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The EcoThermo project: key and innovative aspects

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Abstract

In this paper we present the most innovative aspects of the EC-FP7 EcoThermo project. The main aim of the project consists on innovating the technique of heat cost allocation in buildings with a centralized heating system, overcoming the heat cost allocator drawbacks for reliability, measurement reproducibility and traceability and contexts of applications. Given the complexity of the project, we will focus on its main aspects, such as the use of a virtual sensor to estimate the radiators heating power, the design of electronic valves fitted out with an energy harvesting system and the original wireless communication protocol.

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1. Introduction

In the last few years, energy management arose a great interest not only from an academic point of view, but also for practical reasons due to the increasing restriction on energy consumption in residential and tertiary buildings. Energy saving is nowadays necessary to reduce pollution and operating costs, while management of HVAC systems is aimed at maximizing user comfort and fairly rearrange cost distribution on actual consumption. In 2012 the energy consumption of the European Union (EU-28) was around 1100 Mtoe [1] 19.5% of which came from residential heating consumption. World Health Organization (WHO) estimates that about 2 millions of people a year die because of atmospheric pollution and about 50% of these could be referred to already industrially developed countries [2]. Another WHO study [3] correlates thousands of deaths, hospital confinements, bronchitis and other respiratory pathologies a year to the eight major Italian cities a high level of PM10 and other pollutants concentration.

EcoThermo system has been developed to create an innovative technology in the field of building automation with a particular application to heat cost allocation oriented to convert buildings provided with old central or district heating

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without flat-level indoor temperature control and without cost allocation based on the real heating consumption of each user. EcoThermo project pursued two main goals. The first one was to increase the energy savings to 18%-25% with respect to the poor 8%-12% of the traditional thermostatic valves, adopted in 98%-99% of cases. This aim was obtained designing an electronic valve that solves the drawbacks of all the already existing electronic valves. The second goal was to offer an innovative technique to improve the cost allocation accuracy with respect to the traditional heat cost allocator devices whose efficiency is worse than what promised by manufacturers, see e.g. [4] and [5].

2. System description and problems definition

The system proposed in the EcoThermo project ensures two basic functions not given by old centralized systems: the freedom for each user to set a desired and independent indoor temperature time profile; a cost allocation based on real heating consumption against a property volume allocation.

In general, measuring thermal energy conveyed by means of a heat carrier fluid is quite difficult and therefore an accuracy around 5% is considered good. Metering devices that can ensure at least such an accuracy are called heat meters; they measure the three physical quantities directly involved in the heating process: exchanger inlet and outlet temperatures and fluid flow rate. This type of metering devices cannot be used to allocate cost in old buildings characterized by a vertical distribution circuit for which they have to be installed one for each radiator: there is not enough room to host the flow meter and the meter costs too much and has to be replaced typically every 7 years due to limescale formation in its probe. This determined the success of another metering device called Heat Cost Allocator (HCA) that performs indirect estimates of heating energy by measuring radiator surface and surrounding air temperatures. Accuracy and reliability of HCA devices are not as good as heat meters, see e.g. [4] and [5], and this could be a source of controversies that are difficult to be solved. Another drawback of HCA is the need to dispose and rebuy these devices due to the fact that their batteries are welded to the electronic Printed Circuit Board (PCB).

Dealing with indoor temperature control, thermostatic valves are used in 95% of cases. The drawback is that they do not promote a virtuous usage of the system and major savings obtainable with daily temperature setting according to occupancy patterns. Electronic valves allowing an easy on/off switch operation or even a programmable temperature profile definition exist, but they are seldom used due to their too high cost and too quick discharge of batteries.

Furthermore, a general drawback of these traditional systems is that they are not building automation systems, on line and real time controllable. Moreover they cannot be integrated with the building functions and plants to decrease the maintenance costs of building administrators and heating contractors.

