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Introducing the Web-of-Things in Building Automation: A Gateway for KNX installations

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Abstract: Due to increasing energy costs and the importance of the comfort, smart buildings tend to democratize both in new and renovated constructions, based on management systems relying on dedicated networks. Network heterogeneity leads to complex building management systems having to implement all the protocols of the building networks, resulting in low system integration and heavy maintenance efforts. Those building networks offer no common standardized application layer to build applications. To remedy this, we propose in this paper to leverage on the *Web-of-Things* (WoT) framework, using well-known technologies like *HTTP* and *RESTful APIs*. We outline the implementation of a gateway using the principles of the WoT to expose capabilities of the KNX building network as Web services, allowing a fast integration in management systems.

1 INTRODUCTION

In recent years, building management systems (BMS) have become very common in various types of buildings, such as offices, as manufactures or even private households. They rely on a variety of sensors and actuators composing together a whole dedicated building network. At origin, the heating control of a building was very simple, only composed of global thermostats, or distributed in every room, targeting a threshold temperature value. Motivated by raising energy costs and by the importance of the comfort, more complicated strategies have since then been developed. Modern BMS include many kinds of sensing and actuating devices, managing the HVAC (Heating, Ventilation and Air Conditioning), the lighting, the open and closing of doors, windows and blinds control, and security access systems. Buildings have become "smart" and are now real information systems using dedicated building management networks for communication, as for example KNX, BACnet, or LonWorks. KNX is actually the most used network in Europe. One can find almost every kind of device compatible with this network that offers different types of physical connections like Ethernet, RF, power line, or more widespread the twisted pair (KonnexAssociation, 2004).

Unfortunately, such building management networks do not offer a standardised way to interact with devices connected to them from an application point of view. Due to this, it becomes difficult to build BMS combining multiple networks. This situation can be found in buildings where the network should evolve with new devices that are not compatible with the actual one, or where extending the wiring is not feasible because of physical constraints (Bovet and Hennebert, 2012). This is leading to heterogeneous building management networks as visible in figure 1. While it exists gateways encapsulating the specific telegrams of the building management network in IP packets, there is actually no standard at the application level, resulting in the BMS having to understand and to implement every network protocol.

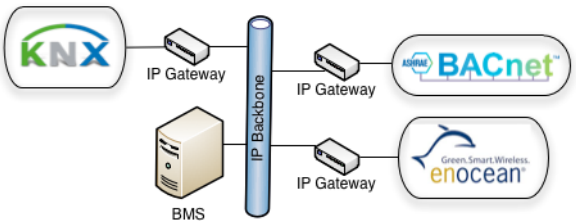

Figure 1: Network heterogeneity in smart buildings

Web services are nowadays widespread in heterogeneous information systems (IS). They benefit from the facts of being platform independent, and of using

well-known standards for data exchange that ensure the interoperability, as it is the case for SOAP. Unfortunately the SOAP protocol is not well suited for accessing sensors and actuators considered as *things*, because of the large overhead of XML and the complexity of the service description language WSDL. On the other hand, the emerging *Web-of-Things* framework (WoT), offers new ways for accessing things in a resource oriented architecture (ROA) (Guinard et al., 2011), which are more suited for BMS.

In this paper, we present the implementation of a gateway allowing access to devices connected to a *KNX* network in a Web-of-Things manner. By taking advantage of the bests practices of the WoT, we guarantee a fast integration of KNX in every control system. In addition to this, we put importance on the fact that our gateway must be simple to use, low-cost and easily integrable in an existing environment.

This paper is organised as follows. The next section refers and summarizes related work. In Sect. 3, we provide an overview of the Web-of-Things paradigm. Its application to the KNX network is discussed in Sect. 4. Sect. 5 describes the implementation of the gateway. Performance tests in a real building are shown in Sect. 6. Sect. 7 concludes our paper and provides insights on further research.

2 RELATED WORK

One of the early projects considering people, places and things as Web resources is *Cooltown* (Kindberg and al., 2002). This project introduced a new interaction approach by using HTTP GET and POST requests to manipulate things. Then, with the progress made in embedded systems by offering more computing power on smaller devices, it was possible to integrate Web servers on sensors and actuators. So-called *mashups* were introduced in the *WebPlug* framework relying on the Web-of-Things paradigm, where sensors and actuators play a central role (Ostermaier et al., 2010).

