POWER DISTRIBUTION SUBSTATIONS AND DISTRIBUTION NETWORK INFRASTRUCTURE'S CONTROL TOOL DEVELOPMENT WITH WIRELESS SENSORS NETWORK

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ABSTRACT
The case study is implemented in a liberalized power supply market conditions in Latvia. A research conducted by Riga Technical University and VATS Ltd, Power distribution infrastructure services provider, enables a real life experience, how to transfer legacy power grid into a "state of art" grid by using WSN and creating a framework for new services. The aim of this research is to provide an evidence of practical implementation of a new generation of power distribution network monitoring system, which complies Arrowhead framework approach: open architecture and open protocol implementation, communication between sensor nodes and back-end system, which ensures communication data presentation as web services. The modular technical solution for sensor, repeater, and gateway nodes for aн application on the main types of public utilities networks: electricity, water, heat and gas meters. The described solution has been developed in the Arrowhead project.

Keywords: Arrowhead, System-of-Systems, SOA, wireless sensor networks (WSN).

1. INTRODUCTION

A liberalization of the power supply market in Latvia disclosed the lack of technological solutions to provide adequate customer services by new power supply companies, which maintain mostly legacy power supply networks. Power supply distribution systems needs improvements for effectiveness, flexibility and cost reduction. The upgrading of power grid systems through deploying wireless sensor networks (WSN) – a technology that allows a monitoring and intelligent control operation of the power systems - will foster effective use of electrical energy. It also enables a provision of qualitative customer services, as the data related to the status of networks are available in a timely manner and in stated amounts. WSN will provide also an opportunity of a flexible billing to end users.

Furthermore, effective monitoring and control of the heat energy consumption, preventing thermal energy losses in district heating networks, allocation of undetected accidents, hidden leakages, and irrational utilization in water distribution networks is an important task of public utilities in the municipalities. However, utilities, municipalities and supplies in their practice encounter real problems preventing introduction of WSN: underestimated cost of technical solutions, frustration in selecting technical solutions relevant for local needs, a lack of technical competences and incompatibilities between a plenty of protocols used at existing and new equipment offered by different suppliers.

Therefore, developing of sensor networks for monitoring and control of power grids, utility's networks and its maintenance is a challenging process due to plenty of human work related to configuration of sensor networks. These systems rely on large-scale sensor networks and take advantage of the availability of external collaboration services for continuously sustaining. Such collaboration services to accepted and agreed by systems owners on quality of service according to the negotiated Service Level Agreement (SLA). Hence, the aim of the Arrowhead project is to rationalize the notion of collaborative automation by applying and extending the concept of state-of-the-art Service-Oriented Architecture (SOA) onto Internet-of-Services (IoS) solutions (Delsing 2013).

The aim of this research is to provide an evidence of practical implementation of a new generation of power distribution network monitoring system, which complies Arrowhead framework approach (Delsing 2013): open architecture and open protocol implementation, communication between sensor nodes and back-end system, which ensures communication data presentation as web services applying the most suitable IEC standards.

A new generation of the modular technical solution for sensor, repeater, and gateway nodes for application on main types of electricity, water, heat and humidity meters has been developed in the framework of the Arrowhead project.

The paper is structured as follows. Authors summarize related works in the area of WSN and SOA in Section 2. A legacy power supplier case is described in Section 3. New system's architecture is depicted in Section 4, which describes a model view, high level communication between elements of System of Systems (SoS) and an implementation of the services. Section 5 describes a hardware implementation of WSN nodes, which monitor and control power distribution electrical networks. The main contribution of the research, general results and possible directions for future works are discussed in the chapter Conclusions and next steps.

2. RELATED WORKS

Service Oriented Architecture (SOA) represents a distributed computing concept. It encompasses many things, including its own design paradigm and design principles, design pattern catalogues, pattern languages, a distinct architectural model, and related concepts, technologies, and frameworks. Transferring the SOA 'idea' to the device level is a promising approach to leverage ubiquitous intelligent devices and create new synergies between software systems and embedded devices (Ferreira 2013).

SOA has been used to great effect in web based systems to create an ecosystem of collaborative parts. The IoT is seeing growth in new application spaces and new application requirements with an evolving ecosystem of platforms, frameworks, protocols and devices (Suresh and Daniel 2014). This means system integrators are presented with the challenge of evolving their legacy systems, and technologies, to satisfy the new requirements and make use of new technologies.