EcoThermo does not use HCA, thus halving the number of devices per radiator and reducing the installation cost. An innovative electro-mechanics of the valve drastically reduces the consumption per each actuation to less than 1 J letting its batteries stand for 4-5 years. To increase accuracy it has been designed and internationally patented an innovative metrology procedure to refer heating energy transfers to directly involved physical quantities, similarly to the heat meters, without the need to install a flow meter per each radiator. Two temperature probes are clipped on the inlet and outlet radiator pipes and are managed by the EcoThermo electronic valve that samples and logs the measured figures. The flow rate of each radiator is estimated by a virtual sensor having as inputs just the plant global flow rate measured by a high accuracy electromagnetic flow meter and the knowledge of the radiators open/closed state. The accuracy of this technique has been tested in a Thermal-Fluid-Dynamic MockUp (TFD-MU) built at Istituto Nazionale di Ricerca Metrologica (INRIM) provided with 40 radiators, a central heater and a set of 4 high accuracy sensors per each radiator: two temperature sensors, one electromagnetic flow rate meter and one differential pressure sensor.

To represent a given heating system the installer has to draw by means of an easy tool the hydraulic circuit topological scheme and to launch an automatic identification procedure to evaluate all the equations constants of a suitable mathematical model. The complex non-linear mathematical model of the flow Virtual Sensor (VS) runs on a remote server and this implies that a huge flow of rough data shall be continuously uploaded from the end devices to the remote server. Moreover this issue requires to fulfil other challenging system requirements, such as: real time commands to be sent on the opposite direction from higher level devices to end devices; management of batteries powered devices that are sleeping for the 99.9% of time; mobile devices handover; complete on air collision-proof; self-configuring; data redundancy; high data rate on SRD bands, because only narrow sub-channels are available. This brought to design an innovative protocol on SRD bands named wiNET because no one of the existing protocols could satisfy the communication needs, functional and performance requirements of the EcoThermo system.

3. Virtual sensor

As stated in the previous Section, a soft or Virtual Sensor (VS) was developed to estimate the water flow through each single radiator. In the last years, VS started to be used in building management, see for example [6] for a general survey and specific building applications, [7] for a flow meter application to a central cooling plant and [8] for power consumption and cooling capacity applications of a rooftop unit. The VS model requires as inputs the current total water flow measured immediately downstream to the boiler and the current opening state of every radiator valve. The electronic Body Valve Actuator (BVA) switches between two valve states: completely open or completely closed. Date and time of every actuation is logged and available to the EcoThermo procedures. The VS is based on a flow distribution solver that adopts a mathematical model of the structure and of the characteristics of the hydraulic plant. The solver output is an accurate estimation of the fluid flow rate through each radiator.

The development of the EcoThermo VS procedure is based on a Hardy-Cross like algorithm that needs head loss parameters for each pipework stretch and it uses the energy conservation law over a closed loop and the mass conservation at each network node to solve the hydraulic network and compute the flow through each branch. In general, for turbulent flow, the head loss ΔP of a hydraulic element is an exponential function of the flow Q and can be represented as $\Delta P = kQ^n$, where k is a parameter proportional to the physical characteristics and n is the exponential factor. An automatic identification procedure has been developed to find the equation parameters pairs, k and n, that fit at best the series of (ΔP, Q) couples sampled for every hydraulic branch. This identification procedure is necessary to represents the physics of each different hydraulic circuit. The procedure has been developed upon a novel approach based on a system of equations, the mass and energy conservation laws and a Levenberg-Marquandt iterative solver to find the optimum solution. It requires to perform a set of flow measurements with a small number of open radiators, usually two or three, in order to identify the branch parameters of their hydraulic subsystem. Repeating these operations for the hydraulic subsets that cover the entire circuit brings to the identification of the whole plant.

It is worth to note that this identification procedure needs to be executed only once in the heating system life or, taking into account plant ageing or modifications, can be, for example, repeated before each heating season beginning. Moreover, the identification procedure needs only to circulate cold water, thus it can be performed during the warm season without interacting with the normal plant operation.

