Experiences and Future Plans for WSN-enabled Service Development in Home Environment

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***Abstract*— A Wireless Sensor Network (WSN) consists of small measuring and actuating devices. The technology has potential for numerous ubiquitous applications in different fields, such as environmental monitoring, building automation, process automation, and health care and military applications. Instead of raw sensor values, the measured data should be processed to extract relevant, value-added information to implement usable services, and presented to the user with an easily comprehensible manner. In this paper, we present a Home Area Network (HAN) service architecture that refines sensor data into insights on the subject and this way promotes automatic data processing and reduces manual labor. The research has been carried out with a real-world pilot study. Based on the experiences, we present potential future application concepts for home area.**

Keywords: wireless sensor networks, home area networks, context aware services

I. Introduction

A Wireless Sensor Network (WSN) consists of a number of small measuring devices (nodes), which autonomously form a communication network. The nodes sense their environment or monitor other devices, process and store data, and deliver data towards other nodes and gateway devices. Gateways connect the wireless networks with other devices, networks, or infrastructure servers.

WSNs are widely studied, as the technology has potential for numerous ubiquitous applications in different fields, such as environmental monitoring, building automation, process automation, and health care and military applications.

WSN technology is a complex distributed embedded system on its own. Typically, WSN nodes are small, low-cost, and low-energy devices, operating years with small batteries or using energy harvested from environment e.g. with solar panels. The main research problems have been platform architectures, communication protocols, security architectures, energy optimization, and application concepts.

Raw sensor values alone have limited value for users. Instead, the measured data should be processed to extract relevant, value-added information to implement usable services, and presented to the user with an easily comprehensible manner. As illustrated in Figure 1, users gain insights and knowledge on examined phenomenon.

In this paper, we present a Home Area Network (HAN) service architecture that allows refining sensor data into insights on the subject and this way promotes automation and reduces manual labor. The architecture and use cases are applicable to existing technologies. The research has been carried out with a real-world pilot study. Based on the experiences, we present potential future application concepts for home area. Detailed presentation of the embedded technology and theory in communications are outside the scope of this paper.

The paper is organized as follows. Section II presents the related work on WSNs targeted at home environment. Section III presents the proposed WSN service architecture. Section IV describes the experiences gained with the home pilot study. Potential application concepts are presented in Section V. Future directions are discussed in Section VI.

II. Related Work

WSN is seen as an enabling technology with few specific market drivers at the beginning. In HANs, wireless technologies are already utilized in home security systems, and the safety and security continue to be strong technology drivers. Smart

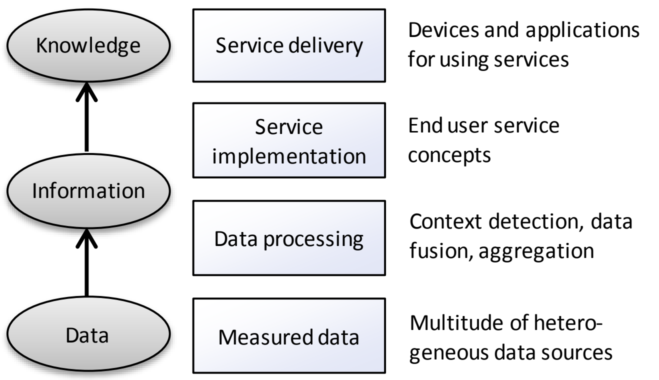

Figure 1. Refining sensor measurements into user services.

