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An Intra-Residential Smart Metering System – Design and Implementation

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Abstract

The purpose of this paper is to describe an intra-residential smart metering system capable of differential metering of individual equipment, as it was designed and implemented as a prototype during the "Intelligent system for trading on wholesale electricity market" (SMARTRADE) project. The proposed system is capable of data acquisition, primary processing, aggregation, long-term storage, and complex data analysis. The hierarchical design is intended to cover the area of a large residential area / large building / building complex.

Keywords: smart metering, edge computing, scalability, Internet of Things.

JEL Classification: C8, Y10

1. Introduction

Residential smart metering systems are designed to ensure the measurement of electricity consumption in an apartment, house or building, thus ensuring a sufficiently fine measurement granulation for companies that sell electricity, but insufficient if a micro-analysis of the consumption is desired - we mean analysis of the consumption profile for each electrical consumer inside a building.

One can also conceive the use of the commercial residential smart metering systems for this purpose, but this way of working would be impractical, due to costs, complexity, and volume occupied by the measuring equipment (Alskaif & Van Sark, 2016).

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For this reason, in order to obtain a finer granulation of the measurement, most of the time one should not use residential smart metering systems, but composite smart home systems that also include components capable of measuring individual consumption.

The purpose of this paper is to describe the design and implementation of an intra-residential smart metering system, capable of differential measurement up to the level of individual equipment.

2. Problem Statement

The minimum requirements that such a system should meet, as it was established during the design phase, are the following:

- Scalability - the system should be able to expand or shrink easily, depending on the number of electricity consuming equipment in the residence.
- Price - taking into account that the usual financial resources of a residence do not compare to those of an organization/enterprise, the total cost of holding (acquisition and exploitation) the system should be small.
- Multiple visualization modes – various data visualization ways should be available so that it can be easily interpreted (e.g., instantaneous consumption level, average consumption, total consumption, at the level of single consumer equipment, at the level of the residence, in the form of a graph, in tabular form, comparative analysis, prediction, etc.) (Kajáti, Miškuf, Ulbricht, & Zolotová, 2018)
- Data analysis - the ability to perform data analysis operations at various levels and of various complexities.
- Interoperability and portability - the data collected and analysed by the system should be available in various forms to the residential user. Hence, the need for at least the final results of the analyses to be available online / on PC/smartphone/tablet, etc., regardless of the operating system and browser used. Also, the primary data should be available for analysis using various data processing applications. Another facet of interoperability would be the possible communication between the components of such a system and other components in the smart-home category.
- Flexibility - the system should be able to analyse data for the whole range of residential electrical equipment, from those with very low consumption, of the order of a few watts or milliwatts (e.g., night light, stand-by equipment), to those with relatively high consumption, of the order of kilowatts (e.g., air conditioners, washing machines, etc.).
- Open source - at least the software component of the system should be available in an open-source variant so that it can be easily adapted to the various requirements of residential users. Besides, the use of open-source software would probably also contribute to a lower TCO.
- Adjustable data sampling frequency - The time interval at which the data is taken should be adjustable, from very short time intervals (e.g., 1-10 seconds) to longer time intervals (30 minutes - a few hours) for one to be able to experimentally achieve the correct balance between a sampling frequency as high possible - to better track the evolution of equipment with high

consumption variability, and the storage space required for data storage - if we are trying to reduce costs, at least the components of the system that will deal with the primary data collection and processing may not have very high performance and storage capacity.

- Ease of use − at least the final visualization components of the analysed/ aggregated data should be easy to use for the average user.
- Super-scalability − systems of this type should be able to be further aggregated into larger systems, which will achieve the accumulation/analysis of data at the level of the residential complex or maybe even more. Fulfilling this requirement would increase the cost requirements and would require the addition of additional levels to the proposed system. Ideally, such an additional level should consist of a single, optional subsystem that achieves this purpose only − the operation of subordinate systems should not depend in any way on its operation.

3. Design and Implementation

The system proposed in this report consists of two distinct layers:

- Primary Data Acquisition and Processing (PDAP) subsystem. Subsystems of this type are designed to cover the level of a small residence/building. The requirements covered are the above, less the requirement of super-scalability and partly those of data visualization, data analysis, and respectively interoperability and portability.
- Aggregation, long-term storage, and complex data analysis (ASDA) subsystem. This subsystem is designed to cover the level of a residential complex / large building / complex of buildings. The covered requirements are super-scalability and, in part, data visualization, data analysis, and interoperability, and portability.

