Wireless Sensor Networks and SOA Development for Optimal Control of Legacy Power Grid

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***Abstract*— Over the last decades, WSN systems enabled quality monitoring of power, heat production and water supply process. Empirical and practical evidence shows that the development of new services, which require new business models, is necessary. To address this issue, a framework for evaluating service prototypes and associated business models is proposed. A pilot 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. During the next three years, the framework will be tested by evaluating a new smart services concept and WSN approach development. The case study is done in a liberalized power supply market conditions.**

Keywords - wireless sensor networks (WSN), System-of-Systems, SOA-based systems.

I. INTRODUCTION (HEADING 1)

Liberalization of 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. Upgrading of power grid systems through deploying wireless sensor networks (WSN) – a technology that allows monitoring and intelligent control operation of the power systems - will foster effective use of electrical energy. It also enables provision of qualitative customer services, as the data related to a status of the networks are available in a timely manner and in the stated amounts. WSN will provide also an opportunity of flexible billing to end users. Over the last decades, the use of WSN systems in enabling quality monitoring of supply and distribution process has been widely discussed, but so fare has been just a little deployed by power supply infrastructure services providers.

The technology development time scale, as well as empirical and practical evidence shows that the development of new services, which require new business models, is necessary for improving business processes effectiveness, improving customer services and for repeated services deployment via SOA application. To address this issue, a framework for evaluating service prototypes and associated business models is proposed.

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 [1]: open architecture and open protocol implementation, communication between sensor nodes and back-end system, which ensures communication data presentation as web services. A new generation of the modular technical solution for sensor, repeater, and gateway nodes for application on main types of electricity, water, heat and gas meters will be developed by the end of the Arrowhead project.

The paper is structured as follows. Authors summarize related works in the area of WSN and SOA in Section II. A legacy power supplier case is described in Section III. The essence of the approach offered in the paper is expressed in Section IV, which details main steps proposed by the authors for the system-of-system model and SOA implementation on WSN nodes, which monitor and control power distribution electrical network. The main contribution of the research, general results and possible directions for future work are discussed in the Conclusion of the paper.

II. 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 [2]. 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 [2]. For example, SOA is able to support cooperative function between district heating system and other energy and comfort related system, e.g. ventilation, heat pumps, etc. [3].

However, SOA application to deeply constrained devices such as sensor nodes is still an open research problem due to unresolved issues. Among them are incompatibility of protocols used by different producers of meters, low data transmission speed from wireless sensor nodes to sinks, limitations of processing capabilities of wireless sensor nodes; low memory of sensor nodes that restricts the use of an excessive XML scheme and a limitation of battery power [4], [5].

The above-mentioned constraints are mostly resolved using two approaches. The first approach is to use middleware in gateway devices for interaction with sensor networks. The second approach is to deploy interoperable Simple Object Access Protocol (SOAP) enabling web services on nodes without using gateway [6], [7].

The majority of research efforts have been directed towards using middleware software, which runs on more capable devices or gateways To avoid resource-intensive operations being performed on the sensor nodes, a middleware software deployed on gateway devices first communicates with the nodes in an ad-hoc manner, and then translates their functionality as web services to external systems [8].

The next important issue is related to software architecture models used to abstract and classify realities into relevant groups. The increasing role of modeling in software system development promotes a methodology, mostly represented by OMG's solution for system abstraction, modelling, development, and reuse—Model Driven Architecture (MDA) [9]. The key component of systems modelling, which underlies the principles of MDA—Unified Modelling Language (UML)—is a widely accepted standard for modelling and designing different types of systems and is used to define several kinds of diagrams, their elements and notation [10].

Furthermore, different types of software architecture models have been created last years. For example, IEEE has defined a standard IEEE 42010-2011- ISO/IEC/IEEE, "Systems and software engineering - Architecture description", for the architectural description of software intensive systems [11]. It includes a conceptual framework to support the description of architectures, and the required content of an architectural description.

Rational Architectural Description Specification (ADS) [12] is able to describe complex architectures, such as enterprise, e-business, embedded systems and non-software systems. It features a formal definition of requirements evolution and architecture testability, and utilizes UML notation where possible.

