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rECC - rational Energy Consumer Control

***Abstract**. This paper presents experiences in the implementation of the development and research project rECC. rECC project deals with the development of an technology platform for efficient management of electricity consumers in the residential units and street lighting systems. The aim of the project was only one - to determine whether the economics of managing electricity consumers in independent housing units and/or street lighting systems can be improved for one order of magnitude and enable an independent execution of projects without construction and installation works. The project has proved to be an interesting combination of hardware construction (with an emphasis on the economics), of the theory of distributed information systems (with an emphasis on responsiveness, reliability and safety) and of cloud services (with an emphasis on connectivity, reliability and scalability).*

*Streszczenie. Artykuł przedstawia doświadczenia w implementacji wyników projektu badawczo-rozwojowego rECC. Wynikiem projektu jest rozwój pratformy technologiczne do efektywnego zarządzania spożyciem energii elektrycznej w niezależnych budynkach i/lub systemach oświetlenia ulicznego. Cel projektu był jeden: określić czy ekonomia zarządzania konsumpcją energii elektrycznej w niezależnych budynkach lub/i w systemie oświetlenia ulicznego może być o rząd wielkości poprawiona oraz czy możliwe jest wykonanie projektu bez prac konstruktorskich I instalacyjnych.W projekce wykazano, że jest on interesującym połączeniem konstrukcj hardwere'owej (z naciskiem na ekonomię), kombinacją teorii systemów rozłożonej informacji (z naciskiem na odpowiedzialność I bezpieczeństwo) I usługami w chmurze (z naciskiem na zdolność łączenia, odpowiedzialność i skalowalność). (**rECC – racjonalne sterowanie konsumpcją energii**)*

Keywords: energy consumer management, PLC - Power Line Communication, Web Socket, Mesh network
Słowa kluczowe: zarządzanie konsumpcją energii, PLC – komunikacja pomiędzy liniami, łącznik sieciowy, siatka

Introduction

Management of electricity consumers is an interesting area in both business and technical fields. Requirements of ensuring efficient energy consumption and simultaneously providing optimal results in energy consumption are becoming day by day more pronounced. Economic effects on one hand and the satisfaction of users on the other, are a reason which is important enough to provide large investments in the mentioned area. There is a great number of providers whose solutions are already present in the existing market. A group of Slovenian companies and institutions has found a common solution on this segment of the market. The scope of the development was limited to coming up with a solution that will enable management of electricity consumers in the residential units and street lighting systems.

At first glance, doing this can be seen as unwise and very risky. To enter a market with a new solution, where there already are established providers cannot be easy, but certainly for a period of time also not profitable. Since most of the current offer is targeted at marketing new constructions and is a combination of a product and of extensive engineering services, a part of the market is located on the diametrically opposite side. Therefore, we want to provide a solution on the market which will enable realization in the existing buildings, with economy, which is one order of magnitude better than the current offer and will enable the user an independent implementation.

Hereinafter the scope of the problems and the nature of the solutions, through which problems were solved and solutions for managing electricity consumers were found are presented. It will be shown how a bunch of concepts of information technologies was used to create solutions, some of the most important achievements will be listed and the whole solution will be presented.

Description of the problem

Management of electricity consumers (for selected areas of residential units and street lighting systems) contains components of monitoring and supervising consumers. We want to monitor what happens to consumers and be able to transmit orders to consumers.

Since electricity consumers are as a general rule "unintelligent" the management solution must contain a control unit which will monitor the status of the consumers and will allow execution of commands. The control unit in topology represents a converter that: (a) converts the command with content (digital) into a signal understood by the consumer of electricity (the control unit of the LED lamps converts the command with content ON into an equivalent voltage level on the power supply, causing the lamp to turn on); (b) is able to transform the events and the status of the consumer of electricity into a sequence of events and digital interpretation of the current status of the consumer (the control unit determines the current consumption of the lamp).