Model driven engineering in the domain of mechatronics and industrial control is not a new discipline at all; various approaches have been researched such as Intelligent Mechatronic Components (Vyatkin et al. 2009), Automation Components (Vyatkin, et al. 2005), Model-Integrated Mechatronics (Thramboulidis 2005) just to mention the most well-known paradigms of the field. All of those rely on the encapsulation of hardware and software models of automation and control systems (ACS) into individually modelled artefacts, which are stored in a centralized knowledge repository and hierarchically composed into the desired system. Different languages and modelling formalisms have also been applied to the description of those artefacts, mainly based on the particular domain specific requirements and abstraction levels, such as Matlab/Simulink, UML profiles, Labview and SysML.

The model proposed in by Gross (Gross 2009) (namely COBRA) was developed with the purpose of flexible composition and reuse of software artefacts accepts ideas from object-oriented and component-based methods. The model understands a System or a System-of-Systems as a component that can interact with others through interfaces and can be decomposed in other Systems or components.

Although function block design view enhances software reusability and provides object-oriented modularity the system design still remains closed-loop. However, in collaborative automation, model driven engineering is mostly used to support the design of System-of-Systems (SoS); hence it is based, at least on the system level, on loosely coupled open loop service oriented control principles (Blomstedt, et al. 2014).

Funded by EU and member countries, project ARROWHEAD focuses research and innovation for collaborative automation using interoperable services for smart production, to improve quality, efficiency, flexibility and cost competitiveness.

3. POWER SUPPLIER CASE DESCRIPTION

The power supplier VATS, which ensures power supply at the territory of Ventspils harbor in Latvia, maintains electricity meters that comply with IEC 62053-11, IEC 62053-22, IEC 62053-21, and IEC 62053-23 standards. A primary monitoring interface is a 20mA current loop operated by a master station.

Communication is performed according to the standard IEC 62056-21 protocol, with appropriate software is used for data reading and processing. For local data readout via electrical interface, an appropriate converter is used (e.g. current loop RS232 or RS485/RS232). For further data transmission Power Line Communication (PLC), RF, PSTN, GSM, GPRS can be implemented.

Existing data reading is implemented both as wire and wireless solutions, when wireless communication comprises GSM/GPRS modem serial bridges. The existing legacy solution has a number disadvantages, e.g. some of them:

- Hardware incompatibility with the generic data processing and end applications functionalities;
- No options for implementation of consumer oriented smart electricity meter readout devices (e.g. IEC1107 optical interface wireless readout device operable by the consumer and his data processing equipment);
- Wireless network shows interference (messages collisions), however a real-time analysis of QoS is not possible.

4. NEW SYSTEM'S ARCHITECTURE

By now a majority of current approaches to IoT and SoS based automation systems have selected SOA as the approach for IoT interoperability and SoS integration. SOA can be characterized by a service based data exchange between a service producer system and a service consumer system. The Arrowhead project among other formulated a number of fundamental properties, defined in more details below:

Loosely coupling. Two SOA systems do not need to know about each other at design time to allow a run time data exchange. The identification of available system services is established at run-time making use of service registry and discovery mechanisms supported by a *service registry and discovery system* see Figure 1. A new SOA service will register itself in the service registry, upon which it will be discoverable by any other service in the network.

The loosely coupling between software systems in SOA is supported by an independent service registry and discovery system, which allows systems to register services and subsequently discover the registered services.

Late binding. In a SOA system, the exchange of data between two systems is established in a runtime. The run-time coupling is initiated by an orchestration mechanism possibly with the support of authentication and authorization mechanisms supported by an *orchestration system*, which provides the end point of the selected producer to the requesting consumer (see Figure 1).

If necessary, the authentication and authorization system is consulted to check, if the service consuming system can be authenticated and authorized to consume the requested service.

The late binding between software systems in SOA is supported by an independent *orchestration service* possibly supported by an authentication and authorization services. Thus, facilitating the necessary endpoint information, authentication, and authorization allows autonomous data exchange.

Autonomy, pull and push behavior. Each device and related software system can act on its own regardless of another systems. Thus, it is responsible for its own data and functionalities. Once a service exchange is set up between two systems, this exchange may go on without further involvement of any supporting services/functionalities. In a SOA environment a service consumer requesting data - a pull behavior, can initiate the data exchange. A timer at the service consumer, thus periodically creating data pulling of a sensor, can for example control a pull behavior. A producer that knows about conditional data request - a push behavior, can also initiate the data exchange. Data is then pushed from the producer to the consumer (see Figure 1).

