YaY - An Open-Hardware Energy Measurement System for Feedback and Appliance Detection based on the Arduino Platform

Christoph Klemenjak and Wilfried Elmenreich
Institute of Networked and Embedded Systems
Alpen-Adria-Universität Klagenfurt
9020 Klagenfurt, Austria
{*name.surname*}@aau.at

***Abstract*---To analyse user behaviour and energy consumption data in contemporary and future households, we need to monitor electrical appliance features as well as ambient appliance features. For this purpose, a distributed measurement system is required, which measures the entire power consumption of the household, the power consumption of selected household appliances, and the effect of these appliances on their environment. In this paper we present a distributed measurement system that records and monitors electrical household appliances. Our low-cost measurement system integrates the YaY smart meter, a set of smart plugs, and several networked ambient sensors. In conjunction with energy advisor tools the presented measurement system provides an efficient low-cost alternative to commercial energy monitoring systems by surpassing them with machine learning techniques, appliance identification methods, and applications based on load disaggregation.**

***Index Terms*---Smart home, smart meter, smart plug, open-source, open-hardware, low-cost**

I. Introduction

At the present day we face the trend of changing housing situations due to demographical developments in our society. Until the year 2100 the European population is expected to decrease continuously [1]. Furthermore, the percentage of single-person households is expected to grow in all OECD countries, especially in European countries [2]. As a consequence, innovative forms of compact one-person households are on the rise in order to provide an alternative to larger, expensive rental flats for future households. Of interest will be how this development will influence human biorhythm, consumption habits, presence at home and many other factors. In order to record and identify these changes, a specific measurement system is required that monitors the resident's habits and the consumption behaviour. Data of interest in this kind of instrumentation is the consumed power of day-to-day used household appliances such as domestic appliances, kitchen utensils, and consumer electronics as well as the entire energy consumed by the household.

Furthermore, the measurement system should be able to detect and record the impact of electrical appliances on their environment such as heat dissipation or sound emission. Such ambient features can be exploited to enrich appliance models. Detailed appliance models can be utilised to detect active appliances or to enhance the detection rate in load disaggregation. Personalised feedback in form of appliance-specific recommendations can be generated in order to achieve energy savings or provide services for ambient assisted living.

In this paper, we introduce a measurement system for households that is able to record electrical and ambient appliance features at several levels of the household's power distribution network and to detect present electrical appliances in the household by means of the recorded appliance features. In order to record the energy consumption of the household, a measurement system can follow three different approaches: A distributed approach, a central approach, or a combination of these. A distributed approach measures consumption at device level, as presented in [3]. To create a consumption profile of a household, several networked measurement units spread across the household are required, as discussed in [4]. Some appliances can't be easily monitored at device level such as water heaters or stoves. In order to overcome this issue, the analysis of the aggregate power consumption provides an opportunity to monitor such appliances by application of load disaggregation algorithms. A second solution for this problem is the utilisation of ambient sensors, which measure the impact of electrical appliances on their environment. For this reason, a measurement system that aims to record changes in user habits as well as consumption behaviour, has to comprise networked meters, ambient sensors, and device-level measurement devices. To measure the energy consumption and forward the gathered data several smart sensors and smart metering units were designed, as presented in [5], [6], [7], and [8]. All these smart devices integrate a processing unit, a metering unit, and one or multiple networking modules. Furthermore, measurement systems in [9] as well as [10] were applied to record the power consumption behaviour of households. Neither the introduced smart metering units nor the measurement systems in household measurement campaigns were designed to record electrical appliance features such as energy consumption and ambient features such as noise emission at the same time, although the combination of these appliance features may allow to analyse the usage history of devices and in consequence help detecting behaviours such as cleaning habits. Such information is highly personal, but when being used in a closed system not involving cloud services they can safely provide recommendations based on personal behaviour and appliance usage. On account of this, we identify the need for a distributed low-cost measurement system for the monitoring as well as the detection of electrical appliances in households.

The paper is structured as follows: Section II depicts design and measurement aspects. Section III introduces our distributed measurement system, which consists of the YaY smart meter, several smart plugs, and networked sensors. Section IV highlights areas of application for the system such as the utilisation as low-cost and open-hardware home energy management system or load disaggregation. Section V discusses functional and non-functional aspects. Section VI presents future work and Section VII concludes the paper.

II. Design Aspects

To provide a detailed overview of the household, it is obligatory for a distributed measurement system to measure the energy consumption at several levels in the internal power distribution network as well as characteristic ambient features in the household.