Because we want to manage consumers from a central location, it is necessary to provide a reliable communication path between the central location and control units. Thus, it is necessary to provide a standard IP connection between the central location and a local device (concentrator for each building, the hub of public lighting), and the link between the local concentrator and control units. In general, there are two solutions: (a) a new communication network with help of additional infrastructure, such as additional wiring or setting up a wireless network (WiFi, BT, RF), is established or (b) the existing electricity network is exploited to communicate through PLC technology (Power Line Communication).

Each of the solutions has its advantages and disadvantages:

- Construction of a wired control network to each consumer (to each control unit) represents a reliable and tested solution. This solution requires implementation of construction works (installation of control connections) and the execution of electro-engineering services. Such an approach is due to the cost and complexity of the implementation not suitable for the project.
- The construction of a radio control network to each consumer represents a solution which removes the need for physical intervention. Such a solution has certain restrictive factors (network range, robustness to external influences, energy consumption and additional radiation in the premises). A disadvantage of such a solution are also additional costs for realization of the control unit because each unit shall also include a transmitter and a receiver unit. Due to technical limitations and a relatively complex method

of detecting points of discontinuities of the network such an approach is unsuitable for the project.

- Using the electricity grid for PLC communication represents a proven technology with low costs of the used hardware. This solution also does not require physical interventions and does not increase electromagnetic disturbances in the premises. However, this technology has limited bandwidth and is sensitive to environmental influences. This technology was selected for the realization of the control network.

PLC (Power Line Communication) [2,3] technology allows the use of electricity networks for the purposes of telecommunication services, thereby it is achieved that the network for the distribution of electricity is used as the transmission medium for data transfer.

Various types of PLC communication use different frequency bands, which depend on the type of installation. Transmission signals on a high-voltage transmission lines operate at lower frequencies (100-200 kHz), because they must overcome distances, which are several kilometers long. In the low-voltage networks higher transfer speeds are achieved by using higher frequencies, which occupy the major part of the radio spectrum for communication, or by using selected narrower frequency bands, depending on the technology used.

The advantages of the PLC communication

- *For data transmission the already existing infrastructure is used.* Re-installation of network cables is usually not an option or does not correspond to a style and free hanging or lying cables are not practical. Therefore, the only possible alternative solutions are in these cases, a wireless network or the use of an existing electrical wiring.
- *PLC communication combines the communication and energy entry point into one network.* The advantage of PLC communication is in the installation of devices. By connecting the power supply from electricity grid (power supply of the device) the communication interface is automatically connected, and thus communication via electricity grid is enabled.
- *It is an affordable solution, because electricity network is available everywhere.* Due to the simple and practical installation of devices with PLC communication, this represents a cost-effective solution, as the electricity network is accessible everywhere and because of this there is no need for additional investments in new communication infrastructure.

The disadvantages of the PLC communication

- *Problems with reliability.* A reliable information flow between devices connected via the electric power system is one of the foundations of a reliable operation of the system. A key restriction for fast and reliable PLC communication are the noise characteristics of high-voltage electric conductors. Any disturbance in these conductors is consequently reflected in the reliability of communication. The more "noise" there is in the surrounding, the more problems there are with the reliability of the system.
- *Sensitivity to electromagnetic interference.* The reflection of the signal and electromagnetic noise characteristics represent major limitations for the reliable operation of the PLC communication. Technical limitations of high-voltage electrical conductors are essential for reliable narrowband and broadband communications. Noise and reflection of the signal are the key obstacles for the further development of digital PLC communications systems and replacement of PLC analog interfaces with the digital ones. The development of a fully digital PLC system is currently restricted by the characteristics of high-voltage conductor whose primary purpose is the transmission of electricity. Background noise is a result of the electromagnetic pollution. This is the noise caused by the electromagnetic interference, which can be described as white Gaussian noise. Noise, which results from interference of radio stations, and other high-frequency devices in the lines, is defined as narrowband noise.
- *Operation in a three phase system is not self-evident.* PLC communication is taking place always only on one phase, therefore it is necessary for an operation in a three-phase electrical network to use the so-called phase conjunctions. They capacitively combine all three phases of the network among each other, which enables the transmission of data (communication) through the power network via all the three phases at the same time. If the transmission of the signal takes place only in one phase, phase junctions connect it to all three phases, so that they conduct the power line signal. Thus, for all other sockets in an electrical network the same communication signal is available.