Problems related to performance and memory usage on things leveraging on Web services were quickly discovered. Although the SOAP protocol contributing in a standardization aspect between Web services and being largely adopted on the Web, it is not suited for constrained environments (Groba and Clarke, 2011). More adapted to things, RESTful APIs represent a clear alternative to this drawback, with an increased adoption by many IS, particularly in the fields of *Internet-of-Things* (IoT) and WoT (Aijaz et al., 2009) (Hamad et al., 2010).

Trying to ease the development of applications using KNX devices has been explored in different works. A first attempt was realized with the *BCU SDK* (Kastner et al., 2005), which consists of a script generating C++ classes representing devices capabilities. A more Web oriented approach has been realized in (Neugschwandtner et al., 2007). It exposes KNX functionalities as Web services by using the oBIX (Open Building Information Exchange) standard, which is a special XML schema for representing building data and operations. Unfortunately, oBIX is not at all widespread over IS and BMS probably because of its complex XML schema. In addition to this, the proposed implementation does not allow an easy integration of the gateway in an existing environment, requiring a huge configuration effort for large networks. Our approach tackles these limitations by taking advantage of the WoT's simplicity and by being highly integrable in existing KNX infrastructures.

3 THE WOT FRAMEWORK

The Web-of-Things based on well-accepted standards of the Web, fills the gap left by the Internet-of-Things regarding the application layer (Guinard, 2011). Indeed, the IoT only touches on the IP connectivity of everyday objects, resolving problems linked to the Internet access and network topologies. In order to homogenize the access on things representing resources, the technologies of the Web as URL representations for identifying resources, RESTful APIs and the HTTP protocol represent a good approach because of being strongly standardized and already widespread. In this chapter we will provide insights of the main concepts building the WoT.

3.1 Resource identification

In the WoT, every capability or property of a device is considered as a resource. As for example, a temperature sensor could return the measured value both in Celsius and in Fahrenheit. This would give us two resources that can be read. More precisely, some resources can allow multiple operations as read and write. So, we first need to be able to identify and address those resources in a simple way before we can interact with them. This is realized by using *URLs* in the same way as for identifying Web pages on servers. An advantage of this approach is in its hierarchical way to organize resources reflecting the physical world. This principle is shown in figure 2. For accessing the Celsius temperature value, one would use following URL: *http://<DOMAIN>:<PORT>/generic-nodes/1/sensors/temperature/celsius*.

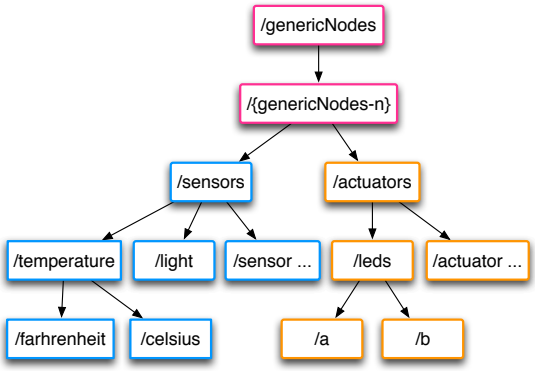

Figure 2: Resource hierarchy example of an abstract node

The domain part of the URL also allows to be hierarchically structured to match a virtual abstract structure or a real physical organization. URLs can give insights on the location of devices inside a building organization by decomposing it in sub-domains according to buildings, floors and rooms.

3.2 RESTful APIs

RESTful APIs are really the communication and application layers in the WoT by leveraging the HTTP protocol. Unlike SOAP, HTTP is used as application protocol and not only for transport. REST has several advantages over SOAP by having less overhead and being resource oriented, which fits naturally with physical objects. With the WoT paradigm, every object or thing is embedding a Web server exposing an API for acting with its sensing, actuating and configuration capabilities. Those services are located through the URLs as explained previously. The interaction with the resources is achieved by sending HTTP requests containing a so-called *HTTP verb* that can be one as follows: GET, POST, PUT and DELETE. These verbs reflect actions that can be performed on resources. The GET is for retrieving information, POST to modify information, PUT to add information, and DELETE for removing information on a resource. The GET and POST verbs are in the context of WoT the most used ones. For example, one will use the GET verb to read a sensor's value, and the POST one for actuating a relay.

