Independence and Interdependence of Systems in District Heating

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Abstract—In this paper, a fully operational wireless sensor and actuator network is presented. The network has the ability to control a district heating substation to ensure indoors comfort while minimizing energy waste by maximizing heat extraction from the distribution network. Introduced here is the foundation for a systems of systems approach within a district heating application, where several substations cooperate with the heat production plant. Presented are also the first steps to a service oriented architecture (SOA) where sensor nodes in the district heating network can cooperate with other nodes and systems, for example a ventilation control network.

I. INTRODUCTION

In our current era, it has become clear that we, as a society, must take care of our resources since they are not unlimited and their use can generate pollutions in various forms. In this paper, we present a wireless sensor network, initially developed to optimize a district heating substation, that eases the implementation of a system of systems within a district heating network. The proposed architecture additionally offers a service oriented architecture (SOA) that enables the introduction of new sensor nodes while letting the system reconfigure itself. SOA further opens for cooperative function between district heating system and other energy and comfort related system, e.g. ventilation, heat pumps, etc. This approach will both enable energy savings and quality of service for indoor comfort.

We begin the paper with a quick description of what district heating is. Subsequently is the presentation of a fully operational implementation of a wireless sensor and actuator network that optimizes the energy transfer to the building. We then discuss the independence of the system, that is the system must function on its own and handle local failure as far as possible. From an independent ability, we discuss the integration of a complete district heating distribution to form a systems of systems, where the systems are then also interdependent. Before concluding we consider an implementation of service oriented architecture of wireless sensor nodes and control systems.

A. District heating

District heating is an environment friendly and efficient method of heating buildings within an area. In other words, several buildings and quite often large portions of a city can have their space and water heated from a central heat plant. An analogy to this efficiency is public transportation where a bus is more efficient at transporting fifteen people than are

Fig. 1. Traditional control and communication architecture in a district heating substation. Please note the heat measurement at the primary side has no communication to the control at the secondary side (red line).

fourteen cars. The concept of district heating is quite appealing when the heat comes as the byproduct from an industrial process. When heat is produced in combination with electricity generation, district heating more than doubles the efficiency of the power plant [12].

In general, the heat from the plant is usually distributed under ground through a closed network of insulated pipes within which the heat is carried by water or steam. Water is prevalent in Europe while steam is more common in North America [11], [15]. The heat from the distribution network is transferred to the building through heat exchangers within a substitution where the space heating and domestic hot water are the secondary circuits (c.f. Fig. 1). There are various variations to the theme of energy distribution and transfer in district heating but the general description is sufficient here.

B. Wireless Sensor and Actuator Networks

This is the age of Information Technology; the Internet has been a dramatic catalyst providing information access to a worldwide population. In a similar fashion, supplying information within a district heating substation dramatically improves the performance of a substation, its quality of service, and offers new services to both the heat suppliers and their customers. For example, sharing information between the primary circuit, i.e. the distribution network, and the radiator circuit results in maximizing the heat extraction from the primary circuit since the control system now knows how much heat energy per volume is available to the substation at its location within the distribution network [9]. There are several other benefits such as reduced pumping through the distribution network and increased efficiency in the case of

Fig. 2. A Mulle wireless sensor node.

combined heat and power plant [13].

Within the new architecture, each sensor and actuator is associated to a wireless node. We here describe these nodes, which are named Mulle [4], [10]. Their roles in the district heating substation are described in section II.

The Mulle platform is a small embedded system capable of communicating wirelessly with other nodes using TCP/IP over either Bluetooth or IEEE 802.15.4. As all embedded systems, it is able to measure and process a sensor's signal and/or request an action from an actuator.

The Mulle features a 16-bit Renesas M16C/62p micro-controller and a Bluetooth 2.0 module or a ZigBee compatible (IEEE 802.15.4) transceiver. It has an on-board 2 MB flash memory, allowing storage of large amounts of sensor data, its configuration settings, and web page data and applications for the on-board web server. Flexibility as well as time driven operation are provided by a real-time clock, a temperature sensor, a battery monitor, LEDs and a high density expansion port. The latter is a 60-pin connector that enables connection to analog and digital I/O pins, power supply, and serial communication lines. The compact design occupies a total of 24x26x5 mm. It is so small that none of the commercial components (heat meter, motorized valve and pump) had to be redesigned to be upgraded to hold a wireless sensor node.