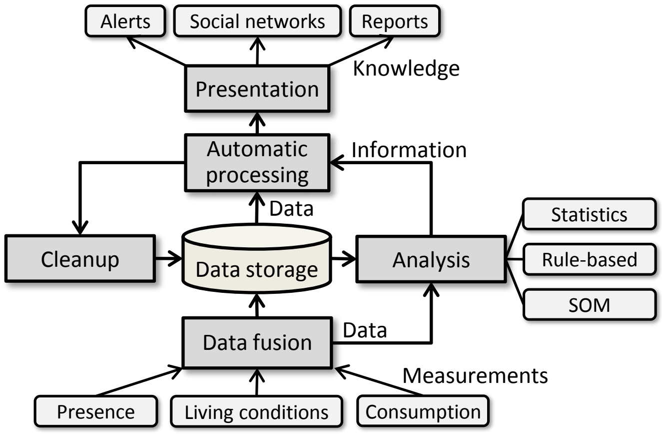

Figure 2. Sensor data processing flow for enabling value-added services at home.

grids are drivers especially in the industry but also homes benefit from them as energy saving and green applications. Remote health care and assisted living are the third application area where WSN technologies are expected to emerge in near future, especially due to aging population.

A. *Home Pilot Studies*

WSN development has been relying for field piloting to achieve reliable results in technology performance and application/service feasibility. In practice, prototype applications are implemented on a selected WSN technology and study-specific user applications are developed on these. In prototyping, the system reliability becomes a limiting factor, as application pilots operate end-to-end, covering physical durability of devices, embedded software, and infrastructure interfaces and data collection.

In [1] the authors present a ZigBee-based WSN living laboratory pilot. The paper concentrates on signal and sensing reliability in home environments. An architecture for smart home including sensors/actuators, home server, home management server, and users is presented in [2]. Also, [5] and [13] present similar ZigBee-based network architectures for home installations.

A middleware for home WSN installations is presented in [3] with limited prototype testing. The authors propose to divide WSN middleware into two categories: network control for device specific tasks, and system control for higher level services. Another middleware called ZUMA for interconnecting all kinds of devices in home environment is presented in [9]. The main content of the paper is a centralized smart-home platform, and the paper focuses on WSN communication operations.

In [4], the authors present a multi-tier WSN for home applications. The primary content of the paper is to define the requirements for WSN at home, and to propose an energy efficient WSN for meeting the requirements. The results are evaluated with the NS-2 simulator.

B. *Energy Metering and Management*

Energy saving is expected to be the main motivator in bringing WSNs to homes. In a smart energy home [14], a consumer has a real-time access to energy consumption and pricing information, and has more control over the consumption profiles. This also means that home appliances are equipped with energy metering and interfaces for accessing them. In [6], the authors propose a scheme for managing home appliance energy consumption by shifting appliance start times to off-peak hours. The evaluation of the scheme is carried out in simulations. Energy metering for households using multihop IP network on IEEE 802.15.4 is presented in [7]. It presents an energy metering architecture but does not consider other use cases.

According to On World's research on public utility project managers [15], 7 out of 10 utilities are planning in-home energy management products that integrate with HANs. Consequently, the marker research company predicts a multi-billion ecosystem to grow in HANs within next five years. Health Care

Authors in [8] propose a smart gateway for WSN health care systems at home environment. The paper concentrates on prototype network design. Similarly, [10] presents a methodology and applications for applying WSN in various areas of homecare. The paper concentrates on a generic hardware platform called Universal Communicator for smart sensor technology. A ZigBee-based heart rate and blood pressure sensor for home environments is presented in [11].

Personal assistant system architecture with prototyping and a pilot study is presented in [16]. The system targets at open interfaces where off-the-shelf technologies can be connected to a common architecture to assist elderly people to maintain the capability of independent living through reminding of daily activities, monitoring of physiological functions and mobility, and real-time communications with remote care providers.

C. *Potential Technologies*

IEEE 802.11 WLAN, and Bluetooth are potential wireless technologies for HANs due to their existing wide use. However, the technologies are generic and do not specifically address HAN applications, thus requiring manufacturer specific solutions.

ZigBee [18], Z-Wave [19], Enocean [20], and Insteon [21] are industry specifications that target HANs. They define common message formats and application profiles for sensing, lighting and window shade control, turning devices on/off, intruder detection, security alarms, and the control of home entertainment devices. Unfortunately, the specifications are somewhat competing and incompatible with each other.

