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An interoperable tool-chain for energy monitoring applications

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***Abstract*—Non-Intrusive Load Monitoring (NILM) is the disaggregation of the power consumption of individual appliances from agglomerated measurements taken from a single point of measure. The paper proposes a NILM methodology based on load signature analysis, and it then suggests that to deploy NILM in the large, a set of interoperable tools should support each stakeholder of the NILM value chain. This tool-chain is made interoperable by a shared domain model based on well-known ontologies, such as Saref and Schema. The paper shows that this approach enables smooth NILM-based industrial innovation, because the toolchain may be easily extended to provide capabilities such as predictive appliance maintenance, appliance aging understanding, fault detection and interaction with the utility companies. The paper proposes a NILM tool-chain development road-map based on an interoperability platform named Arrowhead to increase the value proposition of the NILM device.**

***Index Terms*—Near sensor processing; non intrusive load monitoring; NILM; Service-oriented architecture; SOA; Ultra Low-Power Processing**

I. INTRODUCTION

Combining new technologies and novel service architectures with flexible tool-chains for life-long support originates new products that bring in disruptive innovation in challenging application domains. This paper highlights a novel and uncommitted current sensor with embedded neural computing capabilities, that can be tailored to provide in-situ load identification and Non-Intrusive Load Monitoring (NILM) in industrial as well as domestic environments. Its architecture inherently supports life-long learning and adaptation to the changing current profiles of the sub-grid monitored. Consequently, the proposed sensor may produce not only measurements but also anomaly detection and predictive maintenance calls.

The flexibility enabled by its computing and feature extraction capabilities rises the interest of a community of stakeholders playing entirely different roles, such as users, service providers and owners of the monitored space, as well as manufacturers, service providers of the monitored appliances, and the utilities themselves. An inherent and hard to measure business potential may originate from these sensor capabilities, up to the point that new stakeholders, new jobs, and new business models will likely appear based on the proposed approach. To turn this vision into reality, we propose to wrap the sensor within a set of innovative tools supporting all phases of its life-cycle, from design to deployment, commissioning maintenance, and evolution. Such tools are innovative at least for two reasons: they support innovative functions (such as NILM, in-situ load identification, life cycle adaptation, anomaly detection) and they are interoperable and chained in a round-robin fashion, exchanging data according to a shared semantic data model.

This paper describes the proposed sensor architecture, envisions the mentioned tools and introduces a just started >80 M€ European Innovation Action, titled Arrowhead Tools[1], aiming to build a European culture of engineering tools to support the ongoing cooperative-automation revolution in the industry and in everyday life. This Action intends to demonstrate the potential of such a revolution through several use cases wrapped around an advanced System Oriented Architecture and its framework (named Arrowhead Framework). The plan is to demonstrate the proposed sensor and associated tool-chain integrated within this framework.

This paper is organized as follows: Section II presents related works and shows the recent approaches for load identification. Section III is dedicated to the architecture of energy meter sensor node with near sensor processing capabilities. Section III-A enlightens the computational approach taken and the algorithm to deliver in-situ load identification and Non-Intrusive Load Monitoring (NILM). Section IV will point out the chain of tools needed to support the design, the configuration, the operation, and the evolution of the sensor, along the life cycle of the monitored environment. Section V introduces the data model shared among the tools Section VI concludes the main body of the paper with a quick introduction to the arrowhead framework and the proposed sensor and toolchain integration therein. Some concluding remarks and plans for future work complete this paper in Section VII.

