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Intelligent energy management in residential buildings with a real-time control & wireless meter-recording system

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***Abstract*—Industrial evolution brings major new challenges due to increasing energy demands. This phenomenon encourages the improvement of control methodologies that reduce resource requirements. Lately, it has been observed that the building sector contributes considerably to final energy demand. Consequently, studies have been conducted on the technical systems and solutions applied in this sector to the intelligent management of energy. Our work focuses on the smart control of energy management systems to monitor operation of electrical equipment. This paper starts by addressing the structure of the control system in buildings, which involves the connection of equipment, to enable communication with each other, and the integration of micro-sensors to enable automatic control of meter-recording systems. We then present an application for a heating control. This application uses a new real-time control method that allows peak consumption to be reduced while maintaining thermal comfort. It is based on wireless sensor network (WNS) technology which offers simultaneous measurement, and an interoperable communication network for the control method proposed. This method is tested and the results demonstrate the outstanding quality of its capability to control heating load and to adapt to any problems that may arise (by taking into account changing price, signals from energy provider and distribution system operator, etc).**

Index Terms - Smart Home, WNS, Building Energy Management System (BEMS), HVAC equipment, Machine-to-Machine (M2M).

I. INTRODUCTION

In recent years, energy demand in the residential and tertiary sector (buildings) has become a crucial issue. For example, electricity used in France by this sector has reached 284TWh, accounting for 65% of all electricity consumed in 2007 (434TWh) [1], and this situation continues to increase. Moreover, the link between increased CO_2 emissions and the use of energy is also considered, particularly in the building environment. 404 million tones of CO_2 gas is emitted in France, and 22.6% originates from this sector [2]. Furthermore, the sector of the building presents one of the greatest potentials of energy efficiency and reduction of the gas emissions. Therefore, an enormous research effort is being made into improving energy use, in order to reduce energy consumption and greenhouse gas emissions.

For energy management systems in the building sector, the aim is to modify the behavior of electrical loads, usually domestic appliances or commercial/industrial facilities, in order to meet established targets for load management. In the light of developments in microelectro-mechanical systems (MEMS), along with progress made in communication and embedded smart sensors, the residential sector has a huge potential for mitigating demand. The possibilities of creating networks between home appliances, sensors and wireless media, enable the control of domestic equipment locally or remotely via the Internet.

This paper deals with techniques and advanced load management strategies for BEMS. First, we present the architecture of this system that exploits several communication techniques. We then describe an application for a heating control, which implements an innovative real-time control method. The method proposed is based on the architecture described previously. Our experiment results demonstrate that the proposed method is able to control heating loads to adapt with new contexts.

II. ARCHITECTURE OF ENERGY MANAGEMENT SYSTEMS IN BUILDINGS

In general, management systems comprise at least the following items: sensors to measure control variables; a controller able to carry out logical control operations or to provide control signals; actuator devices which accept the control signals and perform actions. Such an energy management system is presented in the figure (Fig.1).