D. *Summary of Related Work*

As a summary of related work, smart homes utilizing WSN as one component are becoming a popular research topic. Related papers in the field present different enablers, and an enabler is a network or a middleware. There is no single solution where one fits all. Only few papers describe end-to-end application scenarios and real-world pilots.

III. Sensor Data Processing Architecture

The proposed sensor data processing architecture is presented in Figure 2. Typical home area measurements

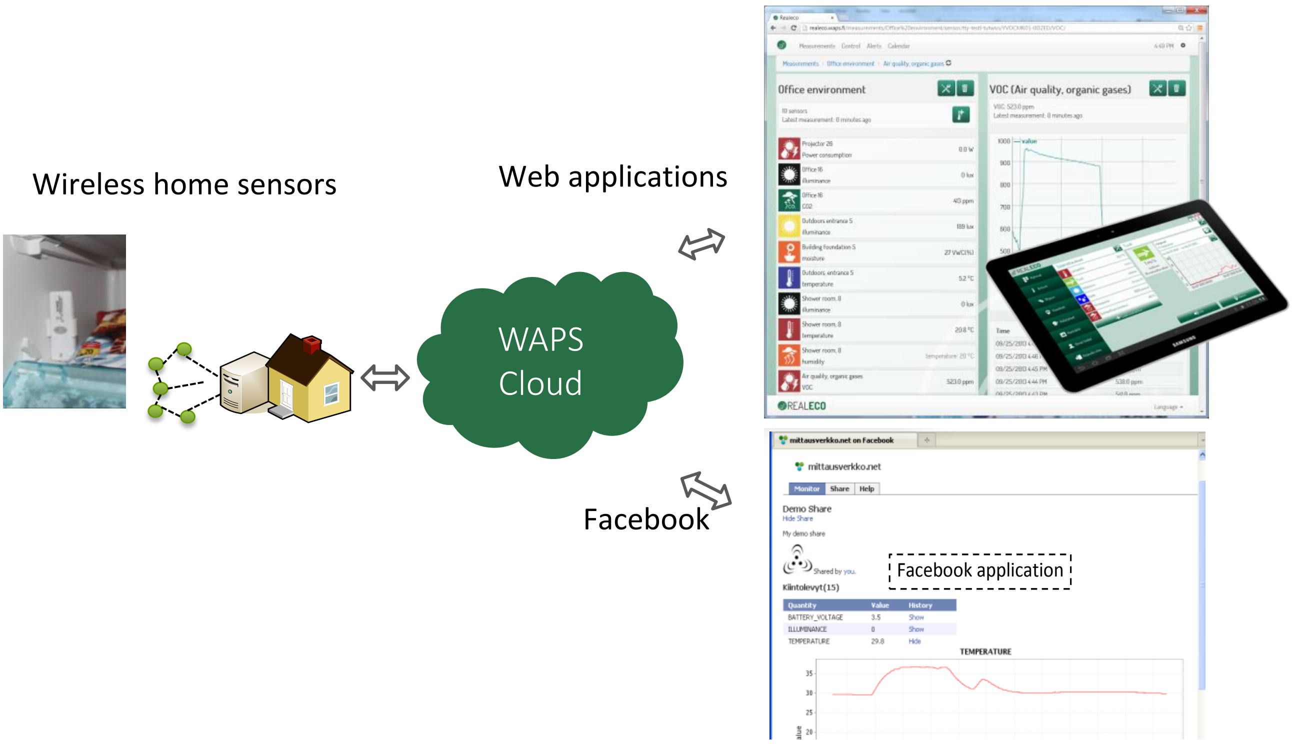

Figure 3. End-to-end WSN service infrastructure used in the home pilot study.

achievable with off-the-shelf technologies include living condition monitoring, presence detection, and consumption measurements. Condition monitoring measures e.g. temperature and humidity used to adjust heating and ventilation for well-being. Presence detection is used for safety and security in elderly care and intruder alerts. Consumption measurements measure power, water, etc. usage for energy efficiency.

Next, data fusion combines measurements to remove redundant data, but can also derive new data from raw sensor values. For example, the usage cycles of home appliances can be derived from its power consumption or vibrations. The measurement data is stored for later use. As the amount of collected data can be vast, old data are cleaned to free storage.