The model proposed in by Gross [13] (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.

A proposed novel approach utilizes different models approach, but it goes beyond of it. It takes into account the variety of stakeholders and their needs, due to specific of the System-of-Systems, which aims to ensure collaboration between existent, legacy and projected systems.

III. 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. The current master station supports by four electricity meter devices, taking into account that eight devices is a maximum defined by the corresponding standards, (the master station provides 26V).

A sample circuit arrangement in four-wire configuration [14] is depicted on Fig.1. Each of the masters is wired to a concentrator unit, connected to a PC operating data requests and replies processing.

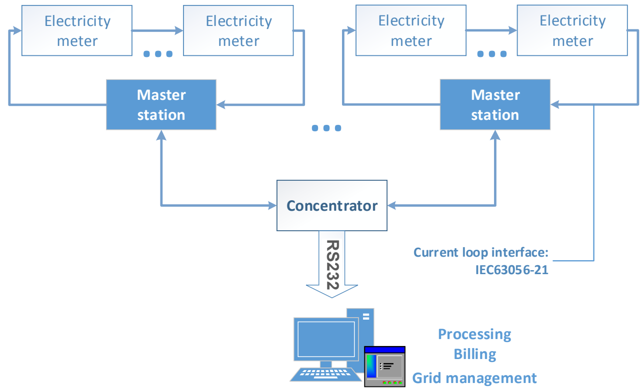

Figure 1. Existing VATS solution for power consumption metering data collection and proceeding.

For scenarios, where data readings have to be delivered without existing wired connection, GSM/GPRS modem serial bridges are used as an extensions of interface lines. This solution is considered as legacy, as it is replaced by the meter manufacturer RS485 to RS232 devices and current loop based remote data readout devices based on GSM/GPRS modem already integrated into the meter readout interfaces.

The main disadvantages of a legacy solution:

- Wiring is not always available, but existing wiring might be a prone to interference problems;
- Power supplier has a high density of meter devices distributed in different buildings, where communication interface hybrid commination might optimize the data delivery;
- Hardware incompatibility with generic data processing – end applications;
- Not suitable for public network communication scenarios (IEEE802.1Q, VPN technologies, etc.);
- No option for meter reading hybrid interfaces at meters – IEC1107 optical interface for data readouts;
- No options for consumer oriented smart electricity meter readout devices (e.g. IEC1107 optical interface wireless readout device operable by the consumer and his data processing equipment);
- No option for wireless network interference real-time analysis (jamming detection);

IV. VATS SYSTEM'S NEW FRAMEWORK

A. New system architecture

VATS legacy system replacement by the system, based on WSN novel solution has been started in a frame of Arrowhead project (ARTEMIS program) applying a new Arrowhead framework concept, which is based on three functional areas, called core functionality. The framework goal is to achieve characteristics that a service-oriented approach enables by fulfilling SOA fundamental principles Lookup, Loosely coupled and Late binding. The purpose is to enable the application systems in an easy and flexible way being able to collaborate successfully. The Arrowhead Framework developed a common approach of how to document SOA-based systems and how documents relate to each other. The documents structure is built on three levels, namely: System-of-Systems, System and Service Level [15].

In the context of the Arrowhead Framework a System is what is providing and/or consuming the services. A System can be a Service Provider of one or more services and at the same time a Service Consumer of one or more services. System-of-Systems can include many internal systems that communicate using the Arrowhead framework technologies, although they can be based on legacy technologies. A service notion is used to exchange information from a providing System to a consuming system. It is based on a number of service orientation principles and it can be realized by an arbitrary number of service producers and service consumers [2].

Further, the authors briefly describe a system-of-systems developed as a novel solution for replacement VATS legacy system. In order to demonstrate novel approach, the charts depicting involved systems, documentation and use cases are presented in this work. A practical implementation is depicted in Fig. 2, which shows the links between documents. Due to the lack of space, only part of the documentation chart is displayed on Fig. 2.