Once all the branches are characterized by the couple of head loss parameters k and n, it is possible, by means of a flow solver, to estimate the flow in each branch necessary for the heating cost allocation procedure that estimates the heating energy released by each radiator.

Both the identification and the heating cost allocation procedures have been tested on the INRIM TFD-MU. Considering, for the sake of simplicity, two columns of the TFD-MU feeding two different radiators for each one of the four floors, the typical obtained accuracies are reported in Table 1. The relative error on the flow rates Q, in percentage, is small and always less than 4%.

Table 1. Flow estimation results.

	Measured Q (l/h)	Estimated Q (l/h)	Error (%)	Measured Q (l/h)	Estimated Q (l/h)	Error (%)
Floor 3, radiators N4 & N5	68.75	66.16	3.76	64.17	62.85	2.07
Floor 2, radiators N9 & N10	78.43	77.22	1.55	67.30	67.51	0.31
Floor 1, radiators N14 & N15	115.32	117.58	1.96	94.94	93.43	1.58
Floor 0, radiators N19 & N20	193.74	197.07	1.72	157.41	158.25	0.53

4. Harvesting system

For traditional conversion systems, based on HCA devices, energy consumption becomes a problem for both the metering and temperature control functions. The metering HCA devices, in fact, have welded batteries obliging to waste 15-18 million devices and primary lithium batteries every year. The electronic valves, that perform actuations to control the indoor temperature, discharge their batteries too quickly, often in less than one year, creating a not affordable users support requests rate.

EcoThermo fixed at first this last issue designing a low energy consumption electronic valve mechanism that increases batteries duration to 4 - 5 years. Besides, a harvesting self-recharge system has been designed and tested to make the electronic valves independent from any need to change batteries. Several techniques have been considered

and tested. A micro turbine in the body valve is affected by limescale issues; mini solar cells are not usable due to insufficient direct light in proximity of the radiator; Peltier cells do not generate enough electric power with small differential temperature, radiator surface-air in this case. On the contrary, pressure variations in the hydraulic fluid can be suitably exploited, see for example [9] and [10].

Following this idea, a promising technique, that has been internationally patented, consists in inducing a periodic pressure variation in the whole hydraulic circuit by a piston in proximity of the central boiler and converting this periodic pressure variation into alternate current in proximity of each radiator body valve. The latest operation has been done by a piezoelectric layer; the induced variations frequency was 5 Hz to avoid any noise and the amplitude was around 0.3 bar. Tests performed on a piezoelectric layer 40 mm length, 9 mm width, 0.5 mm thin, glued on a longer spring steel strip gave the results presented in Table 2. The minimal needed power, 2 mW, is reached with 2 mm amplitude oscillations if the electric load was 40 kΩ, 1.5 mm with 120 kΩ and 1 mm with 195 kΩ.

Table 2. Harvesting device power results.

Load 40 kΩ				Load 120 kΩ				Load 195 kΩ			
Displacement (mm)	Voltage (mV)	Current (mA)	Power (mW)	Displacement (mm)	Voltage (mV)	Current (mA)	Power (mW)	Displacement (mm)	Voltage (mV)	Current (mA)	Power (mW)
0.49	87.33	2.17	0.19	0.49	250.4	2.09	0.52	0.49	382	1.96	0.75
0.99	181.1	4.5	0.81	0.98	365.1	3.04	1.11	**0.95**	**627**	**3.22**	**2.02**
1.54	218.3	5.42	1.18	**1.53**	**508**	**4.23**	**2.15**	1.55	817	4.19	3.42
1.99	**291.4**	**7.24**	**2.11**	2.1	625.5	5.21	3.26	2.07	972	4.98	4.85

