

A novel power line network architecture for managing the energy resources of the residential environment

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Abstract— Given the energy waste problem and the consequent need for energy optimal use, this paper presents a novel network architecture able to perform real time management of the energy consumed by household appliances. Deploying the recent KNX power line communication technology, the proposed architecture performs three main functions; monitoring of the energy consumed by household devices for metering purposes, management of household devices so that the energy they consume is kept within user-defined limits and management of standby devices for minimal energy consumption.

Keywords— Energy conservation, Energy management, Energy optimal control, Power system communication, Gateways, Protocols, Household appliances.

I. INTRODUCTION

Managing the energy consumption of households has been recognised as a very important issue of the worldwide community's efforts in reducing CO₂ emissions and making optimal use of energy resources.

Although significant improvements in energy efficiency have been achieved in home appliances and lighting, the electricity consumption in the average European household has been increasing by about 2% per year during the past ten years [1], with the standby devices accounting for 8% of the total energy consumed in households.

The International Energy Agency (IEA) estimates that, even with a continuation of all existing appliance policy measures, household appliances electricity consumption will continue to grow by 13% from 2000 to 2010, and by 25% by 2020 [2].

The energy reservation concept dealt with in this paper is based on the definition of a generalised method for managing the energy consumption of households by managing the energy of the appliances they consist of, while they are in active or in standby mode.

The proposed solution takes into consideration two main usability factors; the minimal impact on households' communication infrastructure and the introduction of a sort of intelligence in the way the architecture functions so as energy management is performed autonomously.

To satisfy both factors, the architecture brings together the latest KNX power line communication technology [3] and a residential gateway architecture that provides the middleware substrate for the formulation of a number of energy management services targeting three user categories; residential users, network operator and electricity production companies/providers. For the first two the objective is to be able to set thresholds of energy consumption at home and thus rationalize energy consumption, while for the latter one to be able to extract for large population areas statistics of energy consumption to be used for planning their energy generation capability optimally.

The sections that follow recapitulate on the factors that have driven the conception of the architecture (section 2), present the main constituents of the proposed topology (section 3), and outline user-oriented scenarios, addressing all user categories.

II. THE ENERGY MANAGEMENT CONCEPT

Concerning the energy management of home appliances, such as white goods, communication equipment, TVs, lighting, the European Commission has launched, in 1999, two energy management initiatives, the EU Standby initiative [4] and the Code of Conduct initiative.

Through the introduction of energy limits, these initiatives have aimed at consolidating consensus among appliance manufacturers for the energy that their appliances consume in active and standby modes. The idea of setting up energy consumption limits for the various appliance types is the key concept of the presented architecture, which further enhances it with the adoption of energy profiles defined per appliance type and operation mode.

To deal with the multitude of household appliance manufacturers, the aforementioned initiatives have adopted the common policy of defining power consumption levels, rather proposing ways of reducing it. As a result, both initiatives have endorsed, for implementation by the local governments, three procedures for power consumption characterisation: labelling, certification and standardisation. Evolving along these lines, the proposed architecture introduces an energy monitoring and management

mechanism, which is based on the notion of the instantaneous power levels of profiled appliances, instead of constantly measuring the power drawn by the connected electrical devices. This way the architecture has negligible energy consumption, while it remains accurate concerning energy monitoring and control.

There exist alternative approaches in the field of managing residential energy consumption, deploying architectures that: a) constantly measure actual instantaneous power through the use of dedicated components [11]; b) utilise communication technologies that are not ubiquitous within the household, or are not by default available on the concerned devices or appliances (e.g. ZigBee) [13]; c) focus on a specific part of the wider residential energy consumption problem, namely in the heating/air-conditioning domain, and apply custom solutions on it, like the "communicating thermostat" concept [10]. Additionally, there are solutions that target reduction of consumption right at the source by optimising overall system, or power supply design [12].

As is depicted in Fig. 1, the architecture proposed in this paper is built around a residential gateway, which is the core of the system and the offered services. A power line bridge connects the gateway to the appliances of the household, thus enabling control on their internal functions and eventually the energy they consume.