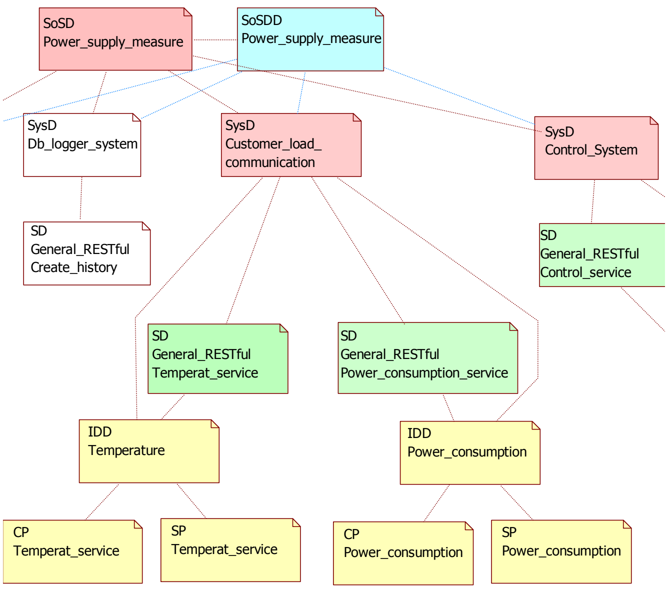

Figure 2. "Power supply measure" system of system documentation

A "Power supply measure" system of systems is defined in the System-of-Systems Description (SoSD) and System-of-Systems Design Description (SoSDD) documents. The correct way of working of each system comprising "Power supply measure" SoS, is represented by three systems in the System Description (SysD) documents. Therefore, each "system type" can talk to each other or identify the gateways/mediators' needs. The Fig.3 illustrates a model view of "Power supply measure" SoS, depicting how Customer load and communication system collaborates with other systems.

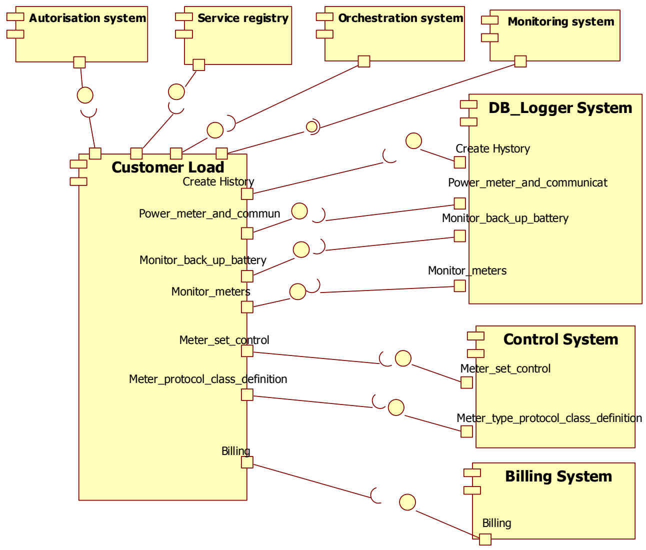

Figure 3. The figure illustrates a model view of the Customer Load and communication system and its collaboration Systems.

A proper description of Systems in the SysD document requires a listing of all the provided and consumed services with references to their Interface Design Description (IDD); therefore, a general temperature service and a general power consumption service to be documented.

At the Service level, the IDD describes how to realize the service identifying explicitly the technologies to be used. This document refers to the Communication Profile (CP), the Semantic Profile (SP) and the Service Description (SD). The CP is composed by the transfer protocol (e.g., HTTP, CoAP), security for the transportation of data and the data format. The SP contains information about how a specific measurement (e.g., a temperature value or a consumption volume) is coded (e.g., in a standard such as XML or SenML).

