

UBI-AMI: Real-Time Metering of Energy Consumption at Homes Using Multi-Hop IP-based Wireless Sensor Networks

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Abstract. We present a system for real-time metering of aggregate power consumption and appliance level loads in homes. The power consumption data is collected by sensors in a multi-hop IP-based wireless sensor network. The data is stored at a central server which prepares various representations of the data to be viewed with a web browser. The findings of a longitudinal user evaluation of our system by seven households testify for a successful design and implementation.

Keywords: IEEE 802.15.4, 6LoWPAN, wireless embedded Internet.

1 Introduction

Despite numerous energy efficiency policies and programs electricity consumption continues to grow. In the EU-25 member states the consumption of the residential sector increased by 10.8% during the period of 1999-2004. In the USA the annual power consumption has tripled during the past two decades. Residential and commercial buildings contribute significant proportion of the total energy consumption, 54% in the EU-25 and 72% in the USA. Further, it has been estimated that 30% of that energy consumption is wasted. [2, 12, 13]

Past studies such as Chetty *et al.* [3] have proven that awareness of energy consumption in homes and offices can lead to up to 20% reduction in electricity usage. While Stern [11] showed a long time ago that real-time, per-appliance data on electricity consumption would provide substantially greater utility and actionable information, the customers of today's utility companies typically have to be content with data that is aggregated, delayed and difficult to access.

Electricity is distributed through a building along a tree-like structure called a *load tree*, where the root connects the building to the power grid and the leaves correspond to individual electric appliances. In an ideal case we would want to have a full, detailed and real-time view of the load tree by monitoring the aggregate load at the root (top-down view) and the individual loads at every appliance (bottom-up view).

However, this is rarely possible in practice due to cost and scalability issues, when a building contains hundreds or thousands of appliances.

Numerous academic and industrial approaches have been proposed for monitoring appliance level loads, for example the MIT Plug [7] for profiling a load over short and long time scales. Many startups have introduced wireless energy monitoring solutions based on ZigBee technology [27]. These products provide detailed power measurements of selected individual loads, which contribute to a bottom-up view of the power consumption.

By monitoring the load at the root a top-down view of the load tree can be pursued. Many utility companies have introduced AMI (Automated Metering Infrastructure) solutions that provide almost real-time data on the aggregate energy consumption of homes. Some utilities are collaborating with aggregators such as Google PowerMeter [18] and Microsoft Ohm [22] to provide more detailed feedback on energy consumption at a household level. Reactive and real power signatures of appliances can be employed for disaggregating individual loads from the aggregate load as originally proposed by Hart [5] and later refined by many studies. The approach is feasible for a small number of loads that have distinguishable differences in power signatures.

We present a system called UBI-AMI for automated power metering of a household by measuring the loads both at the root and at selected individual appliances with wireless sensors. The sensors transmit load measurements over a multi-hop IP-based wireless sensor network (WSN, [10]) to a router which forwards data to a server. The server creates different representations of the data which can be viewed with a web-based user interface (UI) and downloaded as RSS feeds. The UI also allows the user to turn individual sensors (i.e. appliances attached to them) on and off, and request email/SMS alarms based on sensor data. The UBI-AMI system is empirically assessed by a longitudinal user evaluation with seven households.

This paper is organized as follows. The implementation of the UBI-AMI system is presented in Section 2. The setup and main findings of the user evaluation are reported in Section 3. Conclusions and our plans for future work are discussed in Section 4.

2 System Implementation

Fig. 1. shows the architecture of the UBI-AMI system, which comprises of three functional building blocks:

1. Sensors in multiple 6LoWPAN sensor networks measure the loads and turn on/off devices connected to the sensors. Each network has a router collecting packets from multiple sensors over a multi-hop mesh topology, i.e. a sensor is able to forward packets of other sensors.
2. Central UBI-AMI server receives packets from the routers, stores the data in a database and creates different representations of the data.
3. User can browse the measurement data with a web browser and subscribe to RSS feeds summarizing the data. Further, the user can control the sensors and subscribe to email/SMS alerts based on load measurements.