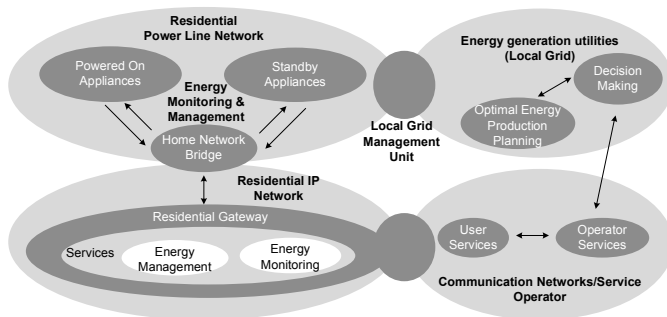


Fig. 1. Concept and general topology for energy monitoring and management

Services for energy monitoring and management are hosted on the residential gateway and are accessible by the residential users either via operator networks or the local IP network. In the same fashion, energy generation utilities perform energy monitoring, either directly, via the local grid management units or through the network operator services.

III. ARCHITECTURE FOR POWER MANAGEMENT OF HOUSEHOLD APPLIANCES

Fig. 2 illustrates a detailed diagram of the overall architecture.

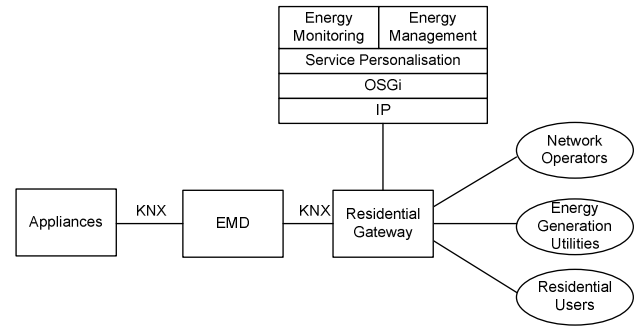


Fig. 2. Outline of the energy management architecture

To realize interworking with the home network a dedicated functional entity has been introduced, called Energy Management Device (EMD). The EMD exploits the KNX technology and power line installation for its communication with the household appliances and the residential gateway (RG), implementing the following functions:

- A uniform application programming interface (API) for all connected appliances to be exploited in the exchange of command, status and flow control primitives.
- Coding of energy monitoring and management primitives: Primitives exchanged between the appliances and the RG are assembled according to the individual interfacing requirements of the appliances.
- Management of active and standby devices, whereby EMD retrieves appliance status information and performs standby management by switching off supply to the mains outlets.

In order to reduce the impact of our architecture on the appliances' operation we have adopted the KNX power line interface as the only means of communication between the appliances and the services of the gateway. This way introduction of extra network components that eventually contribute to increasing energy consumption is avoided, and standby management is implemented in the most effective way, enabling use of KNX-enabled switches for mains outlets. In sleep mode, energy consumption of KNX devices is less than 100mWatt, 10 times lower than the consumption of any single household appliance in standby mode.

IV. POWER MODE LEVELS AND PROFILING OF APPLIANCES ENERGY CONSUMPTION

The concept behind the appliances energy profiling idea is that by using discrete power mode levels, the system shall be aware of the appliance state and consequently the user will be able to control their energy consumption, setting power consumption level limits separately per appliance type and internal function. To deliver this, a number of such power mode levels have been defined, as illustrated in Fig. 3.

Association of power mode levels with energy consumption has been achieved for some appliances exploiting the energy consumption values defined in the CoC of the EC [5] and for other appliances, not included in the CoC, through the conduction of experimental measurements following standard methodologies, (i.e.

profiling) [6].

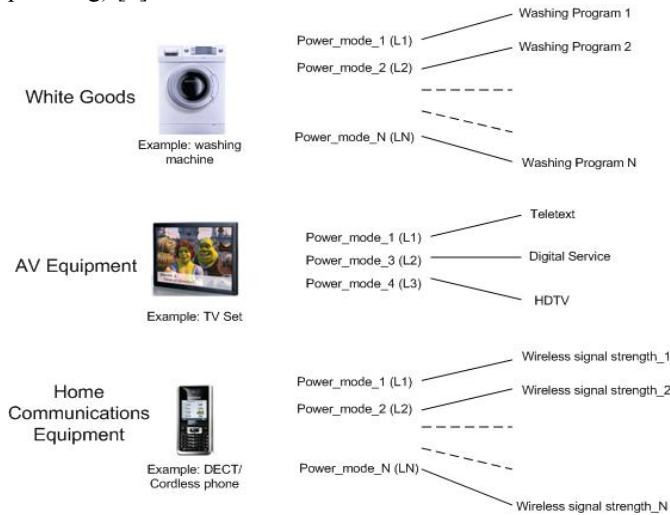


Fig. 3. Examples of associations between power modes and functions per appliance type