The structure of the proposed system is represented in Figure 1.

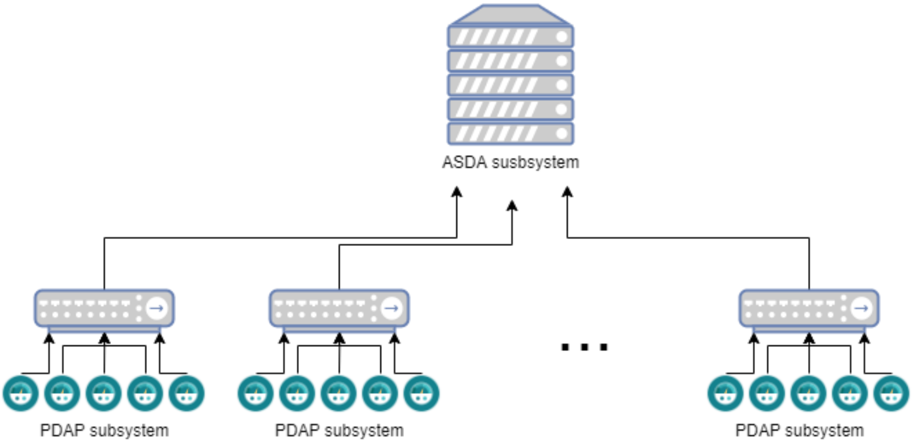


Figure 1. The structure of the data measurement, storage, and analysis system, overview

4. Primary Data Acquisition and Processing (PDAP) subsystems

The primary data acquisition and processing subsystems should contain two types of components:

- Intelligent components for measuring the consumption of equipment, to ensure the data acquisition function of the PDAP subsystem.
- A component of short-term storage and primary analysis of data to ensure the control part of the PDAP subsystem.

A diagram of the PDAP subsystem is shown in Figure 2.

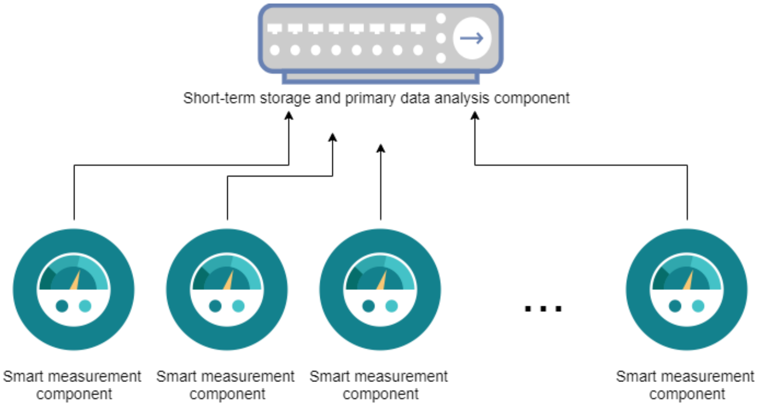


Figure 2. The PDAP subsystem diagram

4.1. The smart measurement component

For the smart measurement components, three possible technical implementations were available:

First alternative. Using various types of analogical sensors, such as current and voltage sensors. Analog sensors can be used with any system that can acquire data in the analogical format. The disadvantage is that the sensors of this type transfer data only by cable, only in analogue format, the installation is more complex (the sensors are placed on the power cords of the tracked equipment) and can prove complicated for an individual without basic knowledge on electronics.

Second alternative. Using IoT current and voltage sensors, such as the one described in (magLab, 2020). Sensors of this type are digital sensors, IoT integrated so they can be used with any connected system.

On these two alternatives, the value of consumed power would be obtained by calculation, from the values of current and voltage, respectively.

The advantage of using this alternative is obtaining more complex information (voltage and current instead of power), thus being able to also track the quality of supplied electricity.

Third alternative. Using smart plugs. Smart plugs are equipment used to measure power consumption. Smart sockets are interposed between the consumer and a regular socket, thus offering the advantage of easy use. Other advantages of using this type of data acquisition are the fact that the data is provided in digital format, the data transfer is done wirelessly and some of these also have data processing and control facilities.

Following the comparison of the two working variants in terms of advantages and disadvantages, for the PDAP subsystems, we decided to use smart sockets.