Measurements are processed automatically and in real time to detect the relevant information for a user. Statistical analysis allows detecting trends and thus predicting e.g. energy consumption. Rule-based analysis can detect abnormal conditions, but defining suitable rules requires a priori knowledge on the acceptable sensor values. This knowledge can be gained with more advanced analysis methods such as Self-Organizing Map (SOM) [12] that ease detecting dependencies and causalities between sensor values. Finally, the processed data are presented to a user e.g. with reports or via social networks.

IV. Home Pilot Study

The WSN home pilot study started in 2008 in Finland near Tampere. Installation comprised 30 nodes and a gateway node. The site was a single family terrace house apartment with a backyard. The persons in charge of the pilot were researchers of Tampere University of Technology (TUT). In parallel to this, several other similar pilot studies were carried out in other locations, with or by TUT's research partners [22]. All WSN pilot studies shared the same server side infrastructure presented in Figure 3. For the clarity of presentation, the examples in this paper consider only the terrace house pilot site.

A proprietary research-based technology [17] was used for WSN. It represents a modern resource constrained, low-energy, off-the-shelf WSN consumer oriented technology. Thus, the results of the paper can be generalized with other WSN technologies having similar resources. The technology consists of hardware platforms, multihop mesh protocol stack, and end-to-end application infrastructure. Data are routed towards the nearest WSN gateway node. WSN nodes are battery-powered embedded sensing devices operating on 2.4 GHz and 433 MHz ISM frequency bands.

The 433 MHz platform has longer communication range making it suitable for geographically large outdoor deployments whereas the 2.4 GHz platform is better suited for dense indoor deployments due to its higher throughput. Wireless nodes are equipped with a wide range of sensors: temperature (both built-in and with a detachable external multipoint connector), luminance, carbon dioxide, air humidity, soil moisture, magnetic switch, motion and presence detection (infrared, noise, and piezoelectric sensor), acceleration, and energy consumption. Depending on the equipped sensors, each node transmitted 120-140 packets containing 8 B sensor sample per hour.

A. Installation

One of the key WSN benefits is the rapid, cable-free, and minimal effort installation. The installation of the pilot was non-destructive, and the nodes were initially placed around the apartment near the points of interest. During the two and a half year pilot, the locations were changed to accommodate sensing requirements, while new features were added by new hardware sensors and software updates.

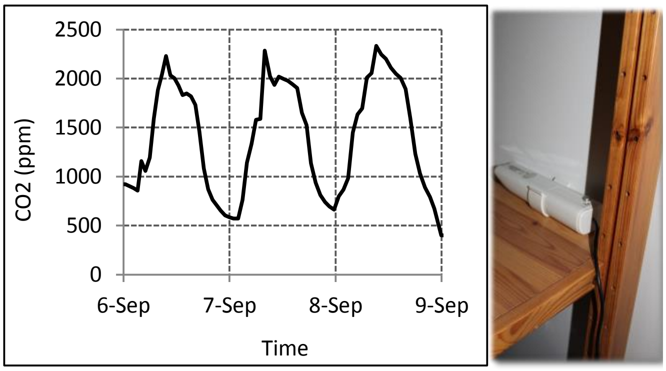

Figure 4. CO2 measurements in the home network pilot.

To make the technology suitable for end-users, an installation should not take too much time (hours rather than days), and should not require technical expertise. An autonomous and self-healing network is a necessity to ensure effortless deployment and to allow recovery from changes in the radio environments (such as RF interference or movement of the nodes) without manual configuration. Multihop routing allows extending the network coverage as long as a routing neighbor node is available. In the relative small apartment of the home pilot study, the typical hop count to the gateway node was 2-3 hops.

In the installation, the gateway node was connected to a regular broadband modem through an Ethernet connection, and a connection to an online WSN server opened automatically. No local software installations were needed.