Three main use cases depict, how Customer load and communication system collaborates with DB Logger, Control and Billing systems (see Fig. 4). A use case No 1 describes, how Control system manages power and temperature meters installed at a customer side and power substations. In this use case, Control system collaborates with Meters type class protocols definition system, Meters set control system and Customer load and communication system. A use case No 2 shows, how Customer load and communication system ensures power meters data reading and data exchange between meters and back end systems (DB logger system etc.). Billing system collects billing details from the power consumption meters in a use case No 3. Billing system requests consumption information from the DB logger system and requests Clients tariffs setting system that responds with tariffs information.

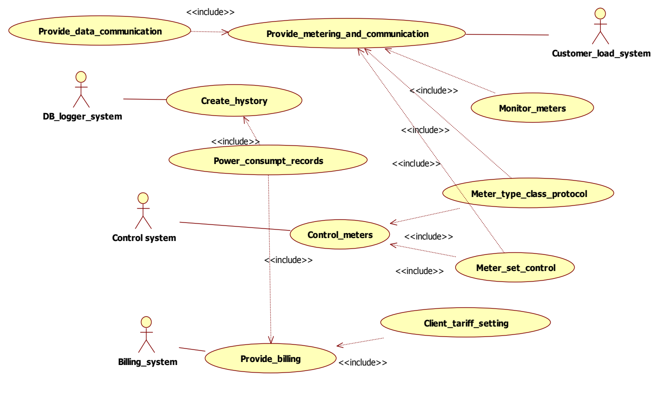

Figure 4. Customer load system high-level user cases.

B. SOA implementation for VATS network

The proposed control system of VATS power distribution network consists of a multi-interface modular platform consisting of three main components.

Metering nodes are connected to the meters via switchable/ selectable interfaces (current loop, IEC1107 optical interface (see Fig.5). Metering nodes are equipped with rechargeable batteries for operation during power outage and for long-term standalone operation in consumer metering scenarios (e.g. wireless IEC1107 interfaces or drive-by current loop interfaces).

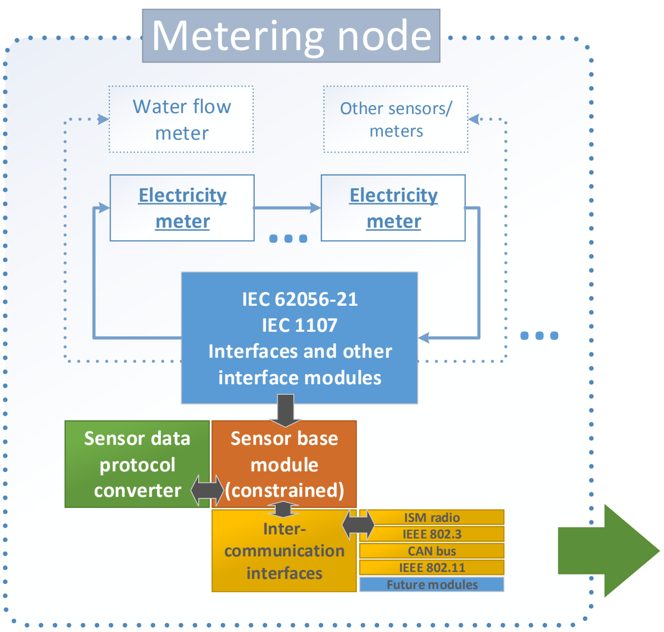

Figure 5. Proposed metering node device.

Gateway node has a selectable inter-system communication interface architecture. It provides requests, readouts pre-processing and secures data delivery and queuing (see Fig.6). Inter-system communication is possible using selectable interface modules (e.g. IEEE 802.3, ISM radio interface, CAN bus, GSM/GPRS).