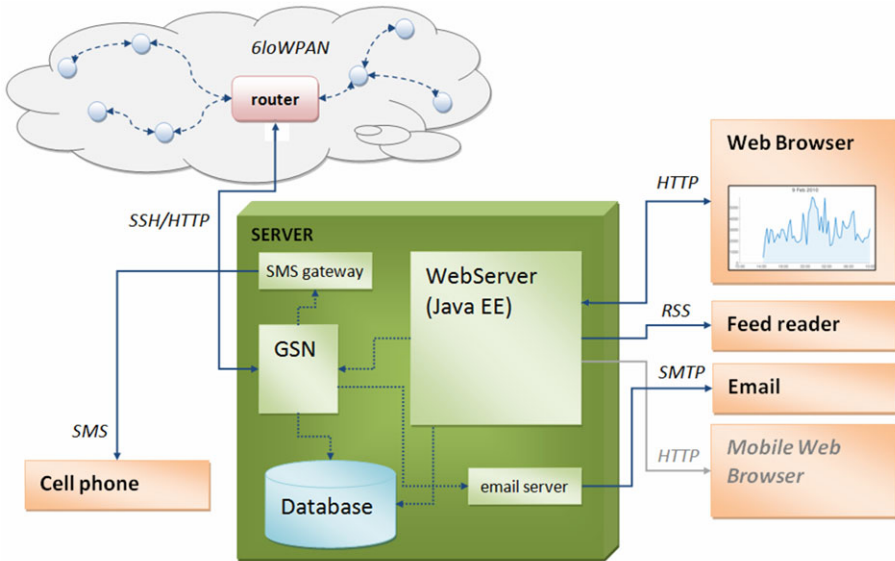


Fig. 1. Architecture of the UBI-AMI system

2.1 Sensors

We have built two types of wireless sensors. A *socket sensor* (Fig. 2(a)) measures the loads of individual devices or groups of devices equipped with pluggable power cords. A *mains sensor* (Fig. 2(b)) measures the load at the root of the load tree of a building, including all non-pluggable devices such as electrical heating, hot water boiler and lighting.

The sensors are furnished with a Radiocrafts RC2301 radio module [24] which is equipped with an IEEE 802.15.4 radio on the 2.4 GHz band. The radio module is flashed with the Sensinode NanoStack 2.0 protocol stack [25] (Fig. 3(a)), which implements the IETF 6LoWPAN specification for transmitting IPv6 packets over IEEE 802.15.4 devices [8]. Effectively, the protocol stack provides the sensors with half-duplex multi-hop IPv6 connectivity. The sensors transmit measurement data every 10 seconds and receive possible turn on/off commands in a response message.

Socket Sensor

The components of a socket sensor are placed on an in-house PCB (Fig. 3(b)), which is isolated from the mains current by an optocoupler and a transformer. The load measurement is conducted with a circuit extracted from a commercial AVEC A9999 energy meter [16]. LM60CIZ temperature sensor [21] and Vishay TEPT5700 illumination sensor [26] are integrated in the enclosure, together with two LEDs providing simple status information.

Atmel ATmega 164P microcontroller [15] collects the data from the energy measurement circuit and the sensors, and communicates the data to the radio module using a socket-like protocol over a serial port. The radio module encapsulates the data

in UDP packets for wireless transmission using the 6LoWPAN protocol over the IEEE 802.15.4 link on the 2.4 GHz band. An external 3 dBi omnidirectional antenna is connected to the radio module to boost the range of the low-power radio.

A relay capable of switching 16 amperes is integrated to turn on/off the appliances plugged into the sensor. The socket sensor is furnished with a 1.5 m three-socket extension cord, to allow easy placement of the sensor unit and the load measurement of multiple appliances simultaneously. The unit price of a socket sensor was 69 EUR when built by us in small quantities.