5. Wireless protocol

In the system, two sensors per radiator and one sensor per control area are used to periodically acquire temperature data to perform the EcoThermo heating cost allocation and to control the indoor temperature of each living unit independently. Besides, the system needs to log and transmit other type of events-data representing the actions made by the end user and the devices status, such as batteries level, percentages of occupied memory, radiator valve opening states, off-nominal states, tampering attempts, etc. Moreover, the entire system is real-time remote controllable and so it has to ensure prompt wireless communication on both the directions, upstream and downstream. The network infrastructure must also guarantee communications between up to 65000 devices, sharing the same physical layer, wireless or cabled avoiding any on-air transmission collision. All these requirements represented a challenge in the development phase: none of the existing technologies, such as ZigBee, could satisfy them. Therefore an innovative protocol, named wiNET, has been developed to fulfil specific requirements: automatic network configuration; simultaneous communication between different devices over different communication channels with no transmission collisions, the cells are organized in a frequency-time framework; higher throughput level than the existent standard; advanced management of battery powered devices, which are in standby for the 99% of time; automatic handover management of system embedded mobile devices; automatic management of missing links and signal losses; automatic retrieving of logged event data with multi-device data redundancy and 100% probability of reception.

The above mentioned requirements affected the functional architecture of the whole communication infrastructure:

- Primary Coordinator (PC): it is the main controller of the network, the one that allocates the transmitting time-windows of every device, receives commands from external users and send them to the proper device, log and send to the remote server the data from all the system devices. This role is implemented by The EcoThermo Building Control Unit (BCU) device that also implements other application layer functions such as the acquisition of the measurements coming from the sensors installed in the boiler technical premise.
- Secondary Coordinator (SC): it is the controller of the secondary network cells of wiNET protocol. In the EcoThermo use case, each living unit is served by a different time-frequency cell. This protocol layer is implemented in the Flat Control Unit - Base Station (FCU-BS) device.
- Router (R): it is a smart repeater needed to extend the physical range of communication of the wiNET protocol.
- End Devices (ED), powered by the main grid or batteries powered: this protocol layer serves all the leaves devices in the protocol functional architecture. In the EcoThermo use case they are the BVA electronic valves, Wireless

Remote air Temperature Sensors (WRTS) and the Human Interface FCU-HI.

The wiNET protocol creates a tree network for which the root is the PC that realizes also a gateway function with respect to the remote server. To increase performances reducing the network maintenance and configuration transmissions, the structure is rigid, but it can manage mobile devices and rebalance automatically the load of number of downstream devices managed by each Router.

The main transmission backbone, that is the *Primary Network*, connects the PC to the SC passing through the Routers and operates on a high speed channel. To minimize walls, floors, furniture abortion guaranteeing transmission reliability at low RF powers low frequencies was a must. Consequently, it is has been chosen to work on the Short Range Device (SRD) bands, particularly for the first prototypes at 868 MHz with 4 (G)FSK modulation; bandwidth of 175 kHz and channel capacity of 230.400 bps for the backbone and bandwidth of 65 kHz with channel capacity of 19.200 bps for the SC cells. To ensure these high performance level on small SRD bands an innovative radio modem, capable also of antenna diversity, has been designed and realized. wiNET allows at freely defining the number of usable channels, their central band frequency, data rate, transmission time-windows period and length to better fit the application needs.

On the main backbone, the PC schedules the communication time-windows and downloads data from the SC periodically performing a polling communication policy. In the *Secondary Networks* either the end devices or the coordinator can trigger the communication exchange. More particularly, each battery powered end device has a proper wake up time and awake duration; when it wakes up at first alert the SC to be on line. On the contrary, main grid devices are always listening from the air, therefore the initiative could be taken directly by the SC.

All these features gives an extra value to wiNET protocol satisfying the communication needs of the EcoThermo system, such as the high throughput at so small SRD bands. For instance, a typical building composed by dozens apartments and hundred devices could generate several GB per year of data that must be transferred from end devices to the primary coordinator. In addition, the final user should access to his data in real time, in order to be able to manage his heat expenditure in an efficient and cost saving manner. A comparison between wiNET protocol and other commercial protocols is given in Table 3.