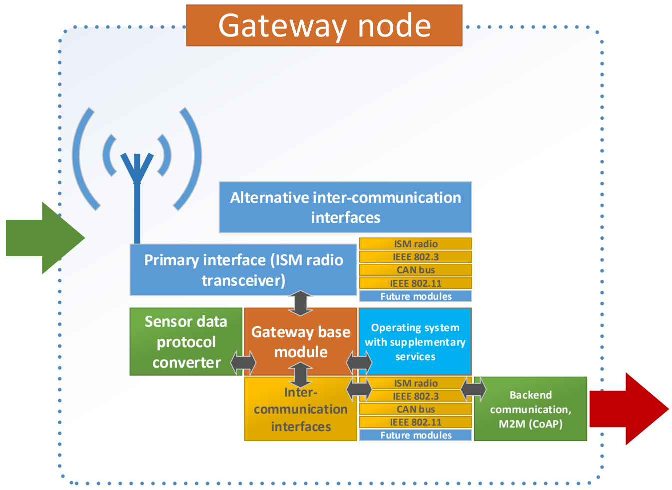

Figure 6. Proposed gateway node device

The proposed platforms architecture is developed on a base system expanded with interfaces as functional blocks. Interfaces in a prototype phase are connected via multiport interface board divided by functions for input and output data logical flow directions. 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 individual configuration of the selected and configured into an onboard non-volatile memory block, which controls the initialization and data sequential redirection from input-to-output interfaces and vice versa, depends on a communication model and application. The metering node provides the interface and RAW data encapsulation where the media type in transport protocols is oriented to SenML compatibility and CoAP integration.

The main advantages of the proposed system:

- Network layout can be optimized to suit environmental situation using selectable interfaces that scale with existing (legacy) infrastructure;
- Modular architecture offers easier extension keeping the base system components;
- Extensibility offers the possibility to expand multi interface operation by combining different communication protocols with external or third-party equipment/systems;
- Inter-system communication data exchange is provided in self-describing formats (e.g. SenML implementation) allowing easier integration and compatibility;

- Cross-system communication data exchange is provided using RESful architecture (e.g. CoAP implementation) allowing IoT convergence and Internet based data exchange;
- Core platform provides expandability for diverse sensor and metering equipment.

C. SOA service for electricity meter readout

To enable compliance between a legacy system and a new system, which comprises SOA approach and smart WSN for power grid monitoring, it is necessary to implement transition from the appropriate communication protocols used by most of electricity meters manufactures to open protocols architecture.

Communication dialogue with ELGAMA meters (LZQM, EPQM) as of IEC62056 is controlled by serialized protocol commands using 20mA current loop or optical interface. A protocol specification example (Fig. 7) describes a data readout process used by metering node that provides the initial request message with an optional device address in multi-device tariff device scenarios at a predetermined initial baud rate of 300Bd.

As the constrained nodes have to maximize idle times, the selected communication is a client-server model, where the metering node initiates requests for readout. 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 of a data message. The same principles applies to IEC62056 compatible heating, cooling energy, gas, and water (cold/ warm) meters.

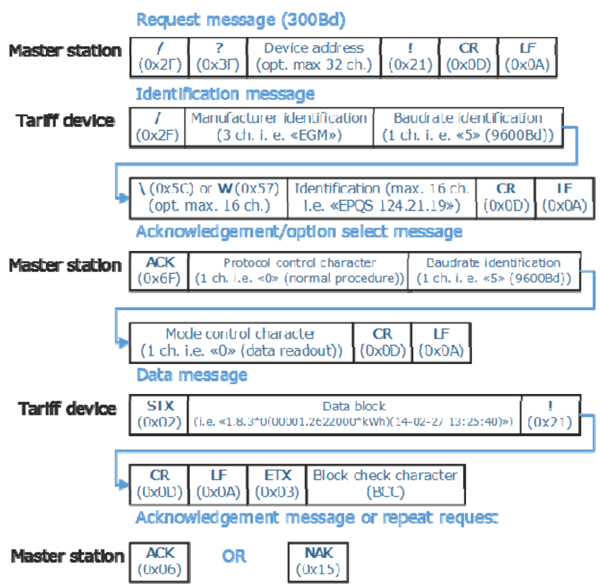

Figure 7. Example of electricity meter readout mode of communication protocol (IEC62056-21).

The data transmission process from metering nodes to a gateway node has to be done with the minimal cost – in context of time and power consumption. Therefore, pre-processing of the raw data and further delivery has to be handled by non-constrained devices like gateway node and back-end processing system connected to permanent power sources.