The aggregate level represents the top level, which equals the feed point of the household. At this level, a measurement device is able to obtain the total power consumption of the household. Therefore, the application of a measurement device at this feed point is of crucial importance since the total power consumption as well as other characteristic physical quantities can be determined. Such characteristic physical quantities comprise parameters that provide information about the state of the grid such as the voltage level or the power line frequency.

The household appliances represent the terminal points of the distribution network. Measurements at this level are referred to as appliance-level measurements since the obtained data describes exclusively characteristics of the respective appliance.

A wide variety of monitored physical quantities allows the generation of precise appliance as well as household models. As a consequence of these precise models, a deep behavioural analysis is possible. From the output of this analysis, predictions as well as recommendations are created in order to decrease the power consumption of the household i.e. to save costs, predict the energy consumption, or optimise the runtime schedule of household appliances.

In order to be in the position to perform such optimisations, a wide variety of physical quantities at the several levels of the household's power distribution network have to be measured:

1) Aggregate level i.e. feed point of the household:
    a) True root-mean-squared value of the voltage U_{RMS}
    b) True root-mean-squared value of the current I_{RMS}
    c) Active power P, reactive power Q, and apparent power S
2) At appliance level i.e. for each appliance:
    a) Active power P
    b) Ambient features such as heat dissipation, light emission, etc.

The obtained measurement data is analysed and device features are extracted from it. For this reason, the measured data has to be sufficiently fine-grained. Hence, an adequate *measurement frequency* has to be selected. In the past years multiple energy consumption datasets of contemporary households were published [9], [10], [11]. Many of these datasets provide data sampled with a frequency of 1 Hz. The authors of [12] demonstrated that an unsupervised load disaggregation algorithm is able to detect more than 90% of the household's appliances on data, which was measured with a sampling frequency of 1 Hz. In order to detect short time energy consumption events and changes in the appliance's state of operation this specific sampling frequency shall also be utilised as the sampling frequency for electrical quantities in a distributed measurement system.

Another important aspect in the discussion of measurements is the *measurement uncertainty*. On the one hand, available commercial smart meters were shown to have a measurement deviation of 10-20% in [13]. On the other hand, open-hardware platforms such as the OpenEnergyMonitor project also reported a measurement error of 10% and more for appliances with a considerably small power consumption below 100 W. Data analysis and resulting decisions based on measurement data demand for accurate data. A field study involving appliance-level power measurements with an average error of 5.35% were reported in [3]. For these reasons, we define a maximal limit for measurement uncertainties of 10% for aggregate level measurements and 5% for measurements on appliance level.

III. A Distributed Measurement System

The main purpose of our measurement system is to measure the power consumption on several levels in the household and record selected ambient features of electrical appliances. The measurement data is stored at a central unit in the measurement system and made accessible to software tools such as energy advisors or load disaggregation algorithms. By this, applications such as smart metering, cost and load forecasting, appliance tracking, and a reduction of energy costs shall be possible. To achieve this, our measurements system consists of three distinct components:

The *YaY (YoMo and Yun) smart meter* comprises a smart metering board as well as an embedded linux platform. The YaY represents the system's centrepiece since it records the energy consumption at the household's feed point, gathers measurement data from the other measurement devices, and utilises an energy advisor tool to provide feedback. To measure the energy consumption of the household, the YaY utilises the YoMo smart metering board, which is illustrated in Figure 3(a).

The measurement system integrates a set of *Plugwise Home smart plugs*. Figure 3(c) shows such a smart plug. These smart plugs are attached to selected appliances and forward their obtained measurement data to the YaY smart meter.

Several *devDuino sensor nodes* are applied to monitor ambient features of selected electrical appliances. Figure 3(b) shows such a sensor node. In order to measure these impacts on the environment, the sensor nodes are equipped with different

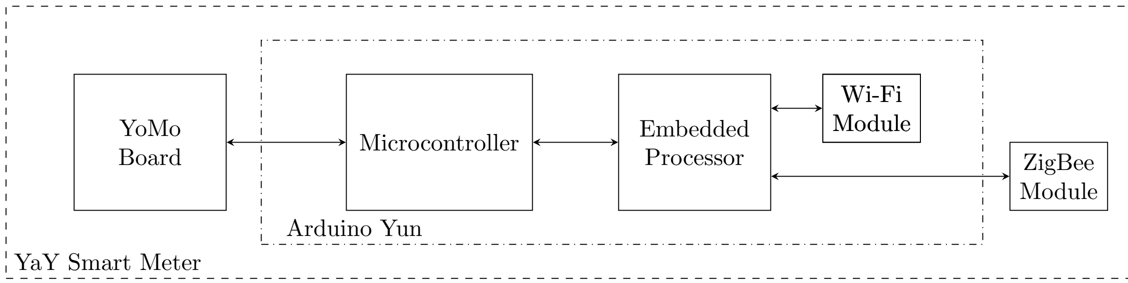


Fig. 1: Components of the YaY smart meter

kinds of sensors such as Piezo sensors, temperature sensors, or sound sensors. The sensor nodes transmit the recorded features to the YaY smart meter.