Power utilization is an issue for the nodes that are not connected to the electrical network or associated to an actuator. The examples that arise several times in our system are the temperature sensors nodes. They must provide information for a very long duration, which ideally should be years. The current approach is to turn off the radio transceiver and put the micro-controller to sleep. The power usage in its lowest sleep mode is only 12 μ W. The micro-controller wakes up every 15 minutes to measure the temperature. If there is a significant change in temperature, the radio module is momentarily turned on to communicate the information to the wireless network. By using this approach, a Mulle can operate for years even when equipped with relatively small batteries [6].

The Bluetooth software is designed in a modular fashion to allow adaptability to the system and its role of the node within the system. The Mulle can communicate with two of the worlds most widely spread technologies: TCP/IP and Bluetooth. The software uses the lwIP stack, and can communicate with several protocols including: IP, TCP, UDP, DHCP, NTP, and HTTP. The lwBT Bluetooth stack provides support for the following layers: HCI, L2CAP, SDP, BNEP, RFCOMM, and

PPP. The Bluetooth Profiles supported are: LAP, DUN, PAN, and SPP.

The use of TCP/IP and Bluetooth enables the Mulle to even utilize Bluetooth-equipped mobile phones as access points to reach the Internet although there is not a need for that in a district heating application. This allows a Mulle to transmit sensor data directly to users on the Internet without any specialized gateways. The advantage of using TCP/IP at the sensor or actuator level is the clear standardization of the Internet Protocol. This detail enables the infrastructure to be flexible to different sensor and actuator suppliers and opens the door to standardized service oriented architecture.

The Mulle with the IEEE 802.15.4 uses an operating system to handle all the different tasks in real time. Contiki [5] and TinyOS [3] are two well known operating systems used in research and commercial products. They are both designed with low-power embedded systems and wireless sensors in mind. Thus making them ideal to be used together with Mulle. Both Contiki and TinyOS also include IP stacks with 6LoWPAN support [14]. 6LoWPAN is a acronym for IPv6 over Low power WPAN and is a standard that allows IPv6 packets to be sent over IEEE 802.15.4. Contiki utilizes the uIPv4 and uIPv6 written by Adam Dunkels, who also is the creator of Contiki. TinyOS uses BLIP, the Berkeley Low-power IP stack.

The nodes can communicate with each other or to an access point creating a wireless network. The next subsection describes the implementation of the wireless network.

C. Wireless network

The network used in this setup is a IP-based network with DHCP capabilities. The DHCP server is implemented in the Internet access point (c.f. Fig. 3), which is a Blackfin based embedded computer running μ Linux [1]. The new version of the access point used in this research communicates with Bluetooth, IEEE 802.15.4 with 6LoWPAN, Wi-Fi and wired Ethernet. Its dimensions are 90x174 mm.

The control loop is today located in the Blackfin device, but could, in the future, be distributed between sensor nodes to improve control robustness. The network setup makes it possible to access all devices (Mulle) in the network from the Internet. This enables the system administrator to reconfigure and update the software on the nodes remotely.

II. SUBSTATION CONTROL

The current problem with commercially available substation is that their control systems today aim only towards comfort but do not optimize the performance of the substation in terms of energy efficiency. Their purpose is to guarantee that enough heat is delivered to the radiator circuit. This results in wasting heat energy that is available in the primary circuit. To optimize the system, additional information is needed by the controller but which is not currently available.

The traditional control and communication architecture is shown in Fig. 1. The heat energy measurement is located on the primary side of the substation. The controls of space heating and hot tap water delivery to the house are on the

Fig. 3. New control and communication architecture in a district heating substation. Here all sensors, actuators and control devices regardless of location can exchange information.

secondary side of the substation, i.e. the radiator circuit and the domestic hot water circuit. These two functions, heat measurement and control, are independent and unaware of each other. For the space heating, there is a feedforward path which measures the outdoors temperature and regulates the flow of the primary circuit to achieve a specific temperature towards the radiators. The colder the outdoors temperature is, the hotter will be the temperature to the radiators. The feedback mechanism controlling the indoors temperature is the thermostatic valves located at each radiators. The flow through the radiator circuit is achieved with a fix speed pump.