Profiling in the current context refers to an off-line process that takes place during the implementation phase, whereas each appliance or device that is to be utilised in the described system, needs to be taken into its various modes and configurations of operation, while being attached to associated measuring equipment (e.g. in a lab, equipped with amp- and volt-meters). The exact state of the appliance together with the associated power consumption are registered, thus building-up a consumption profile for the appliance. The latter shall be utilised, in a certain form, by the RG to associate any given appliance state with the corresponding actual consumption.

Energy profiling is complemented by the definition of the notion of appliance type and operation mode per which profiles are classified on the RG so that the network knows in real time the energy each appliance consumes by reading its status.

A. The Energy Management Device

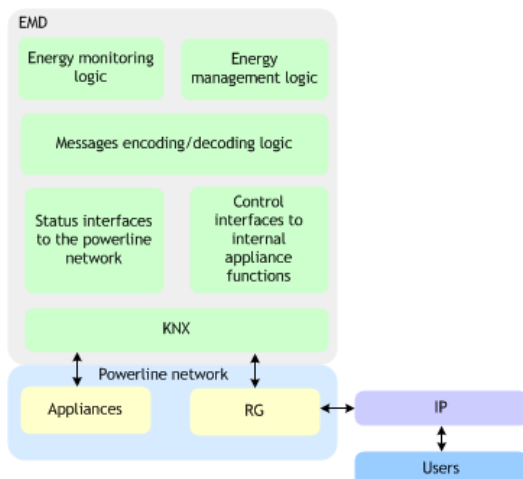


Fig. 4. Internal architecture of the EMD.

The EMD has the role of the bridging device depicted in Fig. 1. The device is able to manage appliances in both active and standby states and communicate with them, and the rest of the components of the home network, through the KNX power line interface (Fig. 4).

The EMD performs energy management and monitoring by means of associating the notion of the appliances' status with the energy profiles stored in the RG for each appliance type. In addition, certain instances of the EMD may even directly measure power consumption of the attached appliance, in case the appliance is not capable of providing information about its present state.

Having that notion in place, the EMD knows in real time how much energy an appliance consumes and performs energy management by means of changing, on several user-defined conditions, the operation mode (appliance program) of an active appliance with another that consumes less. For example, when total energy exceeds the maximum limit set by the user for the household. For standby devices, energy management is confined to detection and switching off of appliances found in standby mode.

Energy monitoring is also performed by means of retrieving the state of the KNX enabled appliances and associating it with the corresponding profile stored in the database, thereby the resultant energy consumption figures are communicated to the RG for statistical measurements extraction. Appliance state (e.g. current mode of operation, washing machine phase, activated components on ovens and hobs, etc.) constitutes the most common piece of information KNX appliances communicate over the power line. Thus, such state information may be directly utilised by the RG to deduce, by looking up the relevant profiles and databases, the current power consumption of the corresponding appliance, without taking any measuring action.

In both EMD functions, the device utilises an intermediate layer that performs messages encoding and decoding to cope with the requirements of the software interfaces of the appliances and the gateway respectively.

V. APPLICATION OF KNX PLC IN THE POWER MANAGEMENT ARCHITECTURE

Among existing power line communication technologies, KNX has received the focus of many large manufacturers of household appliances, because it is well standardised, can be implemented using general purpose chipsets, has an open and extensible range of capabilities and is suitable for deployment in households without the need of altering the mains network.

Further to the protocol, the standard essentially describes the electrical/electronic part for the connection of a digital data processing subsystem, present in the product, to the mains wiring: a coupling circuit and a modem are used to place and retrieve data to and from the line.

KNX was primarily invented for the implementation of low bit rate control applications and therefore is not competent to high bit rate PLC technologies such as the HomePlug [7].

For the implementation of its communication stack, KNX has adopted the OSI model. According to this, KNX utilises a *Physical interface*, which can be twisted pair or power line, a *Data Link Layer* that translates frames into bits rows, a *Network Layer* that performs address resolution and handling of incoming/outgoing messages, a *Transport Layer* that maintains a framing structure for all supported

procedures and an *Application Layer* that offers a programming interface to external user applications.