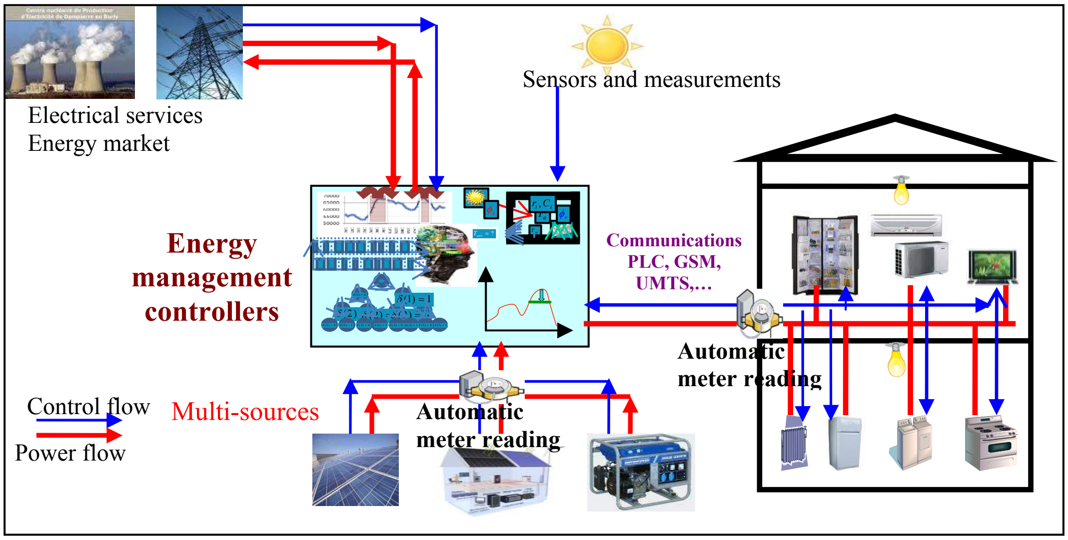

Fig.1. Energy management system

Controllers are typically computing elements which implement the load management strategies via the control programs installed inside. The sensors take measurements which constitute the principal source of information. Furthermore, to a certain extent, energy estimation models can be used instead of direct measurements, but these models are generally based on measurements.

Management techniques implement communication technologies and play a major role in enabling building-wide control. The communication protocols establish links between devices and transfer interoperability functions, so that the devices can send information and implement a control function. Load management strategies, communication and measurement all play an important role in this system.

A. Load management strategies

In the building environment, energy consumption is a complex function depending on climatic conditions, behavior and system characteristics such as home architecture, level of insulation, and type of equipment used (heating, ventilation and air-conditioning -HVAC), etc. Energy consumption is variable and can sometimes generate serious failures (congestion, energy demand peaks, etc), influencing the electrical network and affecting user interests. In this context, research into intelligent load strategy can be divided into two areas of operation:

- Firstly, ***preventive control methods*** are frequently applied to systems in which failures occur when demand load is low or moderate. They are based on anticipative optimal control, keeping the total demand power below a certain predefined limit. To implement this strategy, the loads are divided into homogeneous groups. Electrical equipment is controlled by one group. Control systems and technologies can anticipate load changes and make adjustments [3]. The formulation of this strategy can be treated as an optimization problem. An objective function will be established and must be resolved under the constraints defined. Algorithms can be formulated using Linear Programming (LP), Non Linear Programming (NLP), or dynamic programming, etc [4-7].
- Secondly, ***real-time control methods*** are frequently applied in situations where failures occur during consumption peaks. The objective is to develop a method for controlling electrical alliances, which can react quickly according to total permissible power limits. This algorithm is implemented through a "specific-equation" which gives an image of system behavior in real-time. This program is coded and executed for each time step to identify the current behavior of the system. At each time step, the system is regulated by a set of rules corresponding to its current behavior [8, 9] .

B. Measurement for load management

Information on energy flows and system states is captured for the management system. Based on the data measured, control programs can make adjustments, analyze patterns of use and anticipate changes in load demand in order to achieve the desired load management objectives.

Measurement needs are many and depend on the management strategies implemented. Measurements must be carried out under different conditions, corresponding to the various objectives, as listed in [10]:

- Billing: billing depends on the price. Obviously, modern buildings have a certain production capacity. Consumption and the active power actually produced in real time must both be calculated. However, consumption and production must be measured separately because the prices are obviously different.
- Load forecasting/modeling and load monitoring: the aim of load forecasting/modeling is to create and update models developed from hourly curves. Active and reactive power must be recorded simultaneously. Models obtained by load forecasting depend on individual loads.
- Electrical services: measurements to assess power quality and detect electrical grid failures (for protection purposes).

- Control the end use of electricity: monitoring of electricity use often includes energy management, which controls and monitors loads. Measurement needs obviously depend on the control objective and power usage. Environmental variables, humidity, temperature, light, etc. usually fall into this category.

C. Communication systems

In general, the entire control application relies strongly on the communication network established between the system's components. There are three ways of communicating in energy management systems: power line communication (PLC), bus line communication, and wireless communication via radio frequency (RF).

1. Wireless communication:

Various wireless communication technologies are available for use in energy management systems, including GMS/PPRS network, Bluetooth [11], UWB[12], ZigBee [13], etc. In terms of communication range, wireless technologies can be classed into four categories:

- WWAN (Wireless Wide Area Network) uses mobile telecommunication network technologies, such as UMTS, GPRS, GSM, etc.
- WMAN (Wireless Metropolitan Area Network), such as the WiMAX network, is based on the IEEE 802.16 standard with transfer speeds of 1-10Mbps within a range of 4-10km.
- WLAN (Wireless Local Area Network) has an operating distance of about 100m. Wi-Fi (or IEEE 802.11) and HyperLan2 (High perform Wireless LAN 2.0) are the two most popular standards developed for WLAN communication
- WPAN (Wireless Personal Area Network) is intended for low rate data transmission and its operating frequency is usually 2.4GHz. Bluetooth, ZigBee are two of the most famous technologies using short range radio frequency for the transmission of voice or data, or simple information.