With a wireless connection between sensors and actuators, the new infrastructure allows for the optimization as well as new diagnostics and services. In the hereby presented architecture, shown in Fig. 3, all sensors and actuators are enhanced with or replaced by sensor nodes which form the wireless sensor network based on TCP/IP.

This means that the barrier between the primary side with heat metering and the secondary side with heating and hot water control is effectively eliminated. This opens up for new measurement possibilities as discussed by Yliniemi [18] and new control strategies as discussed by Wollerstand *et al.* [17] and Gustafsson [8]. They take into account that the radiator circuit needs a certain time to heat up in the heat exchanger and a certain time to cool down in the radiators (i.e. heat transfer rates). By varying the flow rate of the radiator circuit, one can optimize the heat transfer in the heat exchanger and thereby minimize the flow through the primary circuit and in the radiator circuit. This requires that the pump has a continuously variable flow rate.

These new measurement and control strategies have substantial economical potentials. Very rough estimates shows savings of more than 1 million € per year when increasing the primary temperature across the substation (ΔT) by 5°C in a 760 GWh district heating system. Correlated with the financial savings are the environmental savings.

III. QUALITY OF SERVICE

The wireless sensor network could offer better diagnostics since it has access to much more information. Fig. 4 illustrates the case where there is a low water level in the radiator circuit. The pump has a pressure sensor and when the pressure is

Fig. 4. Text message to a home owner that there is too little water in the radiator circuit with world wide web address to instructions on how to add water to it.

too low, the Mulle onboard the pump asks the heat provider to send an SMS or telephone text message to the end user to add water to the radiator circuit. Another example is an over dimensioned control valve which results in an on-off type control. The indoors comfort is achieved as the on-off behavior is filtered through the radiators but it creates pressure waves in the distribution network caused by this on-off type of control. The control system is aware of its control attempts and can only now communicate the problem to have a smaller valve installed.

The wireless network with its Internet connection offers new services such as energy separation which inform users how their total bill is divided between space and water heating [19]. This information influences end users' behavior because they can clearly see what their energy use is and its influence on the environment.

Quality of service is related to reliability of the components within the system. To address this, statistics of components are collected from which one can estimate the life of a standard component. To prevent system failure, components are replaced based on an estimated lifetime. However, statistics show only a trend but nothing about a specific installation. With the wireless sensor network, any malfunction in the

substation is communicated immediately to the heat provider or home owner thereby detecting early faults or extending the in-use life of a component until it shows signs of aging. Additionally, statistics are automatically recorded on a server with not only failure rates but also in operation information.

IV. SYSTEM OF SYSTEMS

A demonstration substation is in operation with the wireless sensor network and information about its status is currently available to anybody with a web browser [2]. Direct access to the wireless network and its nodes is password protected such that it cannot be tampered with. From a heat supplier, information from each substation can offer vital information about the distribution network and service requests can help the network save further energy.

A. Network information

Each substation is able to provide information to the heat provider such as the primary supplied and returned temperatures as well as its through flow. This information assembled together from all the buildings in the district allows a real time overlay to a map of distribution area. One overlay of the map can paint the heat distribution over the network and the energy losses in the ground over the portrayed area. This overlay also informs about the differences between buildings. If, for example, a building has a lower supplied temperature, it can be that something is wrong with the temperature sensor or that the underground pipe supplying the building or its insulation is damaged. Another overlay can alternatively show the difference of temperature between the supplied and returned temperature to alert that a building's substation is inefficient or has a malfunction when that difference is too small or too large.

All these views over the district heating network enables a heat supplier to have a better control over its distribution network and address issues in a very short time.

The Swedish District Heating Association has also sponsored the development of a software program that analyzes data to allow a heat provider's energy use and its pollution contribution [13]. The data currently must be manually entered into the program. When using real time data, one can obtain the current and accumulated status of the financial and environmental cost of heating a whole district. This is related to the idea of energy separation mentioned in the previous section where the end user could for example see the carbon footprint of his or hers last shower.

The Swedish District Heating Association has in addition developed an online database to track the failure of components [7]. It requires that each heat provider has a technician to fill in details. With a deployed wireless sensor network, the information from each node is continuously collected in a database. Automatically analyzing this data will increase the quality of the statistics as likewise it considers functional components thereby allowing a correlation between failures and performance to be developed.