These layers constitute the communication system of the KNX kernel, which has to support all network communication requirements of KNX for configuration and management purposes as well as hosting of distributed user applications.

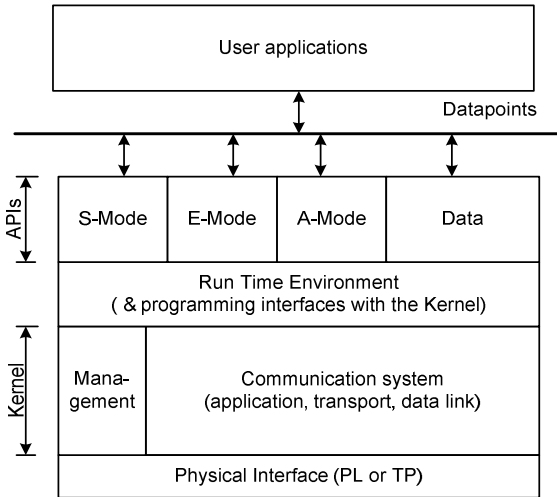


Fig. 5. Outline of the KNX architecture.

The KNX communication capabilities and configuration modes are accessible via the application layer using the concept of *Datapoints*. Datapoints represent ‘channels’ intended for information exchange between the user applications and the internal KNX kernel functions, such as input/output data, diagnostic messages and configuration commands (Fig. 5).

A. Devices addressing

Taking into account the master-slave communication model, KNX gives user applications the ability of communicating point-to-point, point-to-multipoint or with broadcast messages.

In each network setup, every KNX device has its own address on the basis of which messages are routed toward other KNX devices, through the network and are recognised by recipient KNX devices.

For our architecture, broadcasting of messages is particularly useful for the implementation of mode status and energy consumption request messages. Also, the group addressing capability is useful for broadcasting particular commands, such as switch off and on commands, only to some of the connected devices.

B. Support of user-defined messages

KNX foresees a specific frame type for the exchange of any type of message between KNX devices in the power line network. Utilizing this frame type, user applications may submit configuration, management and control commands.

Configuration and management commands consist of modifying internal protocol parameters such as device address, physical layer parameters, Datapoints operation or may be related to more generic operations such as replacement of firmware logic.

Not all configuration possibilities are available on all KNX devices. Finding out which functions are supported is possible via the read out of the embedded device profile.

Messages submitted as control commands need an interworking function on top of the KNX device to translate them into messages compatible to the Datapoint format. For every submitted command the system returns an appropriate response. To facilitate this process Datapoints are grouped in two general types; *Group Objects* and *Interface Objects*. Group Objects are used for servicing multicast messages, while Interface Objects are used for point-to-point communications. Interface Objects are further divided in *System* and *Application Interface Objects*, where the former are used for configuration messages and the latter for application commands. Application commands being broadcasted towards all or some of the connected devices are passed to the KNX device over the Group Objects Datapoint.

Our system makes use of all three message types. Namely, configuration is performed during system installation, whereby KNX devices are associated with the appliance type they are connected with and are given a network address that renders them accessible from the residential gateway.

Retrieval of the status of the connected appliances is performed with management messages, requesting from KNX enabled appliances operation mode status and energy consumption figures.

Commands are submitted using both broadcast and unicast message types. The system uses them to alter the operation of an appliance or switch it off or on respectively.

VI. REFERENCE COMMUNICATION SCENARIO

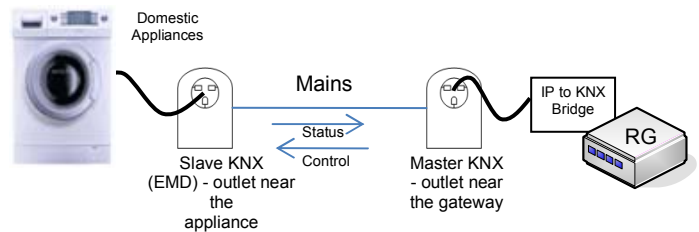


Fig. 6. Reference communication scenario for energy management implementation using the KNX physical power line communication interface

As is depicted in Fig. 6, communication of the RG with household appliances using the power line network becomes possible thanks to the IP to KNX translation unit (IP to KNX bridge) that implements protocol interworking of IP applications running on the RG and the KNX protocol of the power line network.