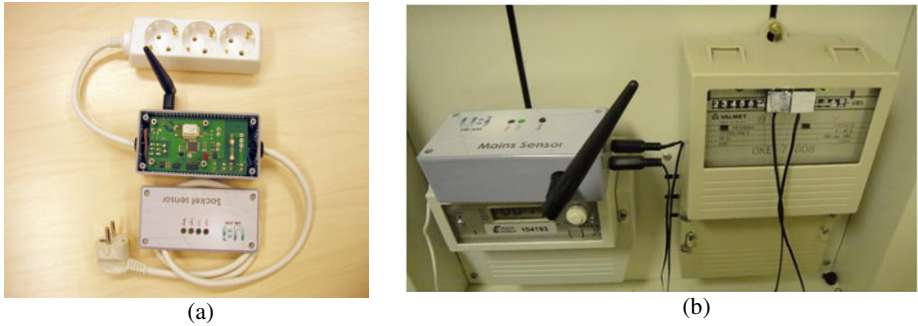


Fig. 2. (a) Socket sensor; (b) Mains sensor

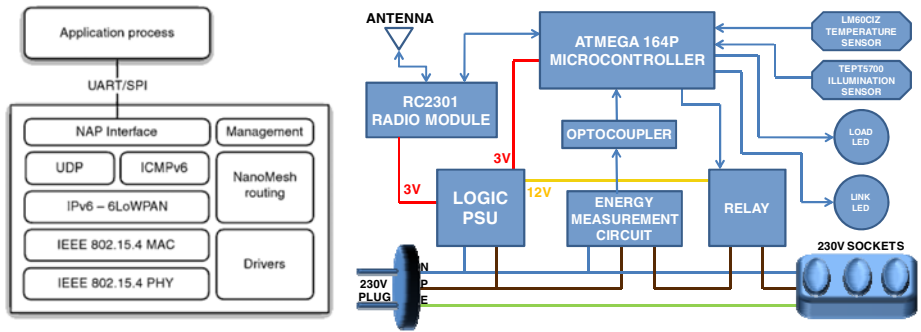


Fig. 3. (a) NanoStack architecture; (b) Block diagram of the in-house PCB

Mains Sensor

The mains sensor is built using mostly the same components as in the socket sensor. It measures the load of a building or a home with a simple phototransistor counting the pulses of the S0 interface of a main switch board. The mains sensor does not have mains current on board but is instead equipped with an external power supply. It does not have the extension cord neither the relay unit. The unit price of a mains sensor was 52 EUR when built by us in small quantities.

2.2 WSN Router

We built the WSN router on an affordable Linksys WRT54GS WLAN router [20] by adding a Radiocrafts RC2301 radio module to a free serial port connected to an external antenna connector (Fig. 4). The Linksys router is flashed with a customized Kamikaze OpenWRT Linux firmware [19] capable of routing packets between the 6LoWPAN network and the Internet. When connected to any IPv4 network providing an IP address via DHCP, the router establishes two SSH connections to the UBI-AMI server. The first connection is used to securely transfer the packets received from the sensors using the HTTP protocol, together with any commands between the router and the server. The second connection is used to access the router remotely for management purposes. The wireless links between the router and the sensors are protected by 128-bit AES encryption. The unit price of a WSN router was 100 EUR when built by us in small quantities.