For a trial-metering network, 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 gateway nodes request update information periodically, but also backend-initiated procedures are possible. The scheduled control methods provide meter protocol definitions aiming to ensure communication capability for the gateway node and the meter nodes (see Fig. 8.).

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. The protocol and meter processing class provides the communication procedure for data readout using modular interface system to transmit data to the metering node directly or via mesh network (repeater nodes).

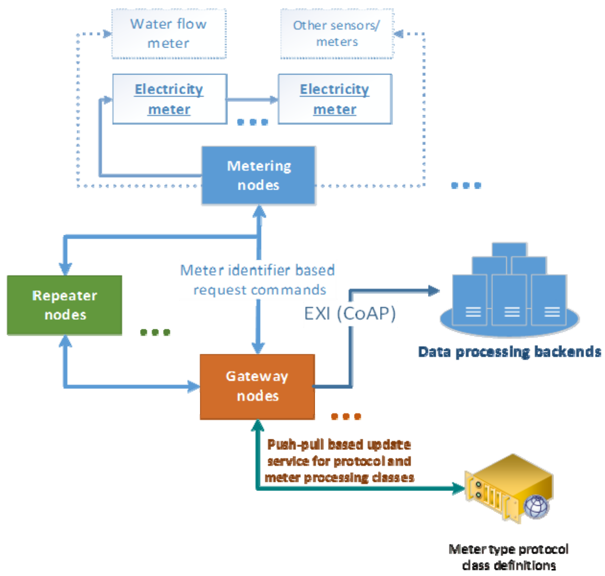

Figure 8. Arrowhead electricity meter trial communication architecture design diagram.

The received readout data is pre-processed by the meter processing classes on the gateway node. The readout data is serialized using SenML, JSON [16], compressed into XML Interexchange (EXI) and is transmitted using HTTP protocol [17] for data registration and processing. 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.

For electricity meters, using current loop or optical interface, the readout data can be serialized by using the corresponding attribute for each readout data subset. A base name attribute is used to identify the device, an additional Unix timestamp (for example, “bt” – 1392126364 corresponds to

Tue, 11 Feb 2014 13:46:04 GMT) of the data readout, the base unit and the version of the media type format are stored. Unfortunately, no definition of the unit type ("u") for kilowatt-hours exists in the SenML draft [16]. Below one can see an example of readout data subset:


```
{"e":[
    { "n": "1.8.1*0", "t": 0, "u": "kWh", "v": 0 },
    { "n": "1.8.2*0", "t": 0, "u": "kWh", "v": 1.2622 }],
    { "n": "1.8.3*0", "t": 0, "u": "kWh", "v": 0 }],
    { "n": "1.8.4*0", "t": 0, "u": "kWh", "v": 0.0512 }],
    { "n": "1.8.0*0", "t": 0, "u": "kWh", "v": 1.3134 }],
    { "n": "3.8.0*0", "t": 0, "u": "kWh", "v": 0.3134 }],
    { "n": "4.8.0*0", "t": 0, "u": "kWh", "v": 0.1351 }],
  "bn": "urn:dev:egm5epqs:00a0b10000001a1a/",
  "bt": 1392126364,
  "ver": 1,
  "bu": "kWh"
 }
```


V. Conclusions and Further Steps

The first steps of the new system 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 IEC62056-31 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 started.

The next steps to be done in the next three years is to find the best way, how to ensure SOA as Restful services on WSN sensor node devices of the legacy power distribution network. Therefore, the task of the further research is to enable compliance between the legacy system and the new system, which comprises SOA approach and smart WSN for power distribution network monitoring. Here are some of planned activities:

- To develop IEC 61107 interface between power meters and WSN sensors – transducers;
- To develop a prototype of a new gateways (ARM Cortex-A8, BeagleBone, Freescale);
- To develop a prototype of a gateway inter-system communication using selectable interface modules (e.g. IEEE 802.3, ISM radio interface, CAN bus, GSM/GPRS);
- To develop a model and technical design for ISM radio MESH communication interface;
- To implement a Constrained Application Protocol (CoAP) and SenML for communication between sensor nodes and back end system.

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