The advantages of this type of technology include:

- Elimination of all costs related to the physical connection of devices.
- Possibility of establishing a single communication interface between several devices, using a communication protocol supported by numerous manufacturers.
- Ability to automatically reconfigure the communication network each time a new element is added.

Buildings represent a challenging environment for wireless communications. Building materials can cause communication losses due to signal attenuation during radio propagation from a transmitter to a receiver.

2. Power Line Communication (PLC)

Power Line communication (PLC) is a popular technique based on the principle of superimposing a radio frequency band of 3 kHz – 30MHz over the 50Hz power frequency. This signal is spread over the existing electrical installation and transmits digital information. PLC is used in buildings to remotely control electrical devices without needing to install new wires [14]. The speed of these networks is 14-45Mbps for indoor environments and can reach 224Mbps for outdoor communication. The main problems related to PLC are signal distortion and signal attenuation through the network, caused by the interference from the electrical network and the electrical devices connected [15].

3. M2M (Machine-to-Machine) system communication

Utility players are now starting to take a more proactive role in the monitoring of their transmission and distribution grid. Solutions are required to meet the numerous challenges of this changing, innovative ICT (Information and Communication Technology). The increasing use of embedded technologies in smart devices and enhanced Internet connectivity have enabled the development of a new range of ICT systems, which integrate remote devices with IT applications[16]. These systems are referred to as M2M systems, defined as a mixture of distributed hardware and software components.

Basically, M2M systems rely on the concept of "distributed intelligence" and a "middleware software infrastructure" that provides reliable and secure communication facilities over heterogeneous networks as well as execution platforms for hosting services. M2M provides a comprehensive solution for the control and management of energy systems.

M2M systems have 3 categories of components:

- Devices, which may embed varying levels of computing intelligence to the connectivity facilities. Such devices may serve as control-points to manage a set of dumb equipment
- Telecommunication components, including convergent points (M2M gateways) between Internet and heterogeneous access networks (PLC, wireless networks).
- Application domains corresponding to IT servers (central and edge servers), running the various energy control and management services.

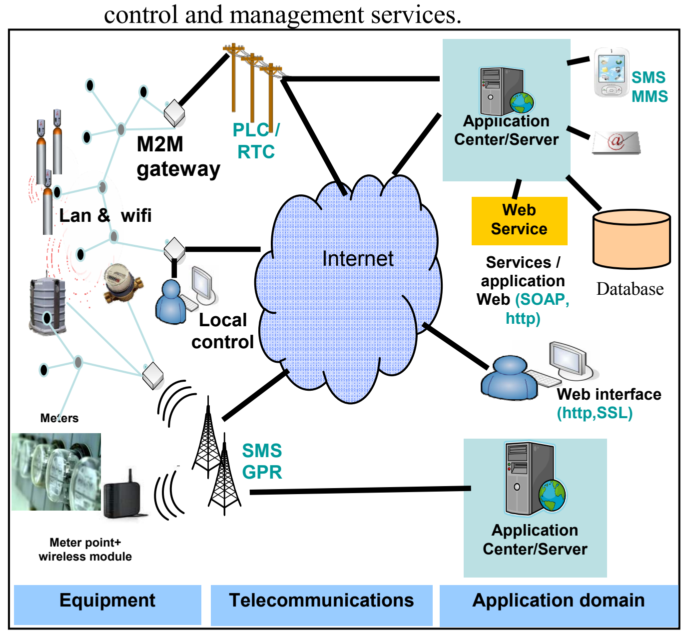

Fig.2. M2M architecture

III. EXPERIMENTAL WORK - APPLICATION FOR A HEATING CONTROL

Heating represents a controllable load and takes up a large proportion (43% on average) of all energy consumed in the building. Thermal loads are therefore suitable for the faster response applications for reducing energy consumption. Demand for electricity has been increasing and is expected to continue to do so in the coming years. A major issue for electrical grids is to maintain the balance between electricity production and consumption permanently and instantaneously. This has led to needs for energy customers to adapt dynamically to the instantaneous maximum authorized demand for power. The method presented here is in order to reduce peak load by maintaining comfort for users of electric heating facilities.

A. Hardware architecture

This application relies on a wireless sensor network (WNS) which allows simultaneous, real-time measurement of indoor temperature and power consumption. The ZigBee communication protocol is used between wireless temperature sensors and equipment.