This reference communication scenario, works for appliances that employ the KNX power line interface for their communication with the network, which is very popular among white goods and audiovisual appliance manufacturers.

Apart from the IP to KNX bridge, the RG employs a master KNX device to communicate simultaneously with many slave KNX devices that are attached to the mains network.

Commands are sent to the slave devices by the master

device and replies are returned in the form of status and acknowledgement messages, depending on the requested operation.

Resolution of the address of the destination slave device is performed by means of using an appliance identification code. Each slave device is aware of the appliance it is connected to. Therefore, while all slave devices receive the transmitted message only the device that is connected to the addressed appliance parses the message and returns a corresponding answer.

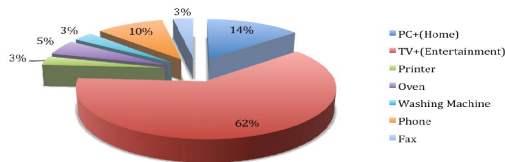


Fig. 7. Standby mode losses contributors (source: Preparatory studies for Eco-design requirements)

Fig. 7 presents the standby mode power loss contributors within a household. Under the given communication scenario the RG may also manage standby devices. The goal is to detect which appliances are in standby mode and switch them off in order to reduce their energy consumption to zero. Technically the procedure is based on the cut off of mains power supply to the connected device and the subsequent set up of the slave KNX device to the sleep mode. In this state its energy consumption is a few mWatts, far less than any appliance's consumption in standby mode.

A. Message flows for standby management

This section outlines how management of appliances in standby mode can be accomplished with the given architecture and within the boundaries of the communication scheme depicted in Fig. 6.

Before an appliance is put in standby mode it sends a *notify* message to the RG. The message is intercepted and stored by the RG in a built-in database holding the status of all household appliances (*store event*).

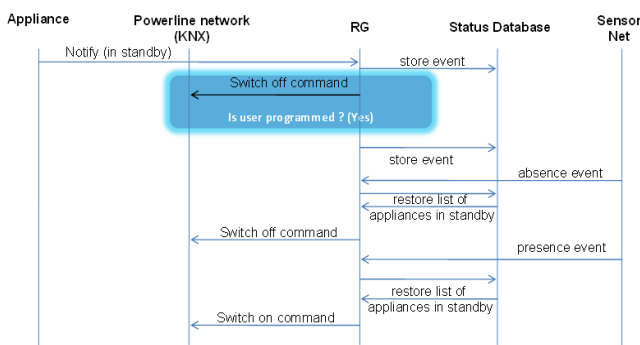


Fig. 8. Message flows for standby devices management

Prior to managing the appliance, the RG resolves internally under which conditions switching off should occur. Two conditions are generally envisaged:

- the user programs specific time zones, e.g. after midnight, or after 9:00 am when no one is at home, within which the RG should have all standby appliances switched off,
- an intelligent way of detecting user's presence at home,

using a sensor network.

When the first condition is met, the RG transmits as many *switch-off* commands as needed to switch off all detected appliances. When a sensor network is employed, the RG is triggered by an *absence event* message.

In both cases, sending of *switch off* commands is accompanied with *store* and *restore status of appliances* messages towards the status database so as the RG is able to retrieve the actual status of the appliances and switch them on again, when needed.

B. Message flows for energy management of appliances in active mode

In active mode two management possibilities are foreseen; a) control of appliances' internal functions so as to conform to particular energy consumption limits, and b) energy consumption monitoring.

In Fig.9, the user sets a limit for the overall energy consumption (*set energy limit*), thus triggering the RG to request the energy that every active appliance consumes (*request energy measurements*).

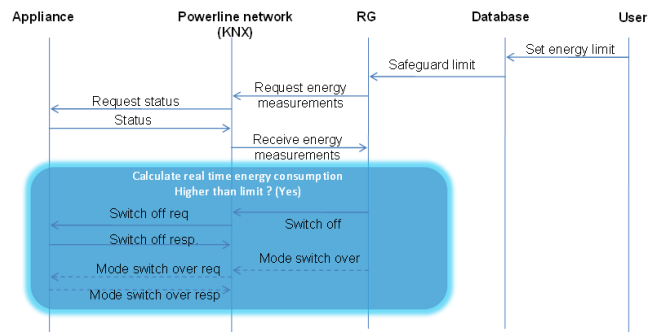


Fig. 9. Message flows for appliances' functions control.