A HTTP communication always consists of a request to a specific resource and a response, this for any kind of operation. HTTP responses contain in the header a code value expressing errors, exceptions and successes. Each code has a well-known meaning listed in the HTTP 1.1 specifications.

3.3 Events notifications

In many scenarios some systems want to be informed as soon as something happen on a monitored resource. Instead of using a polling technique that is resource consuming, the WoT relies on *callbacks*. In an event-based system, the first step is the registration of the consumer at the producer. Working with things embedding a REST Web server, we can expand the API with methods dedicated to registration. A system interested to be notified about a change of state on a resource will announce itself by providing the callback, an URL representing a REST service on the consumer side. We demonstrate this mechanism with a simple example involving a BMS and a motion detector as illustrated in figure 3.

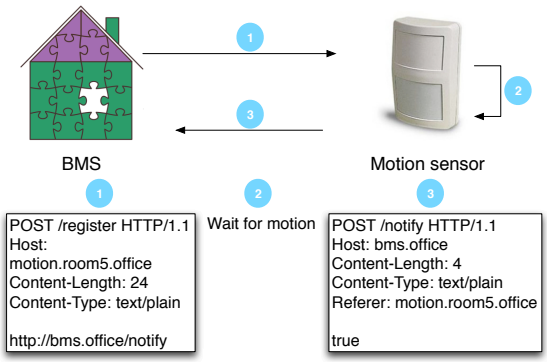

Figure 3: Event notification mechanism with (1) consumer registration step with callback notification, (2) producer value monitoring, (3) producer notification to the consumer.

1 - The BMS will register at the motion sensor in order to be notified when someone enters or leaves a room. This is achieved by the BMS sending a HTTP POST request to *http://motion.room5.office/register* containing the callback URL. **2 -** The producer will then internally watch its resource. **3 -** Every time the value changes the motion sensor will do a HTTP POST request to the callback URL.

The steps 2 and 3 are repeated until the consumer unregisters.

4 FROM KNX TO RESTFUL APIS

As previously outlined with WoT paradigms, every object is expected to embed a REST server offering an API located through URLs for interaction. Unfortunately this approach can not be applied as such to a KNX network. Devices connected to the KNX network have no IP address and therefore will not be accessible by using URLs. In addition to this, KNX

devices are very constrained and task oriented, which makes it impossible for them to embed a Web server.

A way of filling this gap is by proposing a gateway exposing devices functionalities in the form of RESTful APIs. The gateway will hide the complexity of the KNX network and allow clients to interact with KNX devices in a Web-of-Things manner. So, the devices will appear to other participants of the WoT as they would be embedding the API on themselves. Clients will therefore be able to retrieve information from a KNX network (e.g. to read a temperature value) or to interact with the environment (e.g. to move blinds).

This chapter describes how devices functionalities are mapped to URLs and RESTful services. Also, we outline our discovery approach allowing clients to identify which devices are accessible by using RESTful services and what are their capabilities.

4.1 KNX application layer

The KNX application layer, also known as *KNX interworking* was thought to ensure interoperability between devices of various manufacturers. It standardizes the way how payload data inside telegrams have to be structured and interpreted.

Like many systems dedicated to automation, the interworking is based on so-called functional blocks to describe system functionality (KNX, 2012). Logical parts of a device, such as a specific function are symbolized by those functional blocks (FBs). We can illustrate this principle with an example of a light switch FB that is a logical function of a four channels relay. A functional block is always attached only to one device.

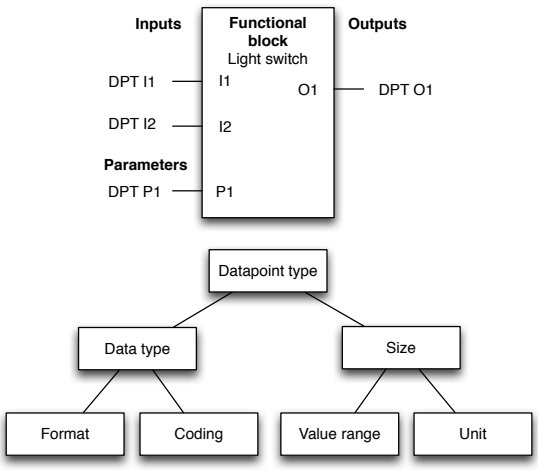

Figure 4: Functional block structure and datapoint type composition

As visible in the upper part of figure 4, FBs are composed of a set of datapoints (DPs). Those datapoints are communication endpoints of devices allowing access to the functions of a block (Neugschwandtner et al., 2007). KNX administrators simply link outputs and inputs together for associating devices. Datapoints are also standardized in terms of syntax and semantics as visible in the lower part of figure 4, and also organized in several categories depending on their FBs purposes. For example, our light switch provides the DP "switch on off" allowing to turn the light on or off. By knowing the datapoint type, one can find in the KNX specification all information regarding the datapoint, including the format, coding, value range and unit.