A. *YaY - Smart Meter*

In general, the smart meter is the successor of the conventional electricity meter, which serves as meter for electricity billing since decades. The main purpose of a smart meter is to monitor the household's electricity consumption and transmit the readings to the electricity supplier. Consequently, the smart meter represents a gauged measurement instrument equipped with communication technology.

In our application, the YaY (YoMo and Yun) smart meter represents the main component of the distributed measurement system. The YaY smart meter fits into a conventional DIN rail enclosure, which is also used for residual earth leakage circuit breakers. Therefore, this special kind of measurement device can be installed in the distribution board. By application of an EIA-485 adapter, the YaY smart meter is able to communicate with other devices in the distribution board. Such devices can be circuit breakers or commercial smart meters. As Figure 1 shows, the YaY comprises a YoMo smart metering board[1] to measure energy consumption, an Arduino Yun microcontroller board to process measurement data, and a ZigBee module to communicate with the Plugwise Home plugs.

The YoMo smart metering board is a self-designed extension unit for Arduino microcontroller boards. Figure 3(a) shows the metering board. As the figure shows, YoMo integrates also a relay beside components required for measurements. This relay allows to switch the connected appliances. The integrated measurement components provide galvanically-isolated measurements of voltage, current, as well as active, reactive, and reactive power at the mains [5]. The maximum sampling frequency of the YoMo is $5\,\mathrm{Hz}$. Table I summarises the main specifications including a maximum measurement error of 3.8% for active power measurements. The maximum electrical load that can be monitored to the YoMo is $4.6\,\mathrm{kW}$ at $230\,\mathrm{V}$.

The components as well as the interfaces of the YoMo are depicted in Figure 2. The key component for measurements represents the energy monitor IC. This integrated circuit computes the level of several physical quantities from the output signals of the voltage sensor and the current sensor. The utilised IC is the ADE7753[2], which implements the serial peripheral interface (SPI). The Arduino Yun reads the measurement results via this interface. Beside the SPI interface, the YoMo integrates several pins for input output operations. Phase in and Phase out indicate the connections for the live conductor. SAG and IRQ represent pins utilised for interrupts. The SAG pin serves as pin for line voltage sag detection. The status of the interrupt request IRQ pin indicates if an interrupt occurred in the ADE7753. The supply voltage is represented by the VDD pin, EN represents the enable pin for the relay.

The Arduino Yun is a special kind of embedded hardware that integrates an 8-bit micro controller ATmega32U4 as well

TABLE I: YoMo Metering board specifications

Feature	Abbreviation	Value
Supply voltage	V_{dd}	$5\,\mathrm{V}$
Max. current	I	$20\,\mathrm{A}$
Max. input voltage	V	$400\,\mathrm{V}$
Max. sampling frequency	f_s	$5\,\mathrm{Hz}$
Max. measurement error	σ_P	3.8%
Max. measurement error	σ_Q	8.3%
Max. measurement error	σ_S	4.04%
Internal resistance	R_i	$300\,\mathrm{m\Omega}$
Power consumption	P	$2\,\mathrm{W}$