B. Inter systems cooperation

Having a communication to a central database operated by the heat provider allows for new cooperation between substations in a neighborhood but also between the heat plant and the customers to further reduce energy waste. We consider two examples here.

When a node or an access point within a substation needs information it does not have, it can request it from the central database. For instance, the outside temperature sensor node has stopped functioning. The node seeking the information notifies the maintenance department to have the node serviced and asks the database if it can get the value of the local outside temperature made available by one of the neighboring substations.

The second example addresses one of the current issues with district heating, which is the daily peaks of heat demand such as the one between 6:00 and 8:00 a.m. when an ample portion of the population takes a shower. If the heat is originally from an industrial process, it cannot be expected that the large excess heat comes from an increase in industrial production. One solution is to use one of the backup heat plants to be powered to intervene for the duration of the peak. However, to be able to turn on and off such a plant rapidly, fossil fuel or electricity are used. They are very expensive financially but also environmentally. In yet another project of the Swedish District Heating Association which is conducted in Karlshamn [16], it was shown that buildings which had stored heat in their structure (i.e. thermal capacity) could reduce their space heating energy consumption in a coordinated fashion to minimize the peak heat demand without affecting indoors comfort.

Therefore creating a system of systems in district heating is an obvious and natural progression to reduce energy usage while keeping end customers thermally conformable and improving quality of service.

V. SERVICE ORIENTED ARCHITECTURE

We here discuss two levels of services. The first is at the node level or within a system while the second one is at the level where systems interact with each other.

A. Sensor nodes

The Mülle sensor nodes are able to introduce themselves and the information services they offer using XML metadata. As an example, a temperature sensor can tell that it measures temperature in degree Celsius. When adding new nodes after the initial installation, the system must reconfigure itself without any nuisance. Two issues appear with this type of concept. The first one is the identity and location of the node while the second one has to do with the repository of application with those services.

For example, a temperature sensor node must know if it is located in the living room or in the kitchen. On the other hand the service client must be certain that the "living room temperature" node is in the same house. Trying to control the temperature in the neighbor's living room will prove to be

quite a challenge. On the back side of the issue, people might want to keep the information of the their indoors temperature a private matter. In any of these scenarios, one solution is to have a service person from the heat provider involved either in the deployment or the sale of the node to pair it to the correct system. Another solution is to use the Mulle's ability to measure signal strength. During pairing to the network, the building owner should place the new node close to the access point, allowing the Mulle to be certain that physical proximity identifies the wireless network it is joining.

The expectation in service oriented architecture is that the client has a repository of procedures to handle different available services. This can prove to be difficult when we consider small wireless sensor nodes (limited memory) and in undefined applications. To illustrate this, consider the substation system has been built for controlling temperatures. When a humidity sensor node joins the wireless sensor network, how should the system use the new service? The proposed solution is for the substation nodes to ask the heat provider if they have in their repository an algorithm which handles humidity information. And if so, each concerned nodes would request to be remotely reprogrammed (a feature the Mulle already has). In other words, the repository is not located at the sensor node but on a server.

B. Systems

Services are not limited to nodes but can include other systems. The example to be addressed is ventilation. Large buildings (office buildings, schools, shopping malls) have advanced ventilation systems to keep a certain quality and comfort. These systems can waste energy when the outdoors temperature is cold and the buildings are not used such as early during the morning peak heat demand. To address this, it is vital for the different control systems to communicate and exchange information. If a ventilation system is upgraded to have a wireless sensor network, it can present its services to the heating system which then will turn to the remote repository to learn how to cooperate.

VI. CONCLUSION

A wireless sensor network in a district heating substation can optimize the heat extraction from the distribution network while it guaranties indoors comfort and quality of service. It is an independent system that function by itself. Within the district heating network, when several building have a deployed wireless sensor networks in their substations, they can form an interdependent set of systems that cooperate by sharing information and support each other. When the heat plant join into the system of systems, the peak loads can be flattened out. All this results in saving natural resources and reducing cost or increasing benefits.

The wireless sensor network offers additionally a service oriented architecture, which at the system level means that two different systems can cooperate together although they initially did not know how to. The example described in the paper is ventilation of large buildings like offices and schools.

Using a wireless sensor network with nodes that communicate with TCP/IP simplifies implementation of a system of systems and the use of 6LoWPAN provide system transparency over the Internet.

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