The KNX protocol identifies two categories of DPs: group objects (GOs) and interface object properties (IOPs). The GOs are endpoints involved in group communications between producers and consumers basing on a multicast approach. This type of DP is used by sensors, actuators and control devices for exchanging information. On the other hand, IOPs are only for configuration and management purposes. One can address an IOP only with the physical address of the device.

4.2 ETS export archive

The KNX association has developed the ETS (Engineering Tool Software) software for configuring a KNX infrastructure. With this software, administrators and engineers have the possibility to create the building hierarchy, the network topology, and finally to create group objects that will represent functionalities between devices. At this time, no other comparable software exists, so that every KNX installation must be configured with ETS. ETS exports projects in an archive composed of multiple XML files, as shown in figure 5. The *knx_master.xml* contains the description of all the datapoint types. The network topology, building organization and group addresses are stored in the *0.xml* file. Finally, there is a folder for every manufacturer, containing a XML file for each device type composing the network. The device file informs about the available datapoints on the device. This archive, being zipped without security, containing XML files easily understandable allows to import all the network knowledge into other applications. By applying a XSL transformation to the XML files inside the archive, we are able to centralize all information necessary for our gateway into one single XML file.

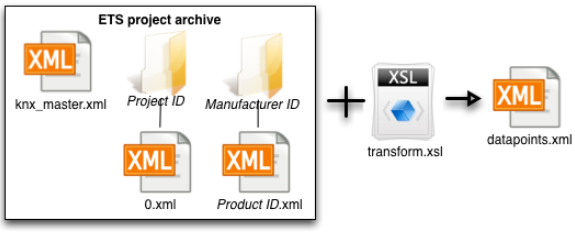

Figure 5: ETS project archive structure

4.3 Datapoints to REST

As previously explained, access to functionalities in a KNX network is done via group objects, which are compositions of datapoints and a group address. In the elaboration of the gateway, we need to match group objects to REST services for allowing interaction with KNX devices. For doing this, we make use of the XSLT output as visible in listing 1. By taking into consideration some fields of the XML, we are able to compose an URL identifying a specific group object. For example, the datapoint shown in listing 1 would result in following URL: *http://heating.office005.ground.leso.epfl.ch/dpt_switch*. The domain part is composed of the physical location of the device inside the building, completed by the domain name of the organization. The last part of the URL that represents the action to perform is the datapoint type name. We can now easily link group objects to URLs by following this rule: http://<GROUP_NAME>.<LOCATION>.<ORGANIZATION_DOMAIN>/<DATAPOINT>.

Listing 1: Datapoint XML representation after XSL transformation

```
<datapoint stateBased="true"
name="Heating" desc="Status"
mainNumber="1"
priority="Low" actionName="DPT_Switch"
actionDesc="on/off" dptDesc="1-bit"
dptBitsSize="1"
location="Office005.ground.LESO">
    <knxAddress type="group">
        6195
    </knxAddress>
</datapoint>
```

Our objective is here to allow the BMS to pull state values and to perform actions on the KNX network by sending HTTP requests to the gateway. A HTTP GET request will result in the HTTP response containing the actual value of the group object inside the payload data. For changing a state, one will send a HTTP POST request containing the new value inside the payload data.

Representing the structural organization of the building inside the domain part of the URL opens a new dimension. By acting this way, we can hide the fact that the device is actually in a KNX network and not directly connected to an IP network. For users of the system, the device seems to be an IP one with its own DNS entry directly pointing to it. However, this brings a certain complexity for the DNS system as it musts contain entries matching with KNX groups. For example, the DNS equivalence of the group *heating* located in room *office005* of the *ground* floor in the *leso* building, giving the DNS entry *heating.office005.ground.leso* has to redirect to the gateway.