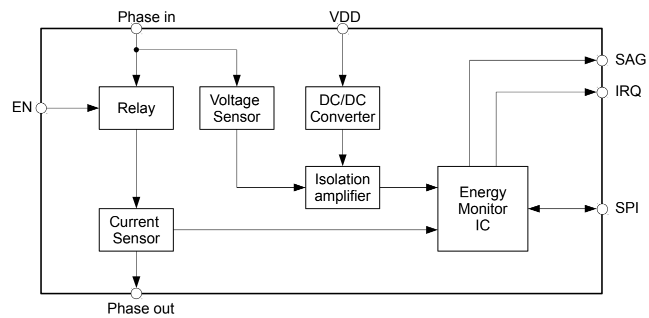


Fig. 2: Components and interconnection of the YoMo smart metering board

[1] http://yomo.sourceforge.net/

[2] http://analog.com/media/en/technical-documentation/data-sheets/ADE7753.pdf

as an Atheros AR9331 processor. This unique combination of a microcontroller and an embedded processor makes it possible to execute simple sequential control tasks as well as complex programs running under a Linux-based operating system with the same piece of hardware. This corresponds to the way the tasks are divided between the microcontroller and the embedded processor in the context of the application as smart meter. The integrated microcontroller reads the measurement data from the YoMo metering board, reacts to occurring interrupts of the energy monitor IC, controls the relay of the YoMo, and forwards the obtained measurement data to the embedded processor. The embedded Atheros processor is responsible for networking, data processing, as well as data acquisition from the other measurement devices. The most important task is to take over measurement data from the microcontroller as well as the other distributed measurement devices and gather them in a database. The distributed measurement devices form a radio network, which is established and maintained by the Atheros processor. This radio network comprises the networked sensors and the smart plugs, which are attached to certain appliances. The embedded Atheros processor operates the Linux distribution Linino[3]. The operating system Linino shares a big number of software packages with conventional Linux distributions for desktop computers such as Debian or Ubuntu. These software packages comprise the database management system MySQL, the high-level programming language Python, and the Apache HTTP server. In particular, the database management systems are of great interest for this application, since a big amount of data has to be expected. Therefore, YaY integrates a MySQL database system, which stores the obtained measurement data. The measurement data comprises the aggregated power consumption data provided by the YoMo, the appliance-level power consumption measured by the smart plugs, as well as environmental data received from the networked sensors. This database can be accessed by software tools such as energy advisors in order to draw conclusions from the gathered consumption data.

B. Plugwise Home - Smart Plugs

The application of smart plugs allows the measurement of power consumption at appliance level. From these measurements, precise appliance profiles can be obtained. The introduced measurement system utilises several Plugwise Home plugs[4]. These networked measurement plugs comply with the KEMA Keur safety certificate (number 211754) and fulfil standards such as the IEC 60884-1:2002. This standard regulates the design and conditions for plugs and outlets in households. The utilised smart plugs communicate via a ZigBee radio network, which is maintained by one of the plugs. The plugs measure the power consumption of the attached appliances simultaneously. For this reason the integrated clocks have to be set initially and are synchronised every hour. The measurement results are forwarded to the YaY smart meter via radio communication every time a new sample is available. The maximum current for such a Plugwise Home plug equals 16 A. From this follows, that the connected appliance has to be a single-phase appliance and has to have a nominal power consumption less than $3.84\,\mathrm{kW}$. Table II summarises the specifications as well as the relevant maximum ratings of the utilised Plugwise Home plugs. One of these specifications is the measurement accuracy σ_P, which represents the accuracy for measurements with a sampling frequency of 1 Hz. This sampling frequency also represents to the maximum sampling frequency. The measurement accuracy for cumulative measurements over the period of 1 hour equals 1%. The smart plugs can only be attached to single-phase appliances. Therefore, multi-state appliances have to be monitored by the application of non-intrusive techniques such as load disaggregation.

TABLE II: Plugwise smart plugs specifications

Feature	Abbreviation	Value
Supply voltage	V_{ac}	230 V
Max. current	I	16 A
Max. input voltage	V_{in}	240 V
Max. sampling frequency	f_s	1 Hz
Measurement accuracy	σ_P	5%
Internal resistance	R_i	$300\,\mathrm{m}\Omega$
Power consumption	P	0.55 W

C. DevDuino - Networked sensors

Not all appliances can be equipped with a smart plug in order to record distinctive features of the respective appliance. For some smart plugs the maximum current of a certain appliance may be too large or the appliance itself may not be accessible such as an instant water heater. The integration of environmental networked sensors and wireless sensor networks in the distributed measurement system allows to monitor the impact of appliances on their environment in form of ambient features such as light and sound emission, vibrations, or heat dissipation. Moreover, these ambient features make context-aware computing possible. Context-aware computing can be applied in order to estimate the power consumption of inaccessible appliances and in particular enhance the functionality of the entire system.

Our distributed measurement system integrates several DevDuino sensor nodes[5], which fulfil the purpose of networked sensors. Figure 3(b) shows a DevDuino sensor node. These sensor nodes can be configured as single networked sensors or form a sensor network. The DevDuino node comprises an ATmega328 microcontroller as well as a low-power radio transceiver nRF24L01+. The node integrates the HTU21D sensor, which serves as temperature as well as humidity sensor. Moreover, up to three environmental sensors can be connected to the sensor node. These sensors are:

[3] https://linino.org/

[4] https://www.plugwise.com/home-basic

[5] http://wiki.seeedstudio.com/wiki/DevDuino_sensor_node

(a) YoMo Smart Metering Board (b) devDuino Sensor Node (c) Plugwise Home plug

Fig. 3: Measurement devices for energy and environmental sensing

- Piezoelectric sensors: Some appliances emit vibrations at a certain state of operation. These vibrations can be measured by sensors that exploit the piezoelectric effect.
- Temperature sensors: Household appliances such as electric fires show a high amount of heat dissipation. For this reason, a sensor node equipped with a temperature sensor is able to measure the temperature flow in the surrounding of the respective appliance.
- Sound sensors: Domestic appliances such as blenders, vacuum cleaners, or coffee machines emit a characteristic noise. This noise can serve as ambient feature in order to detect appliances. The utilisation of sound sensors allows to record this special kind of ambient features.
- Luminance sensors: On the one hand allow luminance sensors the detection of light-emitting appliances such as lighting or television sets. On the other hand provide luminance sensors additional information about the environment. For instance the amount of sunlight in the respective room can be determined by application of this sensors. As a consequence of this, the intensity of the lighting can be adjusted to the daylight.
- Gyroscope sensors: A special category of sensors can also be attached to particular appliances. For instance gyroscope sensors can be applied to track motions.

The sensor node defines the sampling frequency, which is applied in the measurement of the ambient feature. The maximum sampling frequency equals 1 Hz. The obtained data is forwarded to the YaY smart meter, which stores the sensor readings. Beside the support of multiple sensors per device the DevDuino nodes provide another feature of interest, mesh networking. This allows the sensors to form a network, which allows the sensors to be distributed widely in the building. The application of such a sensor network in a household allows to detect and to record influences of certain appliance in a wider sense. This allows the recognition of the purpose, for which the appliance is utilised.

IV. Area of Application

The introduced measurement system collects and stores power consumption as well as environmental sensor data. Consequently, the system can be utilised in order to create energy consumption datasets, which include aggregate-level, appliance-level, as well as ambient data. Such datasets represent ground-truth data for the evaluation of energy management systems as well as appliance detection. Apart from the application as system to create energy consumption datasets we identify two specific applications in the research domain of sustainable smart buildings for our distributed measurement system.

First, the combination of the measurement system and an energy-advisor software tool results in an *energy advisor system*, which is able to deliver device-specific feedback to the resident and provide recommendations in order to achieve energy savings.

Second, the measurement system records appliance-specific characteristics at several levels in the household. These characteristics are recorded at several levels of a household's power distribution network and can be utilised to *generate appliance models*. Appliance models are applied in detection algorithms in order to detect appliances as well as their state of operation. Such detection algorithms can be utilised by load disaggregation algorithms to detect present appliances.

A. Energy Advisor

The distributed measurement system collects and stores appliance data. In order to analyse and interpret the collected data, a specific software tool is required. Energy advisors represent such a software tool. This kind of software tool provides direct feedback as well as recommendations to the residents. Already direct feedback can achieve energy savings up to 10% [15]. To provide such functionality (open-source) energy advisors such as Mjölnir[6] were created [14]. In particular, Mjölnir represents a software framework, which consists of several widgets. These widgets serve to illustrate consumption and production data, give detail about the current energy tariff, show real-time data of the present appliances as well as display current energy consumption events in form of a timeline widget. In general, the widgets display advices and recommendations based on the data, which they read from the measurement database. This database is maintained by

[6] http://mjoelnir.sourceforge.net/

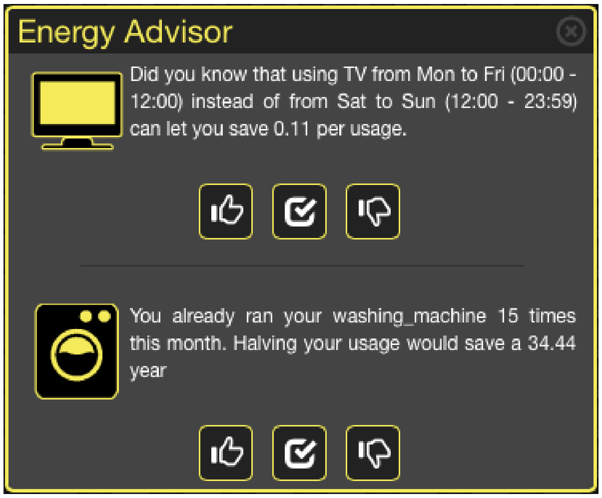


Fig. 4: Mjoelnir Energy advices[14]

the distributed measurement system. Therefore, the database contains measured consumption data of the YaY smart meter, the Plugwise Home plugs as well as ambient features recorded by the networked sensors. In general, Mjölnir distinguishes between data from aggregate-level measurements and data from appliance-level measurements. This distinction fits to the measurement philosophy of our system, which monitors the energy consumption at the household's feed point as well as on appliance level. Mjölnir categorises the aggregated power consumption data of the household as *circuit*. This data is obtained by the YaY smart meter. In contrast to such a *circuit*, the data obtained from appliance-level measurements are defined as *circles*. Each smart plug in the system is represented by such a circle element. The analysis of the obtained measurement data bases on this distinction between circuit and circle elements. The outcome of the analysis is displayed by Mjölnir's widgets, which provide feedback in different ways to the residents.