Table 3. Performances comparison versus competitors [11].

	ZigBee® Mesh	DigiMesh	wiNET
Frame Payload, Throughput	Up to 80 bytes	Up to 256 bytes, depending on product	Up to 512 bytes
Supported Frequencies and RF Data Rates	Predominantly 2.4 GHz (250 kbps), 900 MHz (40 kbps) and 868 MHz (20 kbps) not widely available	900 MHz (10, 125, 150 kbps) 2.4 GHz (250 kbps)	433 MHz (Max. 230 kbps) 868 MHz (Max. 230 kbps)

5. Internet of things

The whole EcoThermo system can be thought as a wide Internet of Things (IoT) system. IoT is the interconnection of uniquely identifiable embedded computing devices within the existing Internet infrastructure for control or data sharing aims. In EcoThermo, internet connectivity is provided by the BCU through its on board UMTS modem, WiFi modem or Ethernet interface. The BCU operating system offers the standard communication services, such as VPN, FTP, TCP/IP, while the wiNET protocol layer ensure building-level communication down to each system end device.

At boot time, before all other internet related operations, a VPN is established with the remote Server. The server has a scheduler to retrieve data from each EcoThermo installation and offer WEB pages for the users' remote interactions. VPN increases both the communication line security and reliability that could be affected by the UMTS line cut off because of poor signal strength, absence of local coverage, system reboot or providers policies that force a line shut down in case of temporarily absence of communication. Since, without a VPN, the IP is allocated dynamically the remote server would be not able to find again the BCU over the Internet because of the not knowledge of the new allocated IP.

The BCU interacts with the external world in two ways: a TCP socket from which it receives commands and gives answers to the EcoThermo server by the wiNET protocol; and an FTP service that lets the server to download the whole system events files including measurement events. The TCP server runs in the BCU on a VPN virtual internet device. In this way the VPN-IP of the BCU is fixed, known by the remote server and dependent by the VPN certificate.

It can be managed during the installation of the system. TCP socket has been preferred because it is *connection oriented*: this feature ensures the chronological sequence of the data stream. The BCU's TCP server is always listening, but every interaction, composed of a request and an answer, is done in different accepted connections; in this way the communication is up only when there are data to send. This behavior is really useful to increase the robustness of the system. The FTP server is used to transmit the system events file collected by the BCU, which are compressed and md5 signed for a consistency verification. Even the FTP server works on the VPN virtual device.

6. Conclusion and future developments

In this paper we presented some of the most innovative aspects of the EC-FP7 EcoThermo project, the aim of which is to renew the heat cost allocation technique in buildings with an old centralized heating system. Further improvements could be achieved implementing optimization politics to push humans and systems to work more efficiently. For EcoThermo use case it will be considered the following two aspects in order to increase the performance of the building, the heating management and the automatic control system integrated behaviours.

- Consumption optimization against maximum heater efficiency: this is a super-system perspective that considers the interplay between the different sub-systems aspects, such as the building/flats thermal characteristics statistically calculated, the weather forecast, the users behaviour forecast, the heater characteristics and efficiency curve, to increase savings during the re-heating phases. Savings can be obtained as solution of an optimization problem that balances opposite phenomena such as the heater efficiency increasing, that for modern condensing heaters needs lower temperature of the returning thermal convey fluid, thus lower thermal power, and longer re-heating period on one side and the thermal wastes that increases when a higher average temperature is kept for longer time on the other side.
- Users' behaviour improvement: two analysis could be performed automatically by the system to generate suggestion supporting the tenants to act in the optimal way without renouncing to their thermal comfort. The first one compares the tenants' temperature settings with their pre-declared habits of living unit usage; the second one compares the tenants' consumption benchmarks with the ones of similar flats and similar families/habits.

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