[1]https://arrowhead.eu/arrowheadtools

II. Related Works

A. Interoperability frameworks

Interoperability platforms and frameworks may address interoperability at many different levels, including communication [1], information [2], [3], service [4], and interaction [5] level. System of systems and IoT applications, such as NILM mostly benefit from interoperability platforms at information and service level. The need for Semantic Interoperability Architectures in IoT based multi-stakeholder scenarios, with examples in the appliance domain is extensively discussed in [6]. Here a network of semantic information brokers is proposed to enable device and service discovery both by name and by a set of properties. An emerging framework based on the conceptualization of any appliance as an interoperable web thing, described in terms of events, properties and actions is the W3C Web of Things [7] and [8] depicts an architecture to support semantics-based web things discovery and interoperability. NILM information an data are of interest for many stakeholders, from industry [9] to data-center [10], therefore it would be useful to make it available in the form of dynamic open linked data. An information interoperability platform providing event-based access to distributed, context-aware Dynamic Linked RDF Data is described in [11]. None of the above platforms or frameworks has ever been used to for the deployment of NILM with the support of an integrated tool-chain. Within the scope of this work, we consider a framework developed within an EU project – i.e. Arrowhead (2013 - 2017) – implementing a SoA for collaborative automation and M2M communication [4]. This framework has been used for interfacing simple wireless smart meters, as presented in [12], and it is expected to host the proposed NILM tool-chain described in Section VI.

B. Load Identification

Non-Intrusive Load Monitoring (NILM) describes the task of disaggregation power consumption of single appliances from an agglomerated mains power measurement. From the machine learning point of view, this is considered a single-channel blind source separation problem, where multiple sources need to be extracted from one combined measurement.

George W. Hart founded the field of energy disaggregation in the 1980s and published 1992 the seminal paper for Non-intrusive Load Monitoring [13], where he introduced different NILM scenarios and implemented first disaggregation algorithms based on low-frequency features at a sampling rate of 1 Hz. Along with the recent rising interest in the machine learning field, the topic of NILM gained a boost in popularity, resulting in various publications combining different classification methods and features [14]. This can generally be distinguished into two different approaches, of which one is using low frequency data and machine learning methods as J. Kelly 2015 with the first application of Neural Networks to NILM [15]. Moreover, the other one is deploying richer features in terms of measurements sampled at higher frequency as S. Gupta [16] by using EMI features in the frequency domain, as done by harmonic analyzers and flickermeters [17]. While the biggest advantage of the low-frequency approach is its applicability in low-cost smart meters [18]–[20], the higher frequency approach can distinguish similar and more complex loads. Since both types have their shortcomings, the presented method here combines low and higher frequency features following the implementation of T. Bernard et al. [21] for a single-channel blind source separation problem. Therefore, we take the active and reactive power consumption as well as the first 15 harmonics of real power consumption into consideration. To measure active and reactive power sample rates lower than 50 Hz (respectively 60 Hz in the US) are sufficient, while for the harmonics higher sampling rates are necessary. To measure harmonics till the 15^{th} harmonic at a power frequency of 50 Hz we need hardware capable of a sample rate $>$1.5 kHz. While many types of the research in the last years focused on low-frequency vectors, since they can be already measured by existing smart meters, [21] shows that it is very promising to take also middle frequency features into consideration, especially to separate loads with similar power intake. Eventually, the feature vector consists of active and reactive power as well as 8 harmonics each with an imaginary and a real part.

III. The NILM Sensor

This section briefly describes the hardware and the test setup we are deploying for our experiment. For both data recording and data processing, we use the same customized measurement device. The key components are two microcontrollers, of which one is active, and one is idle at a time. We deploy one ultralow-power machine learning optimized RISC-V GAP8 processor and the other a power-optimized microcontroller from the STM32-L4 family. Furthermore, we use a dual-channel ADC that is capable of sampling rates up to 1.5 Msps while recording simultaneously. The analog stage contains an ultra-low power operational amplifier that measures synchronous voltage and current via a shunt. For the training phase, we stream the recorded data via Wi-Fi to a server. During the recording and training stage, we use the STM32 microcontroller to record and send the data to a server, where it then gets preprocessed and the training of the algorithm is executed. As proof of concept, we will concentrate on an insulated power net and use a small number of different appliances, which are powered with a specific switching pattern. After the training stage, the trained model gets transferred to the GAP8 microcontroller, where the online classification of data is executed. This measurement device can conduct synchronous voltage and current measurements up to 1.5 Msps. For online classification, considering the available memory onboard, and the choice of features and algorithm described in Sec. III-A, more than 30 classes consisting of 30 cluster points can be stored.