When designing the mechanical part of the solution, we wanted to build an integrated system. When the information aspect is added to the communications aspect, we get a comprehensive look at the solution that we have developed. This solution is shown in figure 1.

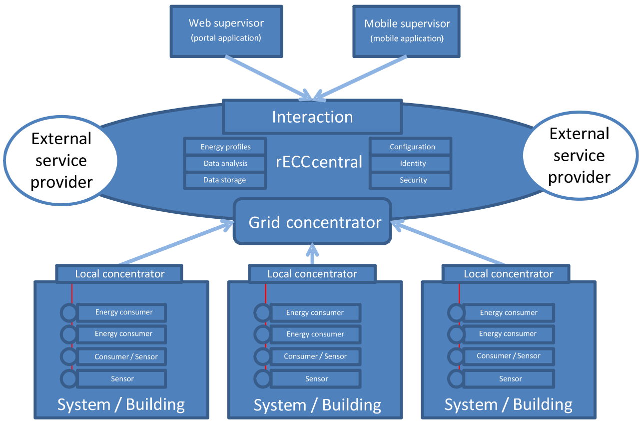

Fig.1. rECC system

As it may be seen in the diagram, the topology is simple, because each block performs a specific role in the system. Therefore, it is possible to imagine a simple scenario in which:

- In the user interface the user selects to forward a command to the consumer of electricity (eg. turn on all LED lamps in the room).
- User interface forwards the request to the central component (rECC central), by which the command is interpreted as a sequence of commands for the individual consumers of electricity.
- By using the TCP/IP network the central component transmits the commands to the local concentrator.
- Local concentrator receives a series of commands, interprets them as a sequence of commands for each specific consumer of electricity and with the help of communication via the electricity grid sends this commands to the control units of the consumers.
- The control unit of the consumer receives a set of commands and implements the conversion into the world of physical quantities (by taking into account the DALI protocol it ensures to turn the LED lamps on).
- The control unit sends feedback about completion of the command in the same way (it sends the type of the command and execution time).

A positive scenario of this kind is simple and its implementation is unproblematic. Most solutions on the market implement management scenarios in such a way - a central component of the system implements full control of the entire topology.

The basic concept of such a system is the provision of communication paths from the central to the final consumer of electricity. In other words, with the help of a programming command that is generated based on the requirements, appropriate actions over electricity consumers are triggered. Figure 2 presents a comparison between an object model (left) and physical components of the system (right).

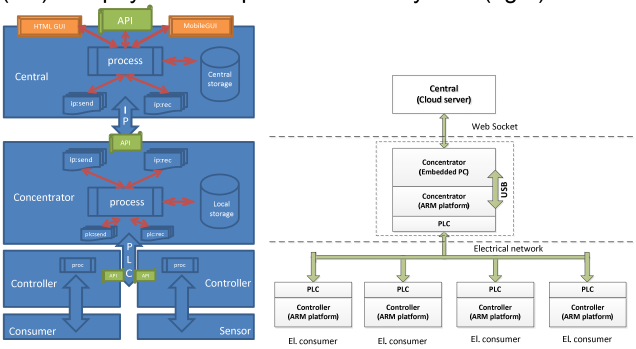

Fig.2. Object model (left), system physical components (right)

The first challenge - the permeability of the control network

The first challenge in the realization of this management scenario is represented by the limited reliability and permeability of the control network (composed of TCP/IP and PLC segment). In our case, the TCP/IP part of the control network is not problematic, since its permeability is at least a few classes higher than the permeability of PLC network. Problematic is the PLC network that for the desired low cost of control units offers a very limited bandwidth (size class 1 kb/s). Such a network is already terminated by a topology that contains a little over 10 consumers, since there is just too much communication (in the PLC network a situation can occur, where by the networks own traffic the capacity of the network is being reduced). We intend to support systems that have three size classes more consumers.