Timeline widget: The timeline consists of subsequent as well as parallel consumption events. A consumption event describes the amount of energy that a certain appliance consumed over a given time window. The widget displays the consumed energy, which is computed from the measured power consumption and the sampling interval.

Device Usage Model widget: Beside power consumption, the distributed measurement system also records the number of times that a certain appliance was switched. The usage model widgets reports the resident how often a certain appliance was utilised.

Time Series widget: The YaY smart meter measures the overall energy consumption of the household. The time series widget displays the total energy consumption of the household.

Real-time power usage widget: This widget shows the current amount of power that the household appliances consume.

Consumption report: The consumption report provides an overview about the energy consumption of the past days.

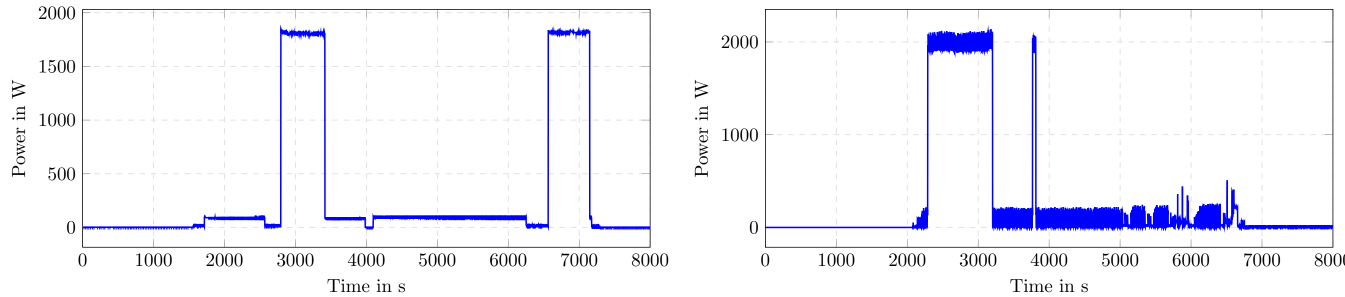
Advice widget: Based on the obtained measurement data, the advice widget generates appliance-specific recommendations, such as Figure 4 shows.

B. Appliance Detection

While an appliance is active, it consumes energy and impacts the environment in a very specific way, including for example specific sound emission, heat dissipation, or vibrations. These characteristic impacts on the environment can be recorded by environmental sensors. For instance a Piezo sensor is able to record the vibration profile of a certain appliance, a temperature sensor can be applied to measure heat dissipation, a microphone can be utilised to measure the sound emission of certain appliances, or a Gyroscope can be attached to appliances in order to detect motions. The electric fire is an appliance, which operates to warm up air. Consequently, the temperature in its surrounding will rise. The increase of temperature over time can be recorded by temperature sensors and stored as ambient feature. This ambient feature can be utilised to detect the appliance in current readings of a certain temperature sensor since the features describes a specific behaviour of a certain appliance. In the same manner power features can be utilised to detect electrical appliances. Therefore, the current power consumption is monitored over time and examined for known power features. These power features are recorded power consumption patterns of appliances. Figure 5 shows consumption patterns of a dishwasher and a washing machine.

Our measurement system generates appliance models on the basis of recorded ambient features and electrical features. Tools such as correlation filters could be applied in order to detect active electrical appliances. Correlation filters examine measurement data for known features. The known features can be a characteristic power consumption behaviour or an ambient feature. These filters apply correlation to analyse the relationship between the measurement data and the respective feature, which the filter seeks to detect in the obtained data. The detection of electric appliances as well as ambient features allows software tools such as energy advisors to generate specific advices in order to achieve energy savings. Furthermore, energy-sapping appliances can be identified by application of appliance detection.

Another research perspective lies in the field of load disaggregation. Load disaggregation algorithms aim to identify electrical appliances in aggregate power readings. The application of recorded appliance features could improve the identification of electrical appliances by means of particular features. Moreover, a big number of load disaggregation algorithms suffers from difficulties in distinguishing between appliances with similar power consumption profiles. The appliance profiles generated by our system consist of power features as well as ambient features. In particular, the ambient features may allow to distinguish between appliances with similar power consumption profiles.