A. Features and NILM algorithm

Based on [21], a modified k-Nearest Neighbor algorithm is deployed. Unlike an unmodified k-NN algorithm, this ap-

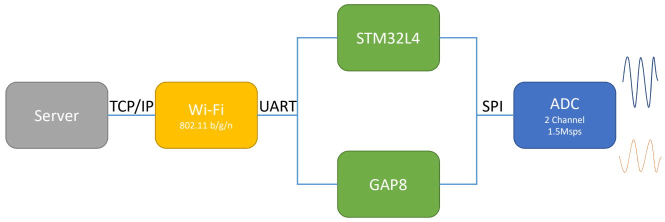

Fig. 1. Schematic Overview of Hardware

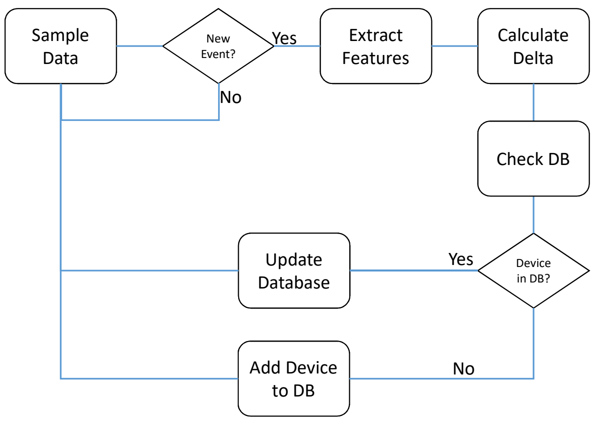

Fig. 2. Simplified Flowchart of Device Matching

proach benefits from a flexible cluster count that is set during operation. Since the user only needs to label every cluster once, this algorithm has the advantage of being mostly unsupervised. Furthermore, we aim at demonstrating that the trained model can be transferred to an unseen household on the one hand and extended by unseen load signatures on the other hand, to gain a maximum in compatibility for the proposed measurement and classification node.

The outline of the algorithm is as follows: first, current and voltage are measured continuously with a frequency of 1 kHz, and the real power is calculated. If a change in consumed power exceeds a certain threshold, a switching event is triggered, the features described are extracted and a delta feature vector is calculated. This vector is then multiplied with a weighing vector and the result is parsed with the current cluster database. If a nearby cluster is found, it gets extended by the weighed delta feature vector and the cluster database is updated. If the distance to all previous clusters exceeds a specific threshold a new cluster is created, to which the delta feature vector is added. The clusters then eventually need to be labeled by the user. We seek to extend this algorithm by Bernard by the option of exchanging the created cluster database between different houses and adding new load signatures to it using the framework.

IV. The System-of-Systems: a "tool-ring" concept architecture

As described above, through the combination of machine learning and clustering technologies, ultra-low-power processing, high-speed continuous sampling and wireless transmission, loads can be disaggregated and characterized from a single point of measure. This approach enables disruptive new models of energy optimization and management to be envisioned, including:

- unobtrusive profiling of individual appliance activity;
- monitoring of power supplies degradation and detection of equipment faults.

Algorithm 1 Hybrid NLIM

```
while |P_diff| < Power Threshold do
    Sample Voltage and Current
    P_diff = ∫_0^T i(t)dt ∫_0^T u(t)dt − P_previous
                                             ▷ Event Detected
Calculate Feature Vector F
δF = F − F_previous
Store F_previous, P_previous
Apply Feature Vector weighing δF_weighed = W · δF
Calculate Distances from δF to all cluster points in DB
if Distances > Matching Threshold then
    Notify new Datapoint for new Cluster validation and
    update DB
else
    Add Datapoint to existing device in DB
```