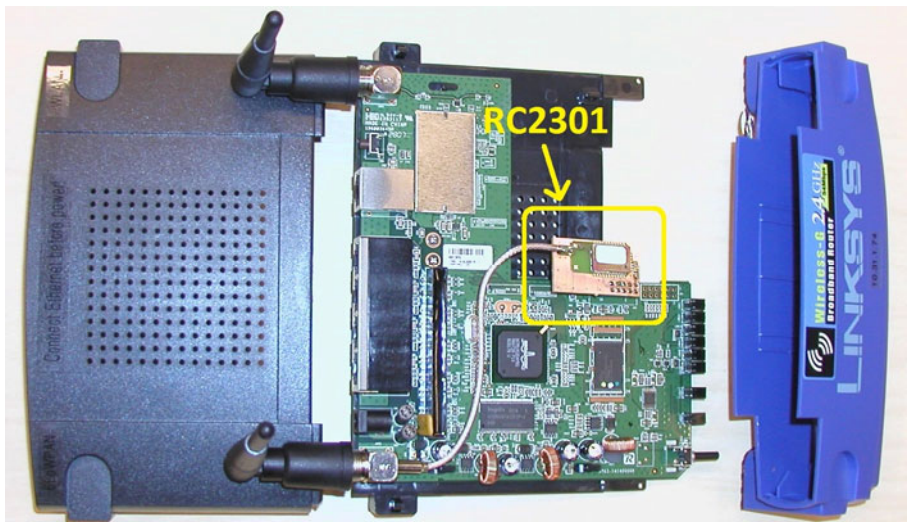
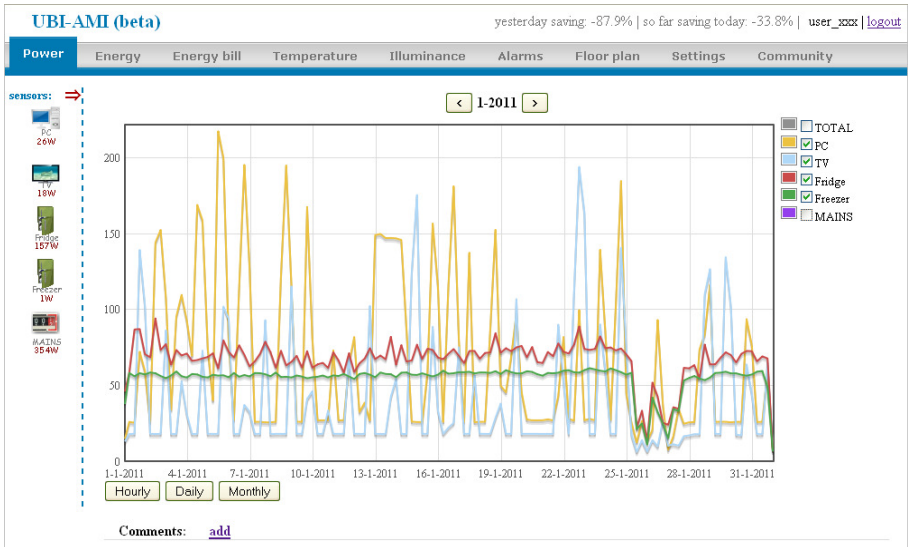


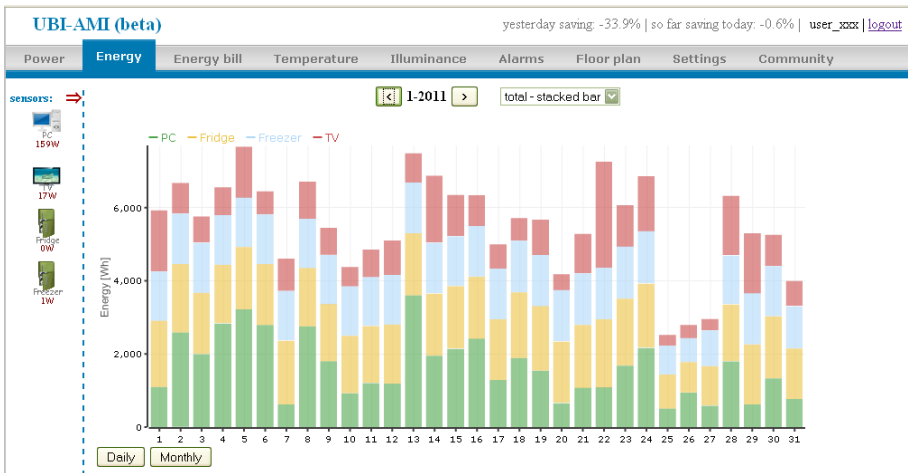
Fig. 4. WSN router with the placement of the RC2301 radio module highlighted

2.3 UBI-AMI Server and User Interface

The UBI-AMI server is realized in Java atop the open source GSN (Global Sensor Network) middleware in [1]. So-called wrapper components receive the measurement data from the routers and store the data into a MySQL database [23]. For security purposes the server authenticates each router with MAC address filtering and all communication takes place through SSH tunnels. To save storage space, at certain intervals the server compresses and disposes of ‘old’ data by representing it with average values. The server also keeps tracks of the alarms configured by the users.



(a)



(b)

Fig. 5. Screenshots of UBI-AMI user interface: (a) power consumption; (b) energy

The UBI-AMI user interface (UI) is implemented as a website atop the open source GlassFish application server [17] as Java Server Pages. Fig. 5 shows screenshots of the two most commonly used pages, power and energy. Other views based on the sensor data include energy bill, temperature, and illumination. Each type of data can be viewed on different time scales (hourly, daily, weekly, monthly). The UI has separate tabs for drawing the floor plan and for configuring alarms received either via email or SMS to mobile phone. To stimulate participation and community engagement the users can view the consumption data of other members in the community.