(a) Power consumption of a dishwasher

(b) Power consumption of a washing machine

Fig. 5: Appliance models based on active power measurements

V. Discussion

Measurement requirements define which physical quantities are measured by the system, at which level of the household's power distribution network measurements are to be applied, and define the applied sampling frequency as well as the maximum measurement uncertainty of measurement equipment.

In the design aspects we stated that a distributed measurement system is obligated to measure a set of physical quantities at several levels in the household. The levels of interest are the household's feed point as well as the appliance level. The YaY smart meter measures the overall power consumption as well as features related to current and voltage. In particular, the YaY obtains measurement data about the following physical quantities on aggregate level:

- True root-mean-squared value of the voltage U_{RMS}
- True root-mean-squared value of the current I_{RMS}
- Active power, reactive power, and apparent power

The aggregate level can be seen as the top level of the distribution network. The terminal points of this network represent the appliances. In the introduced measurement system a set of Plugwise Home measurement plugs is applied to monitor the active power consumption P. Furthermore, the distributed measurement system contains networked sensors, which obtain ambient features at appliance level, which record the impact of appliances on their environment such as heat dissipation.

The second aspect related to measurement requirements is the applied sampling frequency. Throughout the elements of the measurement system, a sampling frequency of 1 Hz is applied. This comprises the YaY smart meter, the utilised smart plugs, as well as the networked sensors. This is consistent with the design aspects.

The third requirement regarding measurements is the maximum measurement uncertainty. The introduced design aspects define a maximal limit for measurement uncertainties of 10% for aggregate level measurements and 5% for measurements on appliance level. The YaY smart meter operates on appliance level. As measurement unit, the YaY integrates the YoMo smart metering board. The authors of [5] reported a maximum measurement error of 3.8% for active power measurements, a maximum measurement error of 8.3% for reactive power measurements, and a maximum measurement error of 4.04% for apparent power measurements. Smart plugs are attached to certain appliances to measure power consumption at appliance level. The manufacturer of the utilised Plugwise Home devices reports a measurement accuracy of 5%.

The DevDuino sensors as well as the smart plugs exploit ZigBee to transmit measurement data to the YaY smart meter. The YaY integrates multiple interfaces, which comprise ZigBee, Ethernet, as well as Wi-Fi. This allows the YaY to communicate with a wide variety of networked devices. Smart plugs, networked sensors, smart appliances, as well as other networked measurement instruments can be read by the YaY. Conversely, this means that a great diversity of devices is able to communicate with the YaY. This provides the residents multiple ways of possible feedback since energy consumption reports as well as energy advices can be displayed in several ways e.g. mobile devices such as smart phones or tablets. Furthermore, the YaY can be equipped with an EIA-485 interface. This industrial interface allows the YaY smart meter to control other devices in the distribution board such as circuit breakers as well as to read other measurement equipment. For instance commercial smart meters, which were installed by the electricity supplier, can be read via this interface.

The distributed measurement system was designed to be expandable. This means that the resident is able to add new measurement devices to the system. In particular, networked devices can register themselves at the YaY smart meter in order to contribute measurement data. For this registration an authorisation key is required, which is generated by the resident in the setup phase of the system.

VI. Future Work

Future work will determine how the distributed measurement system and the correlation filters can be combined with artificial intelligence (AI). By means of machine learning an AI is possibly able to precisely study the present appliances in the household as well as their characteristics. Moreover, an AI may serve as cognitive unit that recognises specific events in the household such as the arrival of a resident or certain habits. The application of such a cognitive unit may allow to achieve significant energy savings by the identification of energy-sapping appliances and the recognition of ageing effects of electrical appliances.

VII. Conclusion

In this paper a novel open source and open-hardware metering approach has been presented and discussed.

The purpose of this distributed measurement system is to record and monitor electrical and ambient features of electrical appliances. These features reflect the power consumption of a certain appliance as well as the impact of an appliance on the environment. Therefore, the introduced system integrates a smart meter, a set of smart plugs, and several networked sensors. The smart meter integrates the YoMo smart metering board. This open-hardware board measures the power consumption as well as V-I features at the household's feed point. The smart plugs are attached to household appliances in order to measure their power consumption. The networked sensors record the impact of electrical appliance on the environment i.e. ambient features. These ambient features comprise heat dissipation, sound emission, or vibrations. The distributed measurement system is utilised to record and store appliance features.