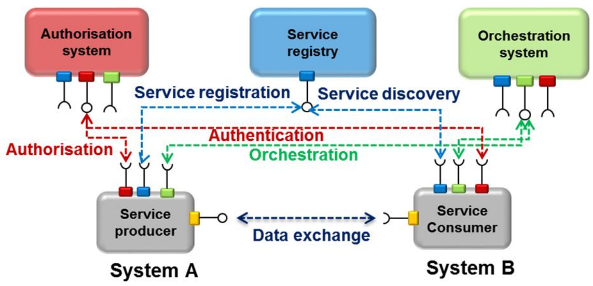

Figure 1: Data exchange between a service producer system and a service consumer system (Delsing 2015).

The architecture being proposed in this paper is built upon the Arrowhead Common Framework, which consists of a number of core services that support the development of generic SOA systems. The Arrowhead Common Framework thus acts as an enabler for systems from different areas (e.g.: industrial automation, energy production, home automation, smart grids, etc.) to facilitate their interaction with each other and exchange information. This multi-area approach can enable considerable savings in terms of efficiency, interoperability and maintenance cost. The purpose is to enable the different application systems in an easy and flexible way being able to collaborate successfully due to support provided by the common core services.

The proposed architecture of "Power metering System-of-Systems" (SoS) is structured upon six modules, where three of them belong to the *core Arrowhead framework* – Service Registry, Authorization, and Orchestration, and the other three modules (*application systems*) exchange business logic data – the "Multi-resource smart meters system", Back end System and Control System (see Figure 2) shows a generic view according to the Arrowhead approach.

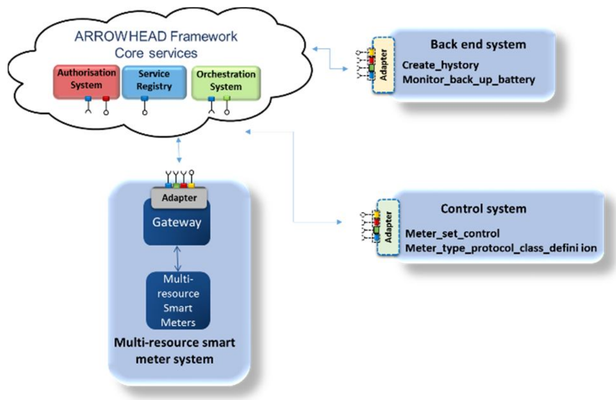

Figure 2: A model (Arrowhead) view of the "Power metering System-of-Systems" (SoS) and its comprising systems.

The core services enable authentication, authorization and services registration for three other application systems. Furthermore, Orchestration system enables algorithms and scenario for communication between three application systems and usage of its services.

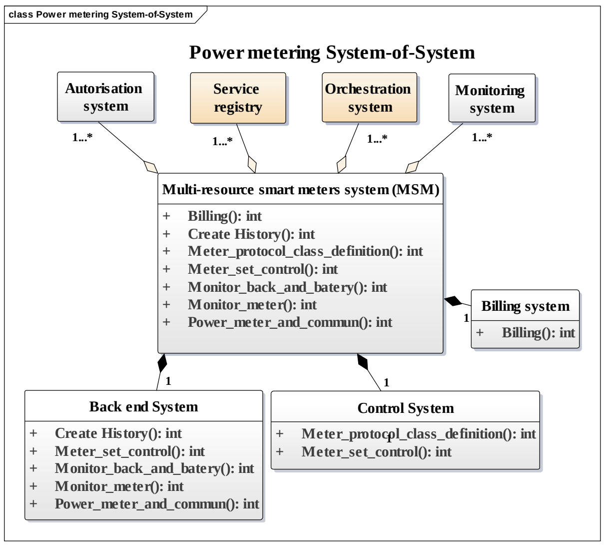

Figure 3: Power metering System-of-Systems

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Applying the Arrowhead approach we described the architecture in several levels, when each next one offers more detailed view. A "Power metering system" (see Figure 3) is depicted in the document System-of-Systems Design (SoSD).
At the next level, each of the systems comprising SoS has been defined in the documents System Design (SoSD) and System-of-Systems Design Description (SoSDD).
The Figure 3 illustrates a domain model of "Power metering" SoS depicting, how "Multi-resource smart meters system" collaborates with other systems. For example, at Figure 4 one can see one of the uses cases depicting collaboration between Control System, MSM and meter-sensors software aiming to define meters type protocols.