We decided to use the products provided by TPLink (TP Link, 2020) for the implementation of the system, for reasons related to the ease of configuration and the multiple ways of acquiring the data offered (both through the software of our product, freely available and separately, through the usage of an open-source script, thus managing to cover the criterion of using open source software for data acquisition, storage, and analysis).

4.2. The short-term storage and primary data analysis component

For the short-term storage component and primary data analysis, two main implementation options are also available:

First alternative. Use of microcontroller-based computers (small computing systems, based on the use of an 8/16/32 bit microcontroller; typical examples of such systems are Arduino Mega 2560, Arduino Uno, Arduino Nano, NodeMCU, Teensy, MSP430, STM32, PocketBeagle, Penguin, ESP8266, Particle Photon, etc.) (Buckley, 2018).

The advantages of using this variant are given by the very low cost, the very low consumption of electricity and in some cases, the very small size.

The disadvantages involved are related to the relatively low computing power of these systems, the need to write dedicated software for each application, the need to directly modify the software for an application reconfiguration, small memory, inability to support large applications such as database systems, in most cases, the lack of an operating system, etc.

Second alternative. Use of a single-board computer (complete computer systems, built on a single circuit board, with microprocessor, memory, input/output system and other features needed for a functional computer; typical examples of such systems are Raspberry Pi 3, Asus Tinker Board, ODroid XU4, Banana Pi-M64, NanoPi NEO4, Rock64, Libre Computer AML-S905X-CC, LattePanda Alpha 864, UDOO X86 ULTRA, NanoPC-T3 Plus, HiKey 970, Parallel) (Kimari, 2019) (ZDNet.com, 2019).

Given the advantages and disadvantages listed and the fact that the APPD subsystems must operate autonomously and provide the features listed earlier in this paper, we chose to use single-board computers. Taking into account other factors, such as price and direct availability on the Romanian market of the electronic components, for the implementation of the system prototype, a single-board computer type Raspberry Pi 3, model B+ was used (RaspberryPi.org, 2019).

This choice of the computing system to be used for the PDAP subsystems implies that there is enough storage space on these computing systems to store a significant amount of data - Raspberry Pi 3, model B+ has a MicroSD slot compatible with high capacity cards (64-128 GB) (Raspberrypi.org, 2020). Part of this space will be occupied by the Raspbian operating system (approximately 8 GB) (Raspberrypi.org, 2020) and a smaller part will be occupied by the various applications required but, on a 64 GB card, approximately 50 GB will remain available for storage. More than enough space for storing a large number of measured values (at a sampling rate of 1 measurement every 30 seconds and considering an approximate size of 1,000 bytes per record, the storage space required for the data provided by a single measuring component is about 1,000 MB per year, considering an APPD subsystem with 20 measuring components, it turns out that on such a card, data covering about 2.5 years of measurements can be stored locally). Based on these considerations, under normal circumstances, the use of cards with lower storage capacities (16-32 GB) can be considered to obtain a reduction in costs per APPD subsystem (on a 16 GB card, data for about 36 days of measurements can be stored, and on one of 32 GB, data for about 310 days of measurements, under the above conditions).

The software of the PDAP subsystem consists of:

- The operating system of the Raspberry Pi 3 single-board computer, model B+ is a Raspbian operating system, an open-source operating system derived from the Linux Debian distribution.
- Various scripts that were written in the Python language.
- A graphical data representation application called Grafana. Grafana allows the interrogation, visualization, warning, and understanding of the values of the available data, regardless of where and how they are stored. The main activity in Grafana is the creation, exploration, and sharing of dashboards containing different methods of visualizing data and analysis results.

The actual retrieval of data from the smart sockets and the writing of this data in the database were done with the help of several Python scripts created within the project. Python scripts are further run through batch files, with separate versions for Windows Command Prompt and bash.

The database used for the PDAP subsystem is a MySQL database consisting of 3 tables.

We opted for the separation of instantaneous consumption data, and statistical data related to daily and monthly use, in two different dashboards.

Grafana dashboards are composed of various types of panels. The first dashboard consists of 12 panels: operating time, status, LED status, Wi-Fi signal strength, instantaneous voltage, instantaneous intensity, instantaneous power, total energy consumed, voltage evolution over time, intensity evolution over time, evolution over time of power and the evolution over time of the total energy consumed (Figure 3).