The second challenge - the reliability of the system

Another challenge that we faced was again of a physical nature. Reliability of the PLC network decreases with distance, which represents a major challenge in the case of street lighting systems, where the distance between the nodes and the lamps can be extremely large (over 1,000 meters).

The third challenge - the responsiveness of the system

The third challenge is the required responsiveness of the whole system. It is impossible to imagine a favorable user experience if the delay between the selected actions on the user interface (smart phone) and executed commands is too large (or greater than 500 ms).

Solutions and results

In the following chapters solutions of the mentioned challenges are described. It should be noted that by solving this challenges we have coordinated actions at the level of hardware design and at the level of information system components design.

Permeability of the control network

If it is not possible to increase the permeability of the network, it is necessary to reduce the amount of communication. The solution was found in the concepts of distributed systems and service orientation.

In the first stage, we have decided that we will distribute processing throughout the topology:

- Component for interaction engages in processing of all user actions, for the realization of functionality it uses a central component.
- Central unit provides functionality of selected eServices (rController, rManger, rVisionary) at the level of the entire topology or a plurality of housing units and the whole system of street lighting. For the presentation level a component for interaction is used. This component receives data and sends commands through the normal TCP/IP communication.
- Local concentrator provides all the functionality to manage individual residential units or nodes of the street lighting.
- The control unit ensures the implementation of commands for managing the consumers of electricity (or sensors of physical quantities). The control unit becomes an active element of the topology, which is able to interpret any sequence of commands with its logic. This is the concept of the so-called »Schedule of commands", by which it can be requested to perform certain commands or sequences of commands within the stipulated time periods

Because we transferred a part of the processing to the control units itself, we have significantly reduced and distributed the amount of communication. Instead of forwarding each command promptly, the commands are transmitted in advance during low network load, while it is also possible to carry out the commands periodically. There is no need to transmit the same command over the network several times. Still, in accordance with the basic principles each command execution means a return communication of the control unit via the PLC network to the local concentrator and then to the central component (whether it is an information that the command was executed or a measured value). About the solution of this problem it will be written a little later.

It is necessary to understand that by transferring the processing to the control unit, requirements for processing power and memory capacity of the control unit also increased. This is really not a problem, since it turned out that the requirements for processing power and memory capacity, do not increase the price of the control unit. We used an extremely efficient 32-bit ARM processors and already standard built-in 64 kb memory.

The next step for reducing the amount of communication was taken from the service orientation of information systems. The concept of the contract is an arrangement between the user and the service provider, which provides to carry out specific functionalities without any side effects and without users knowledge of the mode of implementation.

Using this concept, we designed a system in which participation of components is based on trust that the desired services will be performed (without the feedback that it has been executed successfully), or an exception will be triggered (with information about the reason for the error). This concept has been integrated into the entire network topology. From the central unit via the concentrator and to the control unit, the used conceptual model of cooperation of components is the same. With this concept we avoided confirmatory communication about an executed command. Thus, we reduced the amount of communication to a single transfer of the command and periodical information about the results of the execution of commands. To control the topology we have implemented a verification system that the central component implements for all local systems and the local concentrator for local topologies.

With these concepts we managed to drastically reduce the amount of necessary communication. It is now possible to build topologies with as much as 1000 electricity consumers and this on a permeability of 1 kb/s.

Reliability of the control network

The second challenge was to increase the reliability of the PLC network. This challenge was solved by installing the Mesh [4] mode of communication in the operation of the control units.

The first approach to increase the reliability of the communication is the use of packet-oriented protocol. In this mode, the connection between the control units is not established. Packet-oriented protocols operate on the basis of the confiscation of media or sharing of transmission capacity. Between the control units, data is transmitted in packages. Since the connection is not established, each package must be labeled with the address of the recipient, and usually with the address of the sender. This method usually does not provide specific capacities of the individual control unit, but operates according to the best possibilities and depending on the current occupancy of the transmission medium.