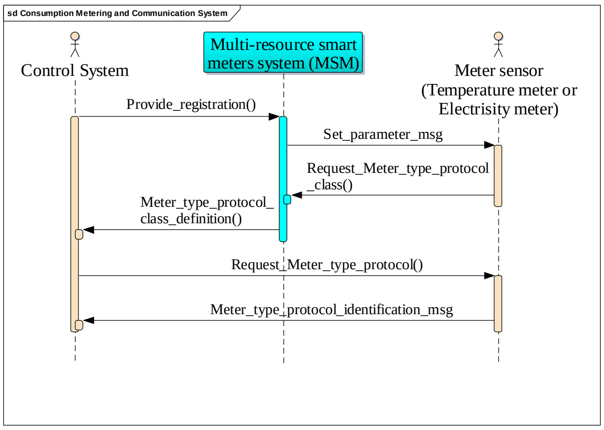

Figure 4: The use cases of collaboration between Control System, MSM and meter-sensors software aiming to define meters type protocols.

Keeping in the mind that proposed multi-resource smart meter solution should comply with IoT approaches and standards we have proposed a mapping of the IEC 62056 standard functionalities to a RESTful approach. IEC 62056 is a set of standards for Electricity metering data exchange by International Electrotechnical Commission. The IEC 62056 standards are the International Standard versions of the DLMS/COSEM specification. DLMS or *Device Language Message Specification* is the suite of standards developed and maintained by the DLMS User Association that has been adopted by the IEC TC13 WG14 into the IEC 62056 series of standards. COSEM or *Companion Specification for Energy Metering*, includes a set of specifications that defines the Transport and Application Layers of the DLMS protocol.
The IEC TC13 WG14 groups the DLMS specifications under the common heading: "Electricity metering data exchange - The DLMS/COSEM suite". DLMS/COSEM protocol is not specific only to electricity metering, it is also used for gas, water and heat metering:

- IEC 62056-5-3:2013 DLMS/COSEM application layer
- IEC 62056-6-1:2013 Object Identification System (OBIS)
- IEC 62056-6-2:2013 COSEM interface classes

The COSEM server model is structured into three hierarchical levels: Physical device, Logical device and Accessible COSEM objects. Therefore, we have proposed a mapping of the IEC 62056 standard functionalities to a RESTful approach. Due to the paths resemble a fully-qualified file-name notations, they can be mapped to a URL, which makes the data model suitable for REST, therefore a REST URL could look something like: http://hostname/device/node/class/attribute .

The "Multi-resource smart meters system" operates as a Power_consumption service provider. This service is used to read instantaneous data from Multi-resource smart meters (MSM). Among the three different types of resource meters - electricity, water and heat, only the Electric Meter has been depicted in this work. The Power_consumption service complies with the IEC 62056 standard. Electrical data provided by this service includes: current, voltage, power factor, active power, reactive power and apparent power. The semantic protocol used by this service is REST_TLS_JSON.
Figure 5 in general describes the Power_consumption service for Multi-resource Smart Meter (MSM) systems, including its abstract interface and abstract information model. The purpose of the Power_consumption service is to provide the instantaneous electric data measured by the MSM device.

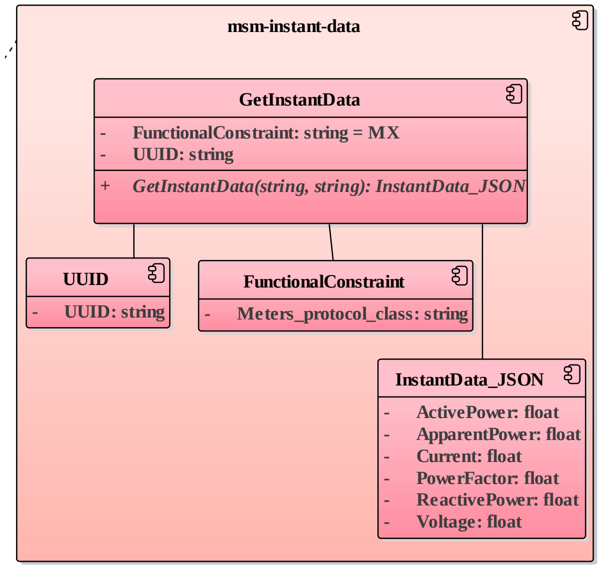

Figure 5: Power_consumption service class components model

UUID, Universally Unique Identifier, is a string used to get access to the services provided by the MSM system. This string is returned by the IEC 62056 Authorization service.
FunctionalConstraint is a two characters string (defined by the IEC 62056 standard) data type describing the type of information that is requested.
InstantData_JSON is an abstract data type describing a set of instantaneous electric variables: current, voltage, the measured instant power factor, etc.