This system comprises an array of wireless temperature sensors, a wireless electrical power sensor, radiators equipped adaptive controls, and a central control unit.

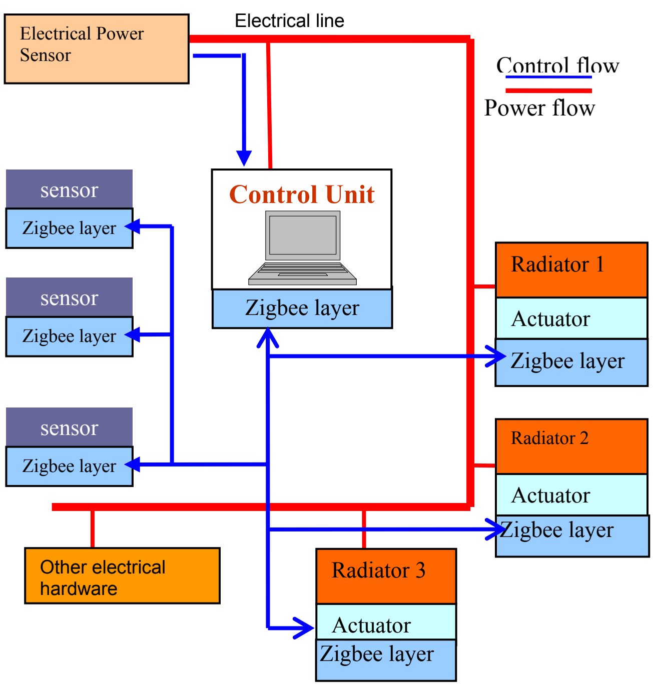

Fig.3. Demonstration system for heating regulation

The *Wireless Electrical Power Sensor* comprises two components: a power sensor and a communication unit. The first component is used to measure power consumption instantaneously. The communication unit transmits this information to the central control unit. The wireless electrical power sensor receives the consumption information and detects excessive power (beyond the authorized power limit).

The *Radiator with Wireless Adaptive Control* is a traditional radiator comprising an actuator and a communication unit. The actuator enables all control actions sent from the central control unit to the radiator. The radiator can therefore be remote controlled. This adaptive radiator comprises the follow components:

Name	Description
Radiator	Traditional radiator
Actuator	Implements control actions from the control unit
ZigBee layers	ZigBee layers for communication

Table.1. Components of an adaptive radiator

The *central control unit*: in our system, the control unit is a computer equipped with a wireless communication module and control software. The central control unit analyzes the information received. The central control unit processes the temperature and power measurements and makes decisions to control the radiators in an intelligent manner, maintaining comfort and keeping power consumption below the authorized power limit.

The array of *Wireless Temperature Sensors* is programmed to measure temperature within the building at all times. After collection, this information is transmitted to the central control unit via a ZigBee communication link.

B. Proposed method of control

Objective: choosing a reasonable energy contract enables financial savings. In France, each customer signs a contract with an energy provider. The energy provider offers customers a choice of maximum authorized power limits in the form of subscriptions. For example, EDF proposes various subscribed power thresholds: 6kW, 9 kW, 12kW, etc. to which different price.

The objective of our method is to decrease the maximum power limit, without losing thermal comfort in peak load period, in order to avoid congestion in power system or in order to reduce the energy purchase of an expensive energy.

We assume that:

- *T_int*: actual temperature,
- *T_max*: maximum temperature,
- *T_min*: minimum temperature,

With respect to temperature, T_max and T_min are modifiable.

The problem can be formulated mathematically as follows:

$$T_{\min}(i) = const$$

$$T_{\max}(i,t) = f(\Delta P, \Delta T, t)$$

$$T_{\min}(i) \le T_{\text{int}}(i,t) \le T_{\max}(i,t) \forall rooms$$

$$P(t) \le P\max \forall t$$

Control principle

If total power demand does not exceed contract power (known as permissible power), the control system operates like a traditional temperature control in order to ensure thermal comfort. This operation also acts like a traditional thermostat. Temperature is maintained so that $T\_\min \le T\_\text{int} \le T\_\max$.

If peak consumption leads to the permissible power being exceeded, our control system switches to the adaptive mode. This mode is based on a variable setpoint value of temperature to limit the consumption peak.