4.4 Events

To avoid control systems being forced to implement a polling strategy for observing changes of states, our gateway offers a notification mechanism allowing to observe every group object. Here, the events notifications principle of the Web-of-Things is applied. Every URL identifying a group object is extended with two sub-resources for registration and unregistration. The *register* and *unregister* key-words are placed after the datapoint type as sub-resource. In our previous example, the URLs for registration and unregistration will be as follows: *http://heating.office005.ground.leso.epfl.ch/dpt_switch/[un]register*. The gateway holds internally a list of all the consumers registered for every group object. For every change of state of a group object, the gateway checks its list of listeners, and will then perform the notification through the callback of the consumers.

4.5 Discovery

Before communicating with KNX devices, a system has first to discover what group objects are available on the gateway. A very simple manner would be to provide a single list informing about all group objects. Such an approach is obviously not well adapted due to its poor structure and the need to transmit the whole list for every discovery request. Here, we expand our concept of building-composition structured DNS. In addition of keeping entries for groups, it does also have entries for the sub-domains composing the URLs. For example, it will store entries like *ground.leso.epfl.ch*. By calling *http://ground.leso.epfl.ch*, the DNS server redirects the request to the gateway. The gateway will perform a lookup in the XML file to find all children and will respond with a JSON structured message.

Once a group has been located, the available datapoints can be known by adding the placeholder * instead of the datapoint identifier. The gateway will answer with a JSON payload describing the datapoints one can interact with, as visible in listing 2. The resulting URL structure is as follows: http://<GROUP_NAME>.<LOCATION>. <ORGANIZATION_DOMAIN>/*.

Listing 2: JSON message structure example of a datapoint description for http://heating.office005.ground.leso.epfl.ch/*

```
{"datapoint_info":"1-bit",
"datapoint_type":"DPT_Switch",
"description":"on/off",
"bits_size":1,
"datapoint_number":"1.001",
"url":"http://heating.office005.
ground.leso.epfl.ch/dpt_switch"}
```

5 IMPLEMENTATION

We provide here more details on a practical implementation of the gateway according to the principles exposed in Section 4. We voluntary restricted the implementation to only state based group objects which are used by BMS.

5.1 Platform

We selected as hardware platform the *Raspberry Pi model B* which is low-cost and offers enough computing power for running our gateway. This tiny microcomputer (Ras, 2013) (85.6mm x 56mm x 21mm) embeds an ARM1176JZFS CPU running at 700MHz with 512MB of RAM. The model B offers an Ethernet connectivity with an RJ45 port. It is composed of a SD card reader, two USB ports, one HDMI video port and a RCA video output. This module can be considered as low-power by consuming only about 4W, powered at 5V over a micro USB port. The Raspberry Pi can be operated by many Linux systems installed on a SD card plugged into the device. Any kind of software compatible with the ARM processor can be installed on it, like Java, MySQL and many others.

5.2 Architecture

Our implementation relies on the *Calimero 2.0* Java library (Cal, 2013). This library provides Java classes and methods for KNXnet/IP tunnel communications, and datapoint object representation allowing developers to build applications dedicated to KNX infrastructures. The Web part of our implementation is composed of a Java servlet running on a *Jetty* server (Jet, 2013). We opted for Jetty instead of other common Java Web servers like Tomcat, Glassfish, JBoss or Grizzly because of Jetty being easily embeddable on low-resources hardware thanks to its lightweight implementation. All components of the implementation are open source and free.

As shown in figure 6, we base our implementation on several logical modules shared in different scenarios of use. The first one is the configuration of the gateway, where the administrator will provide all necessary information for proper running. Once the gateway being configured, it enters in its normal operation where it can serve requests for manipulating group objects. We here detail the role of every module.

The **Datapoints file** act as database even only consisting of XML tags. This file is on the heart of the application and holds all the mandatory information for communication with the KNX devices. It contains a description of every group object reachable on the network, indicating the datapoint type, the group address, and other informal data about the group object. This file also stores configuration data provided through the Web configuration page.

The **Web server** stands as entry point of the application. It implements the *doGet()* and *doPost()* methods for handling the HTTP requests. The first step is to decode the URL in order to identify which action is requested on which group object, as it could be a direct interaction or a notification registration message. Once the operation being resolved, it acts as controller and dispatches the request to the right modules. At the end of processing, it will respond either with a value corresponding to the GET read request, or only with the HTTP response code in the case of a POST.

