, in order to enable the interoperability between heterogeneous devices, different actors can easily share information about the state of the district. Hence, as shown in Figure 2, energy providers, building managers or house-owners can share their information respectively about the state of distribution networks, buildings and houses uploading them in the Cloud. All these information are stored in specific databases that are part of the Cloud itself. It manages and stores the information in two classes of databases (DB). The Measurement DB collects all the real-time or near real-time environmental data about the district. Instead, the BIM and SIM DBs store respectively the virtual models of buildings and systems, such as distribution networks, in the district. We called District Information Modelling (DIM) the integration and correlation of both BIM and SIM models. All this information is available to the applications that can be developed again exploiting the API provided by the middleware's *Application Layer*.

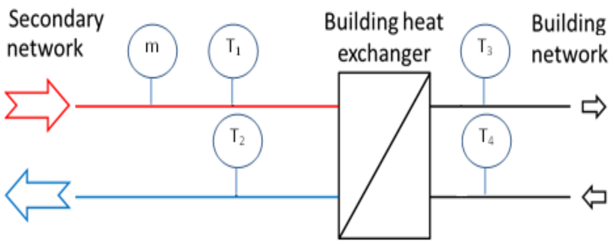

Figure 3. Schematic of the measurements at the heat exchanger in a thermal substation

IV. CASE STUDY

A. *Heating distribution network in Turin*

As case study we selected a district in Turin, in which is present a Heating Distribution Network (HDN) that covers the whole city. Iren, who is the heating energy provider, produces the hot water to heat up the buildings with three heating power plants in the city. The hot water is sent to the buildings through pipelines of the HDN deployed across the city. Then, each building is equipped with a building heat exchanger (Figure 3), which connects the building heating system to the HDN. To monitor and manage the HDN, Iren developed a platform for grid data collection, deploying in each building a Central Unit (CU), which locally collect information form the devices already deployed in the building, such as the temperature sensors in the exchangers. Then it sends this collected information to the Iren databases via Internet.

A preliminary integration of the Iren platform into the proposed software infrastructure has been done at server level. So a specific proxy has been deployed in the Iren database to share in the Cloud its information and make them accessible at the *Application Layer* as described in Section III.

B. *Increasing Energy Efficiency in District Heating Networks*

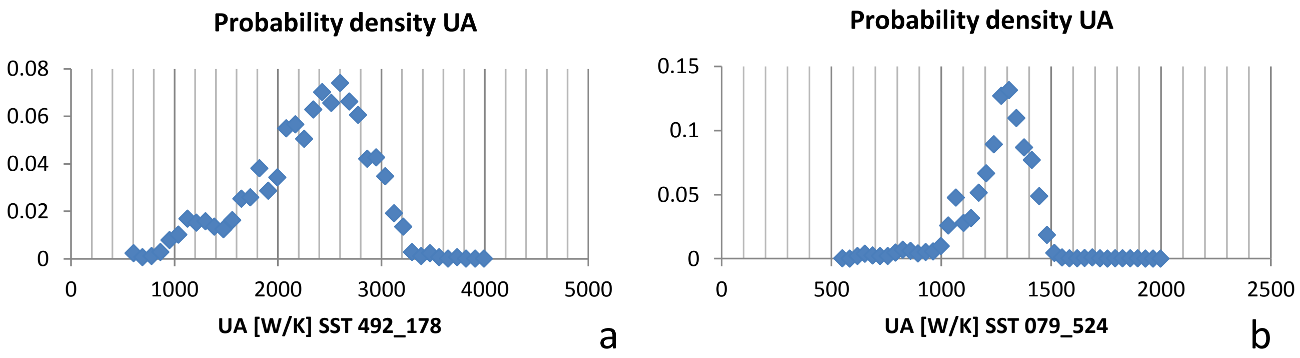

Figure 4. Evaluation of the product UA for the two heat exchangers

Once the information about the HDN is available in the Cloud it can be used, together with data coming from other pervasive sources, to estimate and simulate the energy consumption in the district in order to minimize the waste. In the following, exploiting the real world data for the HDN we analysed how to increase the energy efficiency in the district heating networks. One of the possible options consists in flattening the thermal load diagram of the plants. As a result, the percentage of heat produced through CHP plants, waste heat or renewable systems increases. Such result can be performed by acting at building level, through installation of local storage systems or by modifying the time profile of the thermal request (anticipating or postponing the moment the heating is switched on and off).