5. WIRELESS SENSOR NETWORK IMPLEMENTATION

5.1. MSM smart meter devices implementation

The proposed Multi-resource smart meters system is implemented as *a hardware* in three main node components. This hardware design has been implemented in parallel with the development of the software model solution.

Metering node – is connected to the meter via switchable/selectable interfaces (current loop, IEC 1107 optical interface). Metering nodes have rechargeable batteries for operation during a power outage and for long-term standalone operation in consumer metering scenarios (e.g. wireless IEC1107 interfaces or drive-by current loop interfaces). Inter-system communication is possible using selectable interface modules (e.g. IEEE 802.3, ISM radio interface, GSM/GPRS);

Repeater node – provides data retransmission to a gateway sink node by self-organizing mesh network in ISM band providing balanced power usage for power-constrained system components;

Gateway node – provides a selectable inter-system and backend communication interface architecture. It implements requests, readouts pre-processing and secures data delivery and queuing.

The trial network system is able to comprise different types of transmitters for metering: pulse counters for the water meters (with at least two inputs for cold and hot water), pressure meters from pipeline manholes equipped with temperature sensors, and electricity meter devices (e.g. Itron equipped with a transmitter interface module). The supported meter types are predefined by communication classes in the gateway node and can be dynamically added and updated via an embedded update service at the supervision server. The scheduled control method provides meter protocol definitions aiming to ensure communication capability for the gateway node and the meter nodes.

The received readout data is pre-processed by the meter processing classes on the gateway node. The readout data is serialized using SenML, JSON, compressed into XML Interexchange (EXI) and is transmitted using HTTP protocol for data registration and processing at the server. EXI ensures more efficient data transmission over constrained (i.e. small payload and bandwidth) networks. Further integration of CoAP protocol to be explored on the next project stage.

A communication dialogue with ELGAMA meters (LZQM, EPQM) is controlled by serialized protocol commands using 20mA current loop or optical interface. As the constrained nodes have to maximize idle times, the selected communication is a client-server model, where the metering node initiates requests for readouts. The identification message specifies the further communication speed that is acknowledged by a metering node. The identification message contains a numerical code that is encoded by a tariff device specification table from the codes given. After that, the tariff device (electricity meter) starts transmission of tariff data. An acknowledgement or a retransmission message is sent from the metering node as a response to a data message.

Meter nodes provide raw data exchange by the predefined protocol method using encapsulation into carrier messages. The meter type (i.e. electricity meter, temperature, pressure) is defined in the message header and is provided by the protocol class, which corresponds to the metering node interface type.

5.2. Sensor network gateway implementation

The gateway comprises an open printed circuit board with elements mounted on the BeagleBone Black module using two 13-pin plugs the BeagleBone Black jack. For data collection from sensors – transmitters the RFM31B module is used. RF module captures the radio data packets that arrive at pre-programmed radio channels. If its characteristics correspond to the pre-programmed ones, they are recorded in FIFO memory, and the module generates a break signal. The controller stores packages in its RAM memory and transferred for analysis.

The gateway polls its radio interface for received data, validates the telegrams and prepares them for sending. If the sending operation fails, the gateway moves to offline mode, where data is stored into a local database until network connection is available, if no writable data storage is available, the data is stored into RAM queue until all memory is exhausted and the device heartbeat look forces the device to restart.

Inter-system communication is possible using selectable interface modules (e.g. IEEE 802.3, ISM radio interface, CAN bus, GSM/GPRS) (see Figure 6).