B. WSN Infrastructure

In the implementation, a WSN server can be shared by several gateways. This way, services running on the server can easily combine data from different installations, or from the same installation extending network capacity and coverage with multiple gateways.

WSN server architecture provides a common middleware platform for WSN services by offering database access, security management for user authentication, and message passing between services. Services can be implemented either as Java-based socket applications or web servlets. For rapid web service implementation, the server provides reusable graph, page layout, and database query components. Connectivity to third party systems is supported with database, XML, and Java Messaging Service (JMS) interfaces.

C. WSN Service Delivery

For new service concepts the service must support several user applications. For ease of use, User Interfaces (UIs) were delivered as web services. This allows seamless software upgrades. In addition, a lightweight UI that provided basic reports and was optimized for mobile phones was implemented as web service. Short Message Service (SMS) text messages and e-mails were used for instant alarms. For analyzing the potentiality of WSNs with social networking, an interface for Facebook was implemented. With the interface, user could publish selected sensor values showing current measurements and sensor history charts.

D. Analysis of Sensor Data

The implemented WSN infrastructure supports real-time and historical data analysis for manual analysis and rule-based alerts. As an example, Figure 4 shows CO2 measurements in the home pilot study. CO2 values measure air quality, but can also secondarily detect presence of persons at home.

Sensor data analysis with SOM is presented in Figure 6. Data for different sensors are presented in separate subfigures. Similarly colored areas in the map indicate the fraction of measurements received with certain sensor value. For example, relative humidity was 80% of the time less than 20%.

U-matrix groups strongly correlated samples, and related samples are located at the same place in each subfigure. The data indicates that high CO2 concentration implies high temperature (high values at lower left hand corner of the figures), but a high temperature does not necessary mean that CO2 is also high (values at upper left hand corner). This can be explained in the use case with breathing, which increases CO2 concentration along with temperature. Another dependency is detectable between temperature and humidity, as high humidity indicates high temperature (right corners).

The SOM analysis comprises over 500 thousand samples collected within 2 month time period. This highlights the importance of analysis methods as the manual analysis of large amount of data would be laborious. While the SOM analysis requires interpretation, it can be used as a base for automatic logic. From the previous example, a decision tree can be constructed that deduces human presence when both CO2 and temperature values are high.

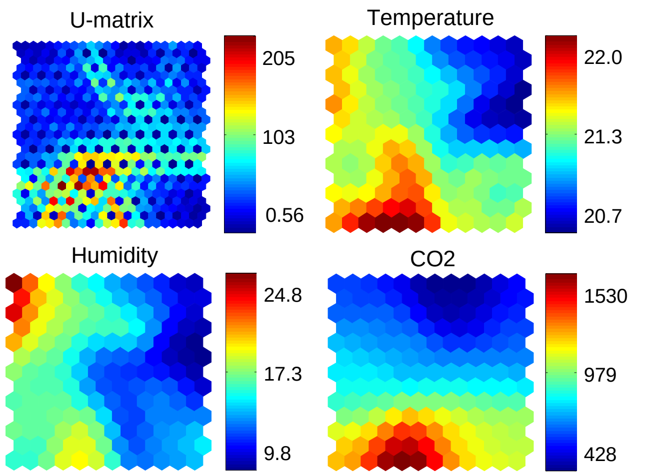

Figure 6. Self-organizing map on room air temperature, CO2, and humidity. A sample is located at the same place in each subfigure.