Any traditional set of appliances connected to a user sub-grid is a system of systems (SoS). Altogether, new requirements concerning normal SoS, operation, life-cycle monitoring, predictive maintenance, and anomaly detection can be satisfied. This value proposition calls for the engagement of many stakeholders, and particularly the appliance manufacturers, the users and the service providers that provide services along the SoS life cycle, e.g. installation and maintenance companies as well as utilities; altogether a very large and relevant community. Clearly, the stakeholders need to interact by sharing and exchanging information, therefore accurate data models and a set of interoperable tools, that should conform to a well-designed tool-chain architecture, are required. Fig. 3 envisions a toolset arranged in a round-robin fashion (tool ring): they set up the conceptual context for NILM deployment at large. The rationale behind such tool-ring follows. At first, the set of features required by the NILM algorithm recalled in the previous paragraph are defined and shared among all appliance manufacturers. Then, at product development time, each manufacturer publishes the set of feature values for each operation step of each of its products. This collection of feature sets is called the Appliance Signature. A tool named *Signature Creator* is expected to support the signature creation process, while a second tool, named *Signature Manager*, handles the exchange of signatures with down-stream tools.

In turn, when the NILM-device is installed in the target SoS, it needs to be configured with the signatures of all its SoS appliances. The configuration procedure could be partially automatic (as suggested above), and partially supported by an APP gathering the appropriate missing signatures through

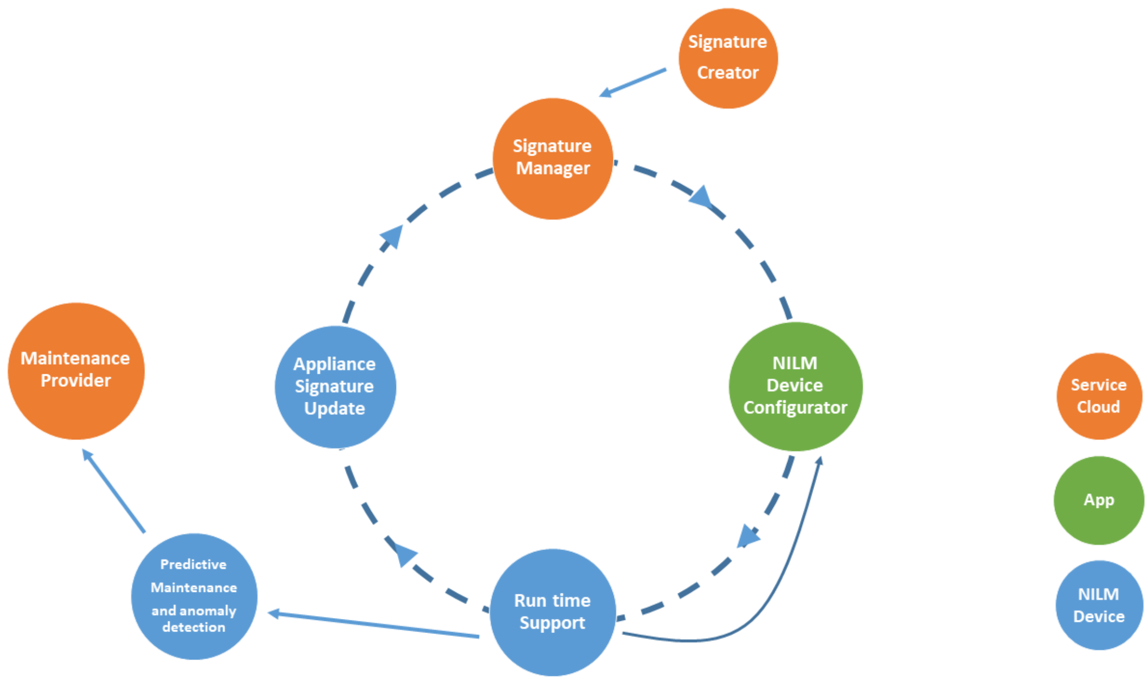

Fig. 3. The Tool Ring Architecture

its interaction with the *Signature Manager*. This APP is an additional tool of our tool-ring, it might be called *NILM device configurator*, and it delivers the signatures received by the *Signature Manager* to the *NILM device run time support tool* through the NILM device wireless connection.

The NILM device may hosts additional tools, including one to understand normal aging of each appliance through variations of its digital signature (this tool might improve the digital appliance signature and might enable a predictive maintenance service), a tool to detect equipment faults and trigger a request for the appropriate maintenance service, and a tool to provide the utility with the required metering info.