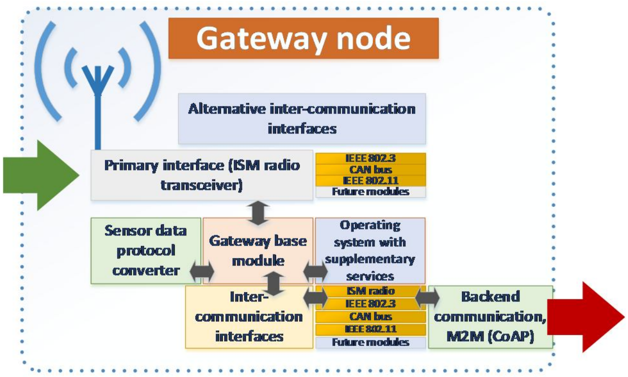

Figure 6: Proposed gateway node device (MSM)

The interface modules are selectable and expandable depending on a target application and data pre-processing. Each node can have multiple interface pairs that act as interface/protocol bridges where the primary communication interface is the ISM RF. A common bus for power control, and communication interface (SPI, I2C etc.) is equipped by pluggable slots that are integrated into a monolithic PCB board for conformity with IEC standards for the final application.

The gateway devices contain an initial firmware, which is running based on Open Embedded operational principles with data pre-processing and delivery service capable of dynamic live module loading and initialization from a centralized server or servers pool

A gateway, when is activated for the first time at the registry server, is waiting until receives commands to start the functions and an address of the target server, where the received data to be delivered. The exchange of data is ensured through the COAP or HTTP protocols using the RESTful data sharing principles.

The registration is confirmed automatically or manually, with the following parameters specified: device name, group, type, network settings, gateway dynamic loadable modules, VPN configuration, Wi-Fi settings, encryption settings and the working mode registration server/service (WMRS) and working mode data submission server/service parameter (WMDSS). The WMRS and WMDSS parameters allow the gateway control function delegation to other servers for load balancing or third party service operators by allowing them to perform parameters and control functions as the FTRS.

The initial registration server can send a redirect to another registration server or to direct the gateway to post received messages at a specific server. This allows the grouping and association of the devices to particular projects and to balance the load of backend servers. All communication is done via XML documents in compressed or uncompressed form (EXI - Efficient XML Interchange).

The return data blocks of metering device are specified as defined by IEC 62056-21, IEC 61107, and adapted to comply with the manufacturer model sub-specification using Object Identification System (OBIS) codes. The system provides standard identifiers for all data within the metering equipment (both measurement values and abstract values). OBIS names are used for the identification of COSEM objects and also for identification of the data displayed on the meter and transmitted through the communication line to the data collection system.

The similar principles can be applied to IEC 62056 compatible heating, cooling energy, and water (cold/ warm) meters, i.e. in the areas where MSM meters could be used.

6. CONCLUSIONS AND NEXT STEPS

The first steps of the new system architecture implementation have been done such as overall system architecture design, diagrams iteration and explanation, and technical design documents for descriptive and technical reference of communication protocols. Furthermore IEC 62056-31 electrical current loop interface analysis (protocol level) and adaption for Elgama, Kamstrup electricity meters, research on compatible interface/protocol standards, spare power supply battery and radio module integration into microcontroller logic have been implemented.

The hardware design of proposed communication system consisting of meter nodes, repeaters and gateways provides the network layout using selectable interfaces that scale with existing/legacy grid infrastructure. Such modular architecture offers easier extension by utilizing the base system components.

The research to achieve compliance between the legacy power meters and the new system, which comprises SOA approach and smart WSN for power distribution network monitoring has been started. To ensure SOA as Restful services on WSN sensor node devices of the legacy power distribution network we applied such standards as IEC 62056-53, IEC 62056-61 and IEC 62056-62 to describe the developed service, its interfaces and data model.

At the first approach mandatory core systems such as Authorization, and Orchestration have been simulated at Arrowhead Test Tool G2 (developed by Arrowhead project partners BnearIT and Lulea Technical University). In addition, part of the functions of Orchestration system has been tested at Ventspils water distribution network, namely, gateway and sensor nodes registration and reconfiguration. The next core system, Data repository – History (locally accumulated for billing and trend analysis), has been developed in the project and piloted at Ventspils water distribution network and at building maintenance systems in Riga.

Sensor data related to water flow, water pressure, temperature, heat consumption, humidity in the building etc., using semantic encodings like JSON, XML, are stored, automatically decoded and processed. The data are automatically recorded with their timestamp and meta-data. Decoded sensor data can later be processed and filtered for analysis and visualization purposes.

However, the further research to be done to implement a mandatory scope of core systems (Authorization, and Orchestration) using IEC 62056 standards and Arrowhead framework approach.

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