In brief, if we assume that there are only two radiators of respective powers P_1 and P_2, and authorized power is *P_auth*. Thermal comfort is maintained if *T_min* is not varied. When the system detects excess power consumption, this information is relayed to the central controller. The central controller converts it to a new temperature instruction in accordance with the required power reduction. This value is then applied for each radiator in order to modify temperature *T_max*. The principle of operation for this case is illustrated in Fig.4.

Using traditional regulation, maximum power is: Pmax = P1+ P2 >> P_auth

Using the proposed method, with the help of the variable T_max, which is the function of the exceeded power, maximum power becomes: P_max = P1= P2 << P_auth

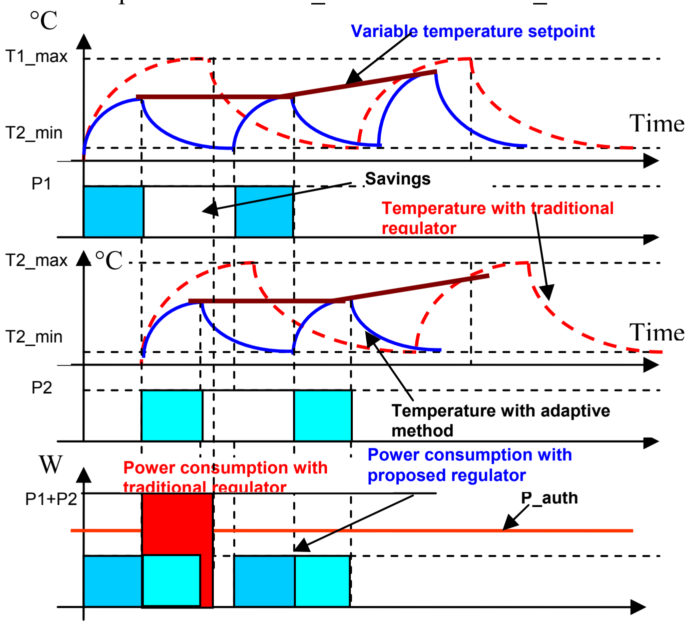

Fig4. Operation of the proposed radiator regulator

IV. Experiment Results & Discussion

A. Case study

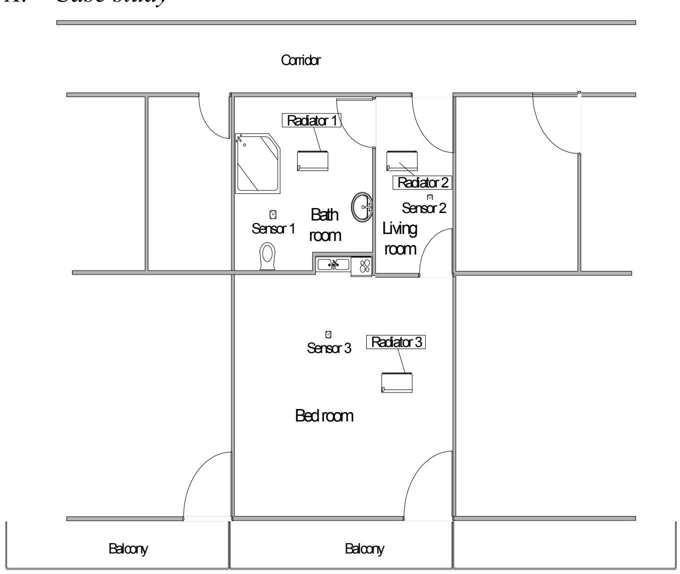

Fig.5. Plan of the apartment

In order to demonstrate the performance of the proposed method, a prototype system was developed and installed in an apartment. This apartment was heated by emissions from household appliances, the occupant, by solar irradiation and by radiators. We assumed that *Tmin* must be maintained at 20°C to ensure thermal comfort.

$P(t) \le P_{\max} \forall t$, with Pmax = 2700W

$T\min \le T\text{int} \le T\max$, with Tmin =20°C, Tmax = 22°C

The apartment consists of a bedroom, a living room and a bathroom. Each room is equipped a wireless temperature sensor and a radiator.

This apartment includes the following electrical appliances:

Equipment	Power
2 Radiators	800 W
1 Radiator	1900 W
1 Refrigerator	150 W
1 Computer	120 W
Total power	3770 W

Table.2. Electrical appliances of the apartement

B. Results & discussion

Figs. 6 and 8 show the total power of the apartment; and Figq.7 and 9 show interior temperatures in the three rooms (with traditional control and the proposed control method).

The results show that without load management, maximum power can reach 3770W (Fig.6), and comfort is definitely assured (Fig.7).