As Fig. 3 shows, at least three different platforms will host the envisioned tools: a cloud, an embedded device, and a tablet or Smart Phone or similar device. For a smooth and controlled interaction among the above tools, as well as a seamless signature-exchange between them, the following approach is here suggested:

1) each tool is implemented as a service registered at the service registry of a secure distributed service-oriented architecture
2) an ontology modeling the addressed multi-stakeholder context is defined, where all entities and their properties relevant in the proposed scenario (e.g. the appliance manufacturer, the appliance and its signature, the SoS, the NILM device) are formally specified.

V. Data Model

A crucial requirement for tool interoperability is common shared knowledge. This can reduce the cost of the integration and the complexity of the software developed to import data. Therefore, this paper introduces an abstract data model that could be used as a reference for NILM tools. The model employs concepts from well known IoT reference ontologies such as schema.org[2] and saref[3], as shown in its schematic view in Fig. 4. In particular, the data model includes 5 main classes of objects:

- **NILM Device:** this class represents the monitoring device installed in the target private or public environment (a System of Systems). It contains the device unique ID as an URN which can be used to identify its instance in different IT systems. Furthermore, it stores the information about the power consumption of the load and the status of the device itself.
- **System of Systems:** this class is a virtual twin of the target environment which is identified by the collection of the connected appliances. Moreover, it could contain relevant information about the context of the systems such as the postal address, if it is part of a condominium building, the presence of other power sources, the number of people who live there, etc.
- **Appliance:** The appliance class derives from saref:Appliance and schema:Product. From schema it inherits human descriptive properties like the Manufacturer, picture, sizes, format. While from saref:Appliance it is used for functional descriptive properties such as "hasFunction" or "hasState".

[2]https://schema.org/

[3]https://sites.google.com/site/smartappliancesproject/ontologies/reference-ontology

- **Organization:** The Organization class identify stakeholders and service providers registered in the Arrowhead framework. Their role inside the tool-ring is identified by their relations with other classes. For example, the manufacturer of an appliance is connected using a property called *Manufacturer* which identify that Organization as the manufacturer of that appliance.
- **Appliance Load Signature:** A generic class which identifies a load signature of a specific appliance. In the future, a standardization process may be needed to prevent the emergence of different signature formats. Otherwise, the data model could be extended with more descriptive classes which inherit from Appliance Load Signature.

VI. The Arrowhead tools Framework

The IoT is a key enabler of Industry 4.0 and all the applications revolving around it, including Home Automation Scenarios. Several research efforts have been made in such direction, as it is explained in Section II, making the world of interoperability frameworks vast. The common trend is to shift from a SCADA/DCS-driven organization of component in an industrial process to a networked IoT ecosystem in which each entity is responsible for producing or consuming services, as in any Service-Oriented Architecture. The Arrowhead Framework[4] is the result of an effort of more than 80 European partners [4] and has been used extensively in several other connected initiatives such as Productive 4.0[5] and Far-Edge[6]. In this work, we use the Arrowhead Framework for the purpose of interoperability between the tools outlined in the previous sections and for compatibility with a plethora of other services in the Arrowhead-Tools workflow.

The Framework consists of connected local clouds, each of them managing their internal services and communicating with each other to separate the control on different scenarios while keeping them interoperable. Each local cloud hosts several Systems, defined as the software components that interact and constitute the application workflow. Each system can expose a number of Services as well as consume other services in the network, thus, for our purpose, we define them as Service Providers or Service Consumers (clearly any system can be both). In order to implement the -key paradigms that characterize a SOA – defined as late binding, loose coupling, and lookup – each local cloud hosts several "Core Systems" (CS) that support and orchestrate the exchange of information. They are divided onto Mandatory CS and Support CS; Mandatory CS have to be deployed within a local cloud to make it an Arrowhead-compatible cloud [22]. A brief description of the Mandatory CS is below:

- **Service Registry**: it is the system responsible for register each service within the local cloud. It acts as a repository, thus other systems can perform a service lookup in order to find the service that they are looking for together with a set of metadata (e.g. endpoint, transport and application protocols, etc.). Service lookup is performed using the well-known DNS-SD lookup protocol [23].
- **Authorization**: it is the system responsible for the correct interaction between producers and consumers according to their rights. In particular, it manages the correct authentication of providers and consumers as well as their authorization for consuming or producing resources.
- **Orchestration**: it is the system responsible for coordinating the interactions between systems without the need for the consumer to define its preferences at design time. The Orchestration system is capable of choosing dynamically the service producer suitable for any request by the consumer on top of a list of orchestration rules as well as the type of service requested. This can automatically handle faults and load imbalance at the producers' side.