The second and also the key approach is represented by the use of a Mesh mode of communication. Which can be used in a wireless and/or PLC network. Mesh network consists of multiple nodes that communicate with each other via a channel, which is accessible on the PLC network. Nodes are organized in a mesh topology in such a way that each node communicates with other nodes in its range. Usually a Mesh network has the ability of dynamic organization and automatic establishment of the network. For proper operation, the nodes must cooperate with each other and exchange the necessary information.

Mesh network is one of the key broadband technologies in heterogeneous communication environments of the new generation, it provides the creation of an efficient, robust and self-curable wireless communication network. Thanks to the distribution of intelligence the Mesh network has no central point of failure and is therefore used for a wide range of applications.

The PLC module of the control unit [5] is set for operation in B area, thus it operates outside the communication area of electricity meters (it does not interfere with communication). The amplitude of the modulated signal is 1V. The data transfer rate is adjustable within the range of 1200 and 4800 bps. In order to provide a higher quality of data transmission the following hardware supported methods are used - "preamble detection with conditioning" and "hardware frame synchronization". The first method transmits only packages to the application, of which the packet header matches with the expected ones (thus we do not receive anything else, but only packets that are intended for him). The second takes care for automatic verification of synchronization between transmitted packets including the "zero-crossing" phenomenon (the transition of 50 Hz sine wave voltage signal through 0). The module enables multi-master connection and communication as such (multi-master allows multiple simultaneous master and slave PLC units in the same common network).

System responsiveness

The third challenge - the responsiveness of the system was solved in three segments:

- Communication between the user interface (mobile and web) and the central component.
- Communication between the central component and the local concentrator.
- Communication between the local concentrator and the control unit.

Speed ratings of communication between the local concentrator and the PLC control unit were already discussed in the previous paragraph. Because we are dealing with communications among devices that are not very distant (in smart houses within the range of as few as 10 m, and in public lighting more than 1000 m), there is no significant delay.

A more difficult challenge was to ensure adequate response in the communication between the user interface and the central component, and between the central component and concentrator. The challenge is even greater when we consider the use of service oriented architecture, in which the central component is located in the cloud, thus potentially over 1000 km away.

First of all, let us try to answer the question, why does such an architecture make sense in our solution. Partly the reason lies in the key objective of the project, which is to improve the economics of managing electricity consumers. Using a service oriented architecture can additionally reduce the cost of the initial investment. Even more important than this are the functional and business opportunities that the use of the cloud brings.

Let us first mention the functional point of the solution form the users' perspective. If the solution would be made as a classic solution for one user and the cloud would be used only as an alternative to the necessary infrastructure, then from a functional point of view, such an architecture would not bring significant benefits. Therefore, we have designed a solution as a "multi-tenant" service (a single service for different tenants of services). It must be completely transparent to the users, except with the additional functionalities that are only possible in such architecture. A functionality, in which the user receives tips on how to improve the economic use of energy consumers, is based on the good practices identified by other users of the service. The user must explicitly allow such use of their data. The motivation for this are the potential benefits user may have by receiving useful tips.

The second aspect is the business aspect, therefore, an aspect of the service provider. The service architecture allows different ways in which the service provider can realize their business benefits:

- User has to pay for the service.
- The service is free for the user, by this the users data are available to the service provider, so that data can be used for commercial purposes (in our case, the analysis of these data may be interesting for producers of energy consumers and electric energy distributors. Also, the contacts of customers may be useful for service technicians or sellers of electrical devices for which there is a real risk of failure, which can be determined from the degraded characteristics of energy consumption).
- The user pays for the infrastructure and the license (private cloud), which can be interesting for those who want complete control over a service.
- A combination of the described business models is also possibility.