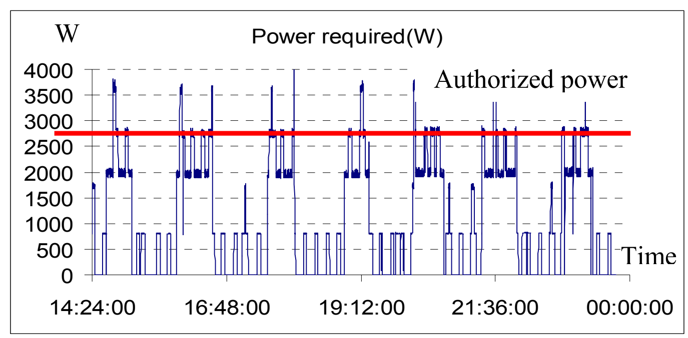

Fig.6. Power required with the traditional heating regulator

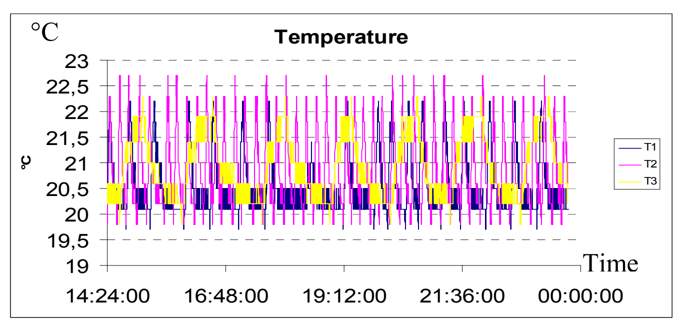

Fig.7. Interior temperature of the three rooms with the traditional heating regulator

To illustrate the advantages of the proposed method, we applied a 2700W limit for authorized power. Thermal comfort is maintained at all times, but *T_max* is adjusted according to the instantaneous power consumption.

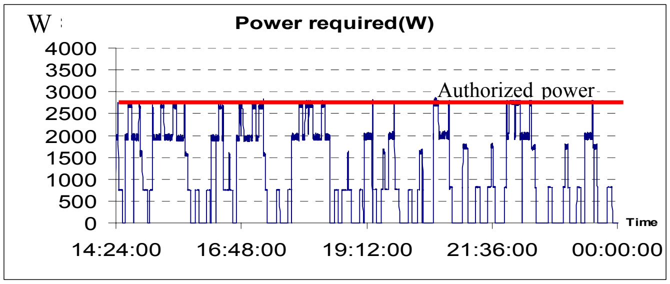

Fig.8. Power required with the proposed method

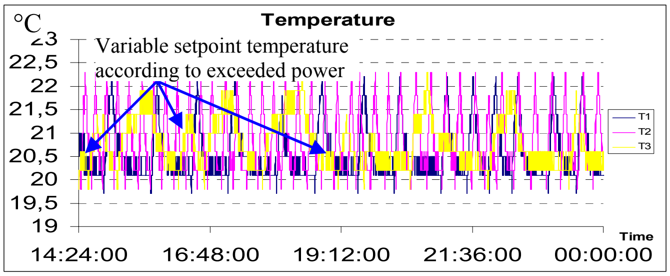

Fig.9. Interior temperature of the three rooms with the proposed method

These results indicate that:

- The proposed heating control allows a reduction in total power demand from 3770W to 2700W.
- Thermal comfort is maintained: the interior temperature of the rooms remains between 22°C and 20°C. With the proposed method, Fig. 9 shows that maximal temperature is variable, and minimal temperature is always maintained at 20°C.
- The reduction of contract power therefore results in a lower cost of subscription.

Temperature was regulated for the two cases over a 24-hour period (from 0h to 24h). The table below shows that the differences in energy consumption between the two cases are negligible.

	Tmin (°C)	Tmax (°C)	Consumption (kWh)	Pmax (W)
Traditional regulation	20	22	22.843	2700
Proposed method	20	22	24.84	3700

Table.3. Energy consumption between two cases

V. Conclusion

This paper presents an energy management system architecture, based on communication technologies, control strategies and measurements. It also presents a real-time heating management system for the residential sector. This system uses the wireless sensor network, ZigBee, and an adaptive mechanism. The experiment results show that this thermal control system enables to reduce peak load while maintaining thermal comfort. The real-time solution proposed can be applied to a load group in buildings in order to satisfy power constraints and reduce peak consumption.

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