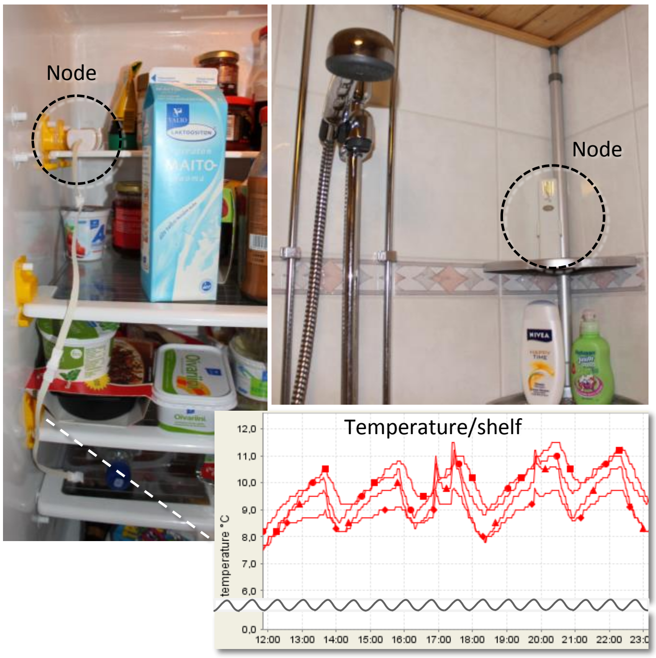

Figure 7. Visual analysis of sensor possibilities. A fridge sensor (left) shows temperatures at different shelf levels and monitors door openings. A shower sensor (right) measures air humidity for sufficient ventilation. Both sensors can be used to monitor that everyday activity is normal e.g. in elderly care.

V. WSN Application Concepts

The locations of the nodes and the sensors equipped in each node dictate the acquired data and the feasibility of the produced services. The following service groups were identified in the pilot study:

1. *Monitoring of the living environment* by room level temperature sensors, humidity, luminance, and CO2.
2. *Monitoring of household appliance* energy consumption, operating temperatures, and vibration.
3. *Monitoring security* by infrared movement sensors, door switches, noise monitors, and node position.
4. *Controlling appliances* by sending actuation commands.

The pilot study concentrated on the monitoring aspect of the sensor network, while in-depth study on the appliance control was left as future work. The sensors and their related services in the pilot study are summarized in Table 1. Application possibilities for humidity and temperature sensors in homes are presented in Figure 7.

Measuring the same quantity or property in several locations improves the accuracy and reliability of the measurements. This is a default case in WSNs. Also, observing the same phenomenon with several sensor types can be implemented for improving the reliability of true positive or true negative classification, which is surprisingly rarely used in sensor data processing [10]. For example, motion detection by passive infrared sensor events and increased CO2 level indicate presence of persons.

VI. Discussion and Future Work

While the technology needed to collect sensor data from home networks is ready, the measured sensor data are typically handled as raw values e.g. as charts. Although such information can be interesting, it has little practical value in long term to the user. Analyzing and understanding it requires a lot of manual inspection and expertise on the subject. Thus, automated data processing for enabling value-added applications is needed.

Table 1. Utilizing multipoint, multichannel measurement data in service implementations.

Sensor	Monitoring of the living environment	Monitoring of household appliance	Monitoring safety and security
Temperatures	Room temperature, storage, outdoors	Operating temperatures and cycles of appliances	Freezing point warning, very high temperatures of objects
Acceleration, orientation		Vibration, orientation of levers	Impact identification, movement of node, vibration of the environment
Luminance	Adequate domestic lighting	Use ratio of lights	Opening of doors
CO2	Air quality	Operation of ventilation	Presence of persons
Energy consumption		Energy and usage cycles	Normal usage profile of appliances
Noise level		Condition of an appliance	Presence of persons
Movement (infrared, etc.)	Presence of persons		Intruder detection
Air humidity	Air quality	Operation of ventilation	Normal usage profile of shower room
Node position			Location of persons and equipment
Soil moisture	Watering of plants, garden	Water leaks	Water leak accidents

The home pilot implementation provided valuable insights how the sensor data can be automatically refined as value-adding services for users. As a future work, we are studying several sensor application areas, including resident wellbeing measurements and social applications. Mobile phones are another future potential in sensor networks. Modern cell phones integrate several sensors e.g. acceleration and luminance. Combined with location information and social media, this opens up new kind of sensor applications.

To make sensor solutions affordable for the mass market, another future study is implementing the web services as cloud services. The main motivations for the research are both shortening the time to market and making the wide spread use of sensors economically feasible as companies can subsidize sensor hardware costs with monthly service fees.

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