The UI has also a separate tab for configuring settings such as the price of energy and RSS feeds reporting the real-time power consumption for the last 1, 4 or 24 hours. The header shows the user's current real-time energy consumption with relative change over the past 24 hours.

When a user starts using the UBI-AMI service, (s)he has to first deploy the sensors around home. Once the floor plan is drawn the icons of sensors can be placed on it and assigned with their friendly names (e.g. 'TV' or 'fridge'). When the icon of a sensor is clicked, a real-time view of the sensor's latest data measurement is provided. Further, in case of a socket sensor the user can turn on/off the sensor, i.e. the appliances plugged into the sensor.

3 Longitudinal User Evaluation

The UBI-AMI system was evaluated by seven households in the Oulu region in 2010. Each household was provided with a demo kit comprising of a router, a mains sensor and four socket sensors. The kits were deployed in late January 2010, so that researchers first conducted an initial interview mapping the household's electrical appliances and attitudes towards saving energy. Then the researchers introduced the UBI-AMI system and showed how to install the router, the socket sensors and the mains sensor and how to use the web UI. Quantitative data has been obtained by logging at the server and qualitative data by follow-up interviews of the test users.

All seven households lived in a detached house equipped with electrical heating, an electric sauna and a hot water boiler. While some of the households had previously used the traditional separate energy meters for determining appliance level consumptions, none of them had used any WSN based monitoring systems similar to our UBI-AMI.

Table 1 shows that the test users listed easy deployment, low operational expenses, possibility to measure electricity consumption of an individual appliance and timeliness of the electricity consumption data as the most relevant features of the UBI-AMI service in the opening interviews.

Table 2 tallies the test users' expectations on the impact of the UBI-AMI service on their households. While all test users expected the UBI-AMI service have some sort of an effect, none expected the electricity consumption to reduce a lot.

While the households have used the UBI-AMI system for 11 months, we only use the quantitative data collected in August- December 2010 in this study. By omitting the first six months we wish to eliminate any bias contributed by the curiosity and novelty value of a new system introduced in a household. Thus, we assume that after six months the UBI-AMI system has turned into one of the many services used by a household. During the five month period a total of 219 sessions took place in the UI. Table 3 shows how these sessions were distributed over the different views of the UI in terms of frequency and browsing time. We observe that the power and energy views dominate the usage as expected. While both of them can be viewed at different time scales, over 90% of the viewing takes place at the default daily view.

Table 1. Relevance of various features reported by test users in the opening interview

Feature	Count
Low purchase price	5
Low operational expenses	6
Easy deployment	7
Good usability	5
Use of the service via web	5
Use of the service with a mobile phone	2
Configurable email alerts	1
Configurable SMS alerts	4
Possibility to measure electricity consumption of an individual appliance	6
Timeliness of the electricity consumption data	6
Accuracy of the electricity consumption data	2
Automatic archiving of the electricity consumption data	5
Comparison of the electricity consumption data with other users	3
Possibility to turn off/on sensors and attached appliances remotely	3

Table 2. Test users' expectations on the impact of the UBI-AMI service

Impact	Count
No effect on the use of electric appliances or electricity consumption	0
We will monitor the use of particular electric appliances more carefully	6
Our electricity consumption will reduce a little	6
Our electricity consumption will reduce a lot	0
Other effect	1

Table 3. The distribution of sessions over different views of the UI

View	Frequency (%)	Browsing time (%)
Power	52.4	62.3
Energy	18.5	24.5
Energy bill	13.2	3.7
Temperature	4.4	1.8
Illumination	5.3	3.8
Alarms	1.8	0.1
Floor plan	2.4	2.1
Community	2.0	1.7

In the follow-up interviews the test users were asked to assess various statements on a 5-point Likert scale (1=totally disagree ... 5=totally agree). Table 4 summarizes responses to selected statements so that responses 1 and 2 are tallied under "disagree", 3 under "don't know" and 4 and 5 under "agree". Exactly one test user reported the UBI-AMI service to have had reduced the energy consumption in their household. Overall, the responses testify for successful design and implementation. In some cases the observed technical unreliability of the system was actually attributed to the household's Internet connection being temporarily disconnected.