To evaluate actions performed in the buildings, thermodynamic quantities should be collected at three different levels: 1) heat exchanger, 2) building, 3) district heating network. First the status of the heat exchanger is evaluated. This refers to the degree of fouling, which affects the energy performance. In fact fouling causes increase in the water temperature exiting the heat exchanger on the HDN side, therefore lower efficiency of the thermal plants. In addition, effective implementation of some of the actions that are discussed hereafter requires efficient heat exchangers.

Heat exchangers in the district heating network are equipped with appropriate sensors (see Figure 3) to measure the water mass flow rate that is supplied to the user on the secondary network together with three temperatures: the inlet (T1) and outlet (T2) temperatures on the secondary network and the inlet (T4) and outlet (T3) temperatures in the building network.

The heat flux Φ that is requested by the user is obtained assuming the heat losses in the heat exchanger as negligible:

$$\Phi = m \cdot c \cdot \left(T_1 - T_2\right)$$

where c is the water specific heat. The fouling grade of the heat exchanger can be evaluated starting from the analysis of the heat exchange at the substation, namely given by the product of the heat transfer surface A times the global heat transfer coefficient U, which is calculated as:

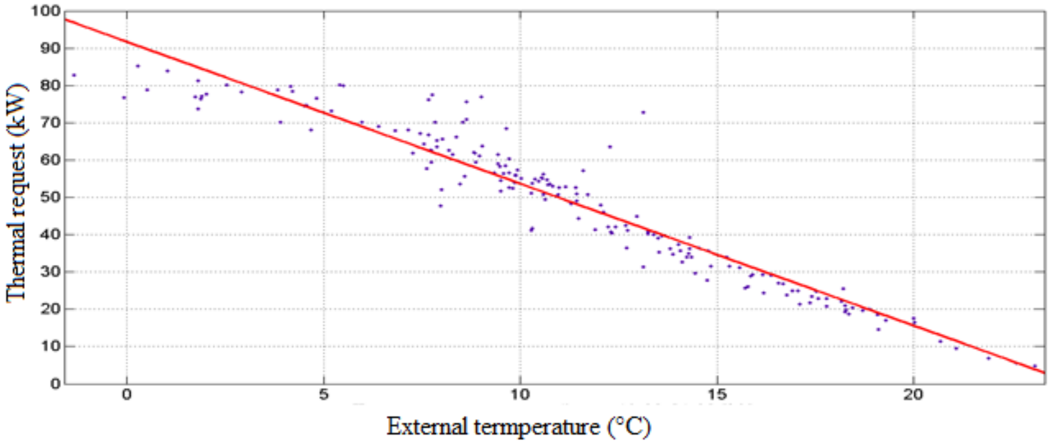

Figure 5. Thermal request profile of a user

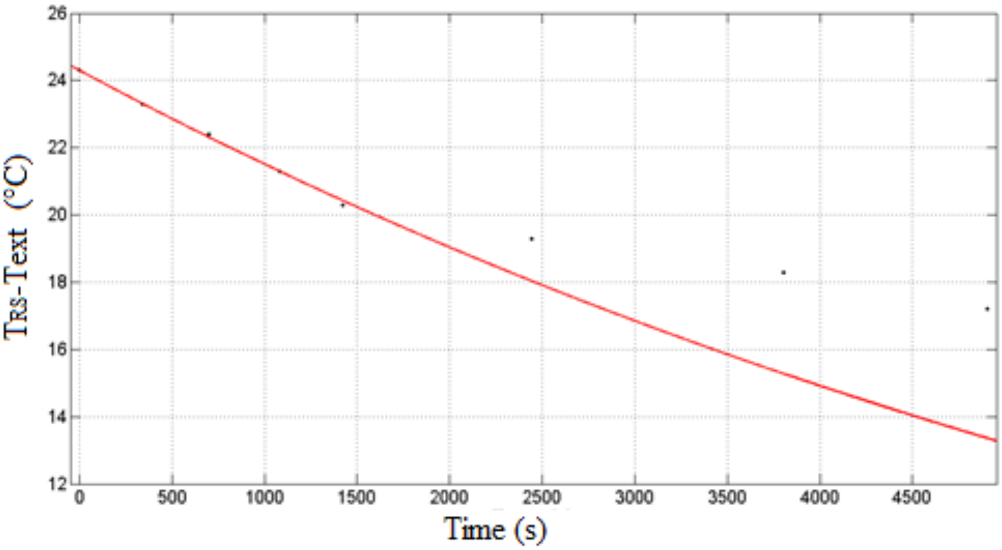

Figure 6. Transient behavior of the system

$$UA = \frac{\Phi}{\Delta T_{m,\log}}$$

where

$$\Delta T_{m,\log} = \frac{(T_1 - T_3) - (T_2 - T_4)}{\ln \frac{(T_1 - T_3)}{(T_2 - T_4)}}$$

The evaluation of the terms UA for two similar users connected with the network for the purposes of assessing the effect of potential fouling in the heat exchanger is shown in Figure 4. User ***a*** is characterized by a larger nominal thermal request (about 20% larger) than the user ***b***, but the product UA is about double. This can be justified by fouling in the heat exchanger of user b.

The second evaluation concerns the thermal behaviour of the buildings connected with the network. This is crucial to implement possible variation in the heat request profile. Buildings can be characterized in terms of global heat transfer coefficient and time response constant. An evaluation of the thermal distribution inside some of the buildings will be also performed and will be related with the geometry of the buildings. These pieces of information can be included in a compact model of the buildings. The average temperature in the buildings can be modelled as:

$$\Phi - kV(T_{in} - T_{ext}) = cV \frac{\partial T_{in}}{\partial t}$$

where k is the global heat transfer coefficient of the building k that should be evaluated and V is the building volume. Figure 5 shows a linear correlation between the external temperature and the thermal request in the afternoon, which can be used to evaluate the global heat transfer coefficient.

Transient behaviour of the buildings can be evaluated when the heating system is switched off. Figure 6 shows the evolution of the difference between fluid temperature in the building network returning to the heat exchanger and the external temperature. Using these pieces of information, it is possible to evaluate the effects of changes in the thermal profiles on the average internal temperatures. This is crucial in order to check the impact on the comfort conditions. At this level of information, it is possible to guarantee the same comfort level when the same value of the average internal temperature is kept. Additional information may be gathered from sensors installed in the buildings, which make it possible to evaluate what are the temperature differences between the various areas in a building.

Last evaluation is performed by using a model of the district heating network [18] to calculate the thermal demand of the plants from the thermal request of the users. The use of a model is necessary since the thermal request of the users and the thermal demand for the plant differ, mainly because of the time delay provoked by water flow in the network and mixing effects between the various streams. The inputs of the model are the temperatures and mass flow rates at the users. Measurements of mass flow rates along the network are necessary since not all the users connected with the networks are currently monitored.

V. CONCLUSIONS

In this paper we presented a software infrastructure, which aims to make a cloud digital archive of energetic information and virtual models about buildings and district systems. This information can be considered as the input for a district decision system, which aims to increase the energy efficiency of the district itself. Moreover, thanks to the exploited service-oriented approach, it enables the communication across different actors and devices in the district.

Finally, as case study, we presented the integration in our proposed cloud of the heating distribution network in Turin and we also presented exploitable options to increase the energy efficiency and minimize the peak request.

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