In combination with diagnosis software (energy advisors) such systems present a low-cost alternative to expensive commercial home monitoring systems. Thus, asset costs can be reduced by the installation of such a low-cost home energy measurement system HEMS. The deployment of a low-cost HEMS would allow the resident to detect abnormal appliance behaviour. Because of ageing, some electrical appliances consume more energy than a new appliance of the same kind. Such phenomenons were reported in [16], where a common household device consumed due to ageing effects three times more energy than at the time of purchase. Such a HEMS would be able to detect ageing effects and would suggest the user to replace the respective device. By means of suggestions like this, such a system assists the owner in saving costs and in detecting power eaters. Furthermore, the system would be able to detect the point in time, where an appliance will require maintenance. The observation of steady-state, transient-state, and ambient appliance features makes this detection possible.

References

[1] D. Coleman, ‘‘V. world population in 2300: A century too far?’’ *World Population to 2300*, 2004.

[2] B. Stevens and P.-A. Schieb, ‘‘The future of families to 2030: an overview of projections, policy challenges and policy options,’’ *The Future of Families to 2030*, vol. 2011, p. 15, 2011.

[3] A. Marchiori and Q. Han, ‘‘Using circuit-level power measurements in household energy management systems,’’ in *Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*. ACM, 2009, pp. 7--12.

[4] A. Reinhardt, P. Baumann, D. Burgstahler, M. Hollick, H. Chonov, M. Werner, and R. Steinmetz, ‘‘On the accuracy of appliance identification based on distributed load metering data,’’ in *Sustainable Internet and ICT for Sustainability (SustainIT), 2012*. IEEE, 2012, pp. 1--9.

[5] C. Klemenjak, D. Egarter, and W. Elmenreich, ‘‘Yomo: the arduino-based smart metering board,’’ *Computer Science-Research and Development*, vol. 31, no. 1-2, pp. 97--103, 2016.

[6] D. R. Muñoz, D. M. Pérez, J. S. Moreno, S. C. Berga, and E. C. Montero, ‘‘Design and experimental verification of a smart sensor to measure the energy and power consumption in a one-phase ac line,’’ *Measurement*, vol. 42, no. 3, pp. 412--419, 2009.

[7] R. Morales, F. J. Badesa, N. García-Aracil, C. Perez-Vidal, and J. M. Sabater, ‘‘Distributed smart device for monitoring, control and management of electric loads in domotic environments,’’ *Sensors*, vol. 12, no. 5, pp. 5212--5224, 2012.

[8] B. Campbell and P. Dutta, ‘‘Gemini: A non-invasive, energy-harvesting true power meter,’’ in *Real-Time Systems Symposium (RTSS), 2014 IEEE*. IEEE, 2014, pp. 324--333.

[9] J. Z. Kolter and M. J. Johnson, ‘‘Redd: A public data set for energy disaggregation research,’’ in *Workshop on Data Mining Applications in Sustainability (SIGKDD), San Diego, CA*, vol. 25. Citeseer, 2011, pp. 59--62.

[10] A. Monacchi, D. Egarter, W. Elmenreich, S. D'Alessandro, and A. M. Tonello, ‘‘Greend: An energy consumption dataset of households in italy and austria,’’ in *Smart Grid Communications (SmartGridComm), 2014 IEEE International Conference on*. IEEE, 2014, pp. 511--516.

[11] C. Beckel, W. Kleiminger, R. Cicchetti, T. Staake, and S. Santini, ‘‘The eco data set and the performance of non-intrusive load monitoring algorithms,’’ in *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings*. ACM, 2014, pp. 80--89.

[12] D. Egarter, V. P. Bhuvana, and W. Elmenreich, ‘‘Paldi: Online load disaggregation via particle filtering,’’ *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 2, pp. 467--477, 2015.

[13] M. Zeifman and K. Roth, ‘‘Nonintrusive appliance load monitoring: Review and outlook,’’ *IEEE Transactions on Consumer Electronics*, pp. 76--84, 2011.

[14] A. Monacchi, F. Versolatto, M. Herold, D. Egarter, A. M. Tonello, and W. Elmenreich, ‘‘An open solution to provide personalized feedback for building energy management,’’ *Journal of Ambient Intelligence and Smart Environments*, vol. 9, no. 2, pp. 147--162, 2017.

[15] K. C. Armel, A. Gupta, G. Shrimali, and A. Albert, ‘‘Is disaggregation the holy grail of energy efficiency? the case of electricity,’’ *Energy Policy*, vol. 52, pp. 213--234, 2013.

[16] D. Benyoucef, P. Klein, and T. Bier, ‘‘Smart meter with non-intrusive load monitoring for use in smart homes,’’ in *IEEE International Energy Conference*, 2010, pp. 96--101.