Up time (hours)

Metric	Uptime
Computer & periphereals	157:38:54
Air conditioner	161:52:11

State

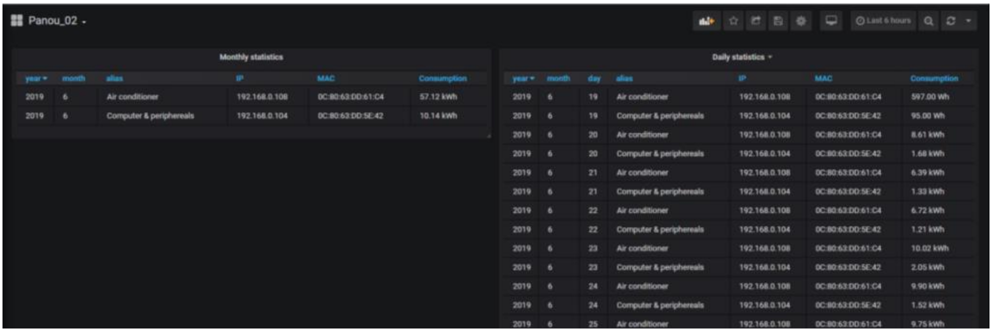
Metric	Current
Computer & periphereals	1
Air conditioner	1

LED state

Metric	Current
Computer & periphereals	1
Air conditioner	1

Figure 3. The first dashboard of the PDAP subsystem

The second dashboard consists of two panels: monthly statistics and daily statistics (Figure 4).



Monthly statistics

year	month	alias	IP	MAC	Consumption
2019	6	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	57.12 kWh
2019	6	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	10.14 kWh

Daily statistics

year	month	day	alias	IP	MAC	Consumption
2019	6	19	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	597.00 Wh
2019	6	19	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	95.00 Wh
2019	6	20	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	8.61 kWh
2019	6	20	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	1.68 kWh
2019	6	21	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	6.39 kWh
2019	6	21	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	1.33 kWh
2019	6	22	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	6.72 kWh
2019	6	22	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	1.21 kWh
2019	6	23	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	10.02 kWh
2019	6	23	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	2.05 kWh
2019	6	24	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	9.90 kWh
2019	6	24	Computer & periphereals	192.168.0.104	0C:80:63:DD:5E:42	1.52 kWh
2019	6	25	Air conditioner	192.168.0.108	0C:80:63:DD:61:C4	9.75 kWh

Figure 4. The second dashboard of the PDAP subsystem

5. Aggregation, Long-Term Storage and Complex Data Analysis Subsystem (ASDA)

The ASDA subsystem is a system that operates autonomously over the PDAP layer, depending on it only insofar as they constitute the source of data to be stored and analysed.

Such a subsystem can be designed both in the older paradigm of the supervisory system model but also by following the newly introduced concept of intermediate data processing − fog computing. This concept was introduced in 2012 by (Bar-Magen Numhauser, 2012) and standardized in 2018 by (IEEE Standards Association, 2018).

Taking into account the specifics of the project and in terms of multiple advantages (better use of existing computing resources, decongestion of traffic in the central area of communications systems, reducing latency of representation and response, etc.), upon the implementation of the ASDA system we opted for a fog-computing solution. Taking into account the target characteristics (mainly the use of open source applications), the software chosen for implementation was FogLAMP.

FogLAMP is an open-source platform for IoT and a component to be used in fog computing. It uses a modular microservice architecture, which includes the collection, storage, processing, and transmission of historical sensor data to Enterprise systems and cloud-based services. FogLAMP can run in highly available, standalone, unsupervised environments, assuming insecure network connectivity. FogLAMP provides a modular and distributable framework under the open-source Apache v2 license. The modules can be distributed in any layer of the IoT ecosystem − Edge, Fog, and Cloud − and work together to provide scalability and resilience.

6. Conclusions

The current paper attempted to sketch the way a fine-grained monitoring system can be implemented for monitoring the electricity consumption data of various existing equipment in a residential or organizational context.

It outlines the requirements that should be met and a technical proposal is presented to ensure that these requirements are met while providing the desired functionality.

The conclusion is that such a system should be implemented as a multi-level fog-computing system in which the Edge level is provided by autonomous subsystems and the Fog level is implemented through a cluster of various type computers. Data storage, analysis, and primary visualization are implemented separately in the Edge area (consisting of PDAP subsystems, in the context of this paper), and the Fog area (referred to as ASDA, in the context of this paper) is based on a local cluster.

A final comment is that it should be preferred that both the Fog area and the Edge area, although having separate implementation and functionality, run a common stack of services, such as FogLAMP.

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