Table 4. Test users' assessment of selected statements

Statement	Disagree	Don't know	Agree
Deployment of socket sensors was easy	0	0	7
Socket sensors functioned reliably	1	1	5
Deployment of mains sensor was easy	1	0	6
Mains sensor functioned reliably	1	1	5
Deployment of router was easy	0	0	7
Router functioned reliably	2	1	4
Web UI was easy to learn to use	0	0	7
Web UI is easy to use	0	1	6
Web UI is clear	1	1	5
Web UI is pleasant to use	1	3	3
Possibility to turn off/on sensors and appliances remotely is useful	1	2	4
Configurable alarms are useful	1	0	6
UBI-AMI is useful service	0	0	7
UBI-AMI gives reliable information on energy consumption	1	1	5
UBI-AMI gives comprehensive information on energy consumption	1	0	6
UBI-AMI gives timely information on energy consumption	0	0	7
UBI-AMI has improved our awareness of energy consumption	0	0	7
UBI-AMI has impacted our way of using electric appliances	3	1	3
UBI-AMI has reduced energy consumption in our household	3	3	1
I wish to use UBI-AMI in the future	0	1	6
I would recommend UBI-AMI to other people	0	0	7

Test users reported that their continuous interest in real-time loads of individual appliances wore out rather quickly. Instead, they would have preferred visualizing the monetary expenses of energy consumption, together with any rapid relative changes, as an ambient media whose observation would not require any conscious or dedicated action on their part. Further, sensors for measuring non-socket appliances such as sauna stoves and hot water boilers were requested, together with automatic incorporation of outdoor temperature, which in Finland is crucial for assessing the contribution of electric heating into the power consumption.

4 Conclusion

Our study shows that visibility to both the aggregate load and appliance level loads in a home is very useful functionality that has an impact on how people use electric appliances. IP-based wireless sensor networks and web provide a very potent technology platform for implementing such functionality in a cost-effective, reliable and standardized manner, in contrast to the many proprietary solutions on the market.

While many systems similar to our UBI-AMI have been proposed earlier, e.g. [6, 9, 14], our study is distinguished from most other studies by the longitudinal evaluation of the system by seven real households. Such long-term assessment by real users in authentic setting is needed to reliably study the adoption and impact of this type of ubiquitous computing systems, which require sufficient technical and cultural

readiness to be successful [4]. Further, our system employs multi-hop data dissemination, and allows users to configure alarms based on measurements and to turn on/off appliances remotely.

The UBI-AMI system has also other shortcomings in addition to those discussed in the evaluation. The sensors use unreliable transport protocol (UDP), assuming that a packet is forwarded all the way to the UBI-AMI server after transmission. However, if for example the Internet connection between the router and the server is disconnected, the packets and thus the data are lost. This could be addressed by either the sensors or the router storing the measurements for delay tolerant delivery or by using a reliable transport protocol, but at the cost of extra computation and communication overhead. The 2.4 GHz radio coupled with the 1 mW transmission power does not provide sufficient penetration and range for networking in brick buildings. The design of our sensor casings and the plastic cables limited deployment to dry indoor facilities with nonfreezing temperatures.

We are currently busy building new types of sensors. Their radios will use the sub-GHz (868 MHz) radio, which provides much better penetration and range than 2.4 GHz. We will integrate so-called clamp sensors into the mains sensor for measuring the loads of non-socket appliances from the main switch board. We are also considering other types of sensors such as environmental sensors. We also need to enhance the UI in many respects, e.g. to include budget tracker and energy bill estimation [18] and mobile phone client [14].

The new sensors and the improved UI will be employed in a larger trial to be conducted atop a city-wide wireless sensor network dubbed panOULU WSN. We have deployed around downtown Oulu dozen routers, which provide half-duplex multi-hop connectivity to low power sensors on the sub-GHz (868 MHz) band using the IEEE 802.15.4 radio and the 6LoWPAN protocol stack. The routers provide typically 500 meter line-of-sight range with 1 mW transmission power. Households within the coverage area of the panOULU WSN will not need the dedicated router used in this study.

Acknowledgments

The authors gratefully acknowledge financial support from the Finnish Funding Agency for Technology and Innovation, the European Regional Development Fund, the City of Oulu, and the UBI (UrBan Interactions) consortium.

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