Using the power line network all connected appliances return their status (*request status, status*), which is combined on the master KNX device to yield the overall energy consumption figure (*receive energy measurements*).

On reception of the requested figure, the RG compares it with the user threshold and, if higher, the RG makes decisions about which appliances to switch off or put through mode change over. The final verdict is based on the examination of the energy profiles of all active appliances, the operation modes they support and the energy consumed in each mode.

Once the verdict is out, decision is implemented by sending as many *switch off* or *mode switch over* commands as needed to obtain an overall consumption figure lower than the user threshold (Fig. 9).

Energy monitoring is performed autonomously by the RG, through regular transmission of *request energy measurements* messages to the active appliances. In response (*receive energy measurements*) energy figures are collected and aggregated on the RG for homogenisation purposes and further maintenance in the database, amended with time stamps. The latter identifiers allow residential users or external actors (e.g. electricity production companies) to poll the energy consumption figure of the households grouped in neighbourhoods or larger

geographical areas and exploit it for statistics extraction.

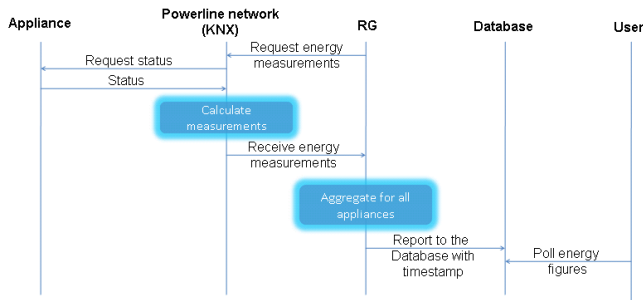


Fig. 10. Message flows for energy monitoring.

VII. USE-CASES

A number of use-cases have been devised to demonstrate how requirements of three dissimilar user types may be addressed by the proposed architecture:

Use-case for residential users (intelligent service for autonomous energy consumption management): In this use-case the information by sensors (presence) and by home devices (typical usage) is collected in order for user habits to be profiled. Using this information the home network is able to administer standby devices autonomously and to configure the power consumption of appliances to levels that meet user criteria. Overall, the system is based on a sensor network, which is integrated with the residential gateway. It may be further assisted by a user profiles database, where user activity data, concerning appliances usage is collected and administrated upon creating individual profiles. Using these individual profiles, usage scenarios for appliance power consumption management is obtained.

Use-case for energy generation utilities (metering service for energy planning): The objective of this use-case is to perform real time acquisition of energy consumption measurements to be massively used for yielding energy utilization statistics and, thus, be used by energy generation and distribution utilities to better plan energy generation and avoid unnecessary resources dissipation. This functionality is delivered in the form of a service invoked either directly by the interested organization or through a network operator.

Use-case for network operators (remote monitoring and household management): With this use-case, the architecture allows residential users to monitor and control residential energy consumption, remotely, while being away from their homes. The use-case is delivered in a set of operator services optimized for mobile phones, through which the user is able to monitor in real time the power consumption at home and do intelligent configurations, such as assignment of alerts in the event of violation of user configured boundaries.

VIII. CONCLUSIONS

In this work we have presented a network architecture optimized for the implementation of energy management services. The network part of the presented architecture is based on the KNX protocol suite and power line physical

communication interface. The KNX protocol is a European low bit rate communication standard. Its implementation does not require alterations on the mains infrastructure within and outside the household, rendering it ideal for simple, low cost control applications implementation. In particular, with respect to the efficiency of the system to support energy saving applications, it was found that KNX, albeit making use of digital and analog circuitry, has very low consumption, that fluctuates between 1 Watt and some tens of mWatts, rendering it ideal for hosting such applications.

Nevertheless, its adoption by household appliances manufacturers is not yet widespread. Nowadays KNX is adopted by most white good manufacturers, many audiovisual equipment manufacturers and some communication equipment manufacturers. In the future, however, new KNX application concepts currently elaborated in the context of the KNX Forum [8] are expected to alter this trend.

ACKNOWLEDGEMENT

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