Using a service oriented architecture that uses infrastructure in the cloud, undoubtedly brings many potential benefits. Unfortunately, it also brings some threats associated with the reliability, security, availability and responsiveness of services. The first three threats can be controlled with general solutions, which are largely independent of the type of service. Risk associated with the responsiveness of services represented a major challenge which could not be easily solved by standard solutions.

First, we faced the selection of a suitable communication protocol. Our first choice was WebSocket communication protocol that provides "full-duplex" (full bi-directional) communication over one TCP connection (HTTP only uses it for handshake). The protocol was standardized in 2011, and by W3C - API has also standardized it for the WebSocket. The disadvantage of this protocol is that it is not compatible with previous versions (meaning it does not work on an older infrastructure or on older versions of browsers).

For a general useful solution, such as a platform for rational management of energy consumers, it is important that the platform operates on the widest possible range of mobile devices, thus we have been looking for a solution, which would solve the problem of compatibility. We have found it in the library SignaR [6], which provides a permanent logical connection between server and client in a way that implements the logic of repetition. In the case of an older versions of the browser it automatically sets up one of older methods of communication. SignalR also supports a number of different scale out scenarios (ensuring scalability by adding affordable computing resources). The library is therefore appropriate for the construction of various types of "real-time web" applications, such as our prototype surveillance applications. Safety of the communication can be provided in the same way as in other web applications, by using the SSL protocol.

Although SignalR is an open source library it is fully supported by Microsoft. Because of this, the choice of Windows Azure [7] cloud platform was logical. A cloud service made by using the SignalR in C# can enable communication with local concentrators as well as with HTML5 interface, developed with the framework for development of mobile application Sencha Touch. [8] Configuration of energy consumers' topology is stored in Azure SQL, while logical operations and energy consumption are stored in SQL or NoSQL database in the form of JSON notation. Figure 3 is showing the technologies used in the cloud.

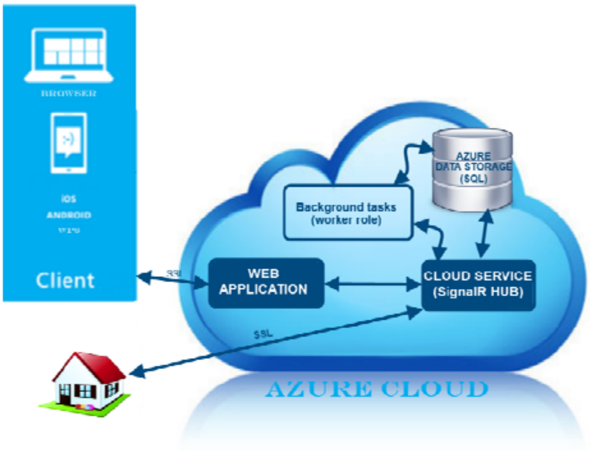

Fig.3. Cloud solution

The described assortments of technologies and architectural approaches were also realized. We have already established a pilot environment - the management of energy consumers in a private house in the Gorenjska region, the management of street lighting in one street in the vicinity of Ljubljana, the central unit functioning in the Azure cloud and users with mobile clients.

And the most significant fact is that in spite of such a distribution of components of the system, we have achieved a responsiveness of the system, which has even exceeded our set goals. If we have set ourselves an objective of achieving a response time of 500 ms (maximum delay that is acceptable to the user), we are nowadays achieving response times during the action carried out at the users interface and command performed on the energy consumer in the range of 100 ms.

Findings and conclusion

The basic finding of the project is, that it is possible to realize a technology platform, which manages the consumers of electrical energy, in such a way that it is economically significantly better than the present solutions.

During the realization of the solution we have used a series of concepts and approaches from the world of information technology (distributed systems, service orientation), which had a major influence on the design of the hardware and the IT components.

We have managed to build a comprehensive system in which both, hardware and software, operate consistently and exploit the technological potential.

With the completion of the project an even more interesting period begins, which is entering the market. The constructed technology platform does not only make the market entry possible, but it also provides flexibility to business models for services that can be technologically supported by the platform.

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