Support CS are not mandatory and can be included in any local cloud upon need. Example of available Support CS are: QoS Manager, Data Manager, System Registry, Device registry, Translator System, Event Handler, Plant Description, and Configuration Manager. A special mention is deserved by the Gatekeeper System and the Gateway System, which are devoted to putting two or more local clouds in communication [24]. We envision every single tool of the architecture presented in Section IV to be integrated as an Arrowhead compatible service, taking an active part in the Arrowhead Framework as a set of service providers and consumers.

[4]https://www.arrowhead.eu
[5]https://productive40.eu/
[6]http://faredge.eu/#/

VII. Conclusion

Technology advances such as NILM enable more and more functionalities to be offered so that new requirements can be satisfied at less and less costs. To deploy NILM in the large, several actors need to be involved, and a "new" value chain may be created. A collection of tools to support such value chain are proposed. Their deployment is enabled by a framework implementing a SoA together with an appropriate ontology describing the semantics of the addressed domain. A European research and innovation project, Arrowhead Tools, started in mid 2019 with the goal to increase the maturity of a pre-existing SoA framework. Future work includes the development of a demonstrator of the proposed tool-ring hosted by the Arrowhead Framework.

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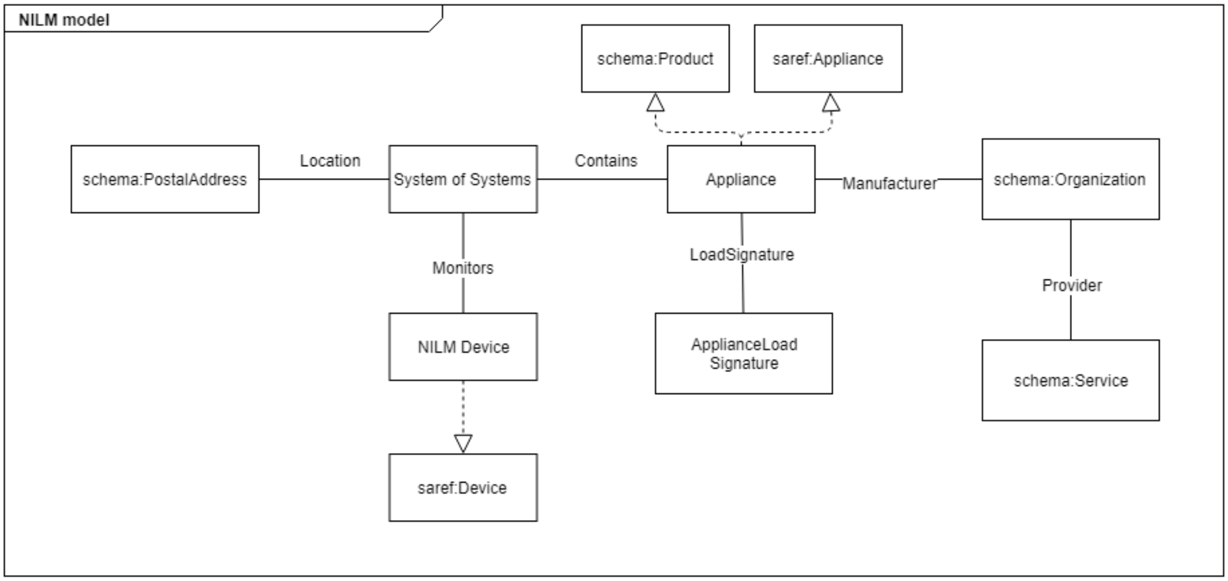

Fig. 4. The NILM Tools data model

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