The **XML generator** processes the ETS project archive for generating the XML datapoints file. It first decompresses the archive and then applies the XSL stylesheet to the project. All special characters as accents are removed during this processing, as they can not be present in URLs. At end, the XML file is placed inside the resource directory of the Web server.

The **DNS manager** is responsible of adding DNS record entries representing groups. This is performed with the DNSJava library (DNS, 2013) offering methods for managing zones and records of a DNS server.

The **Datapoint locator** acts as query engine for the datapoints file. It can lookup specific group objects according to the datapoint type, group name and location, and then returns them in the Calimero datapoint object representation. It is also used for retrieving all the possible domain names for accessing the group objects, used by the DNS manager for adding

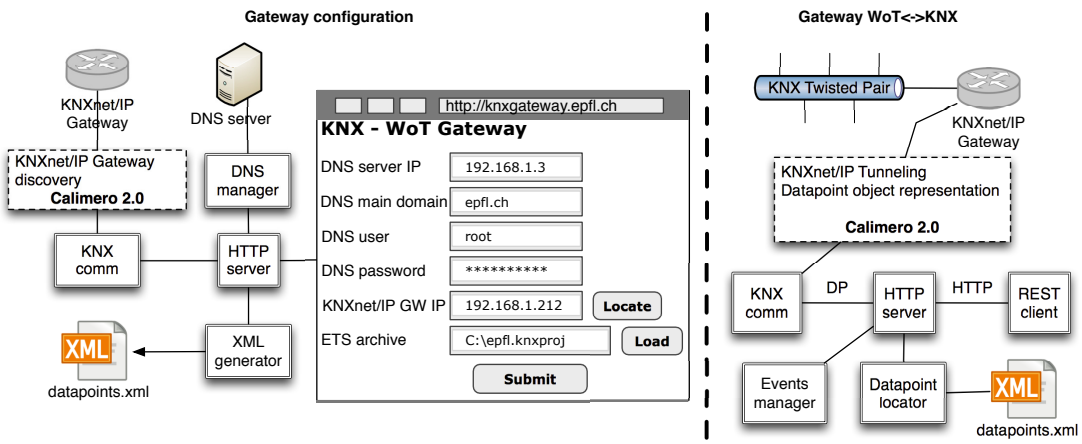

Figure 6: Overall KNX-WoT gateway architecture illustrating the logical modules for two scenarios: gateway configuration (left part) and gateway normal operation (right part).

entries on the DNS server. In the case of a client willing to discover the available datapoints, the Datapoint locator can answer with all sub-domains or with all datapoints descriptions of a group.

The **KNX comm** represents an interface to the KNXnet/IP network. This module can discover KNXnet/IP gateways by sending multicast messages, thus avoiding administrators to look after the IP address of the gateway, some times hard to find because of being DHCP configured. Further to this, it then handles the tunnel connection, allowing to talk with the KNX network. By listening to the network, it will notify the Events manager of incoming telegrams that might concern some consumers. Activating a cache feature can avoid to overload the KNX network due to many clients reading the same group object.

For managing the notification paradigm, we introduce an **Events manager**. This module stores in an associative table the consumers registered on group objects for notifications. Triggered by the KNX comm module, it will lookup if consumers are registered for the group object having undergo a change of state, and then launches the notification by calling all related callbacks.

6 EVALUATION

We evaluated the capabilities and limitations of the implemented gateway through several tests. In order to have realistic feedbacks, we performed our tests on a building already equipped with a KNX installation. From the evaluation results, we also discuss some improvements of the gateway that would be beneficial for BMS.

6.1 Performance

To establish the performances of our gateway, we decided to measure various key-values such as: maximum number of requests per second, maximum simultaneous requests, notification reaction time (from the action on the KNX device until producer notification) and processing time of the ETS project archive (during configuration). All our measurements are done with an existing KNX installation of the 4 floors office LESO building located on the EPFL campus in Lausanne, Switzerland. The installation features 265 devices, distributed in 765 groups, with a total of 795 group objects and represents an average installation that can be found in many buildings.

Measure type	Result
ETS archive processing time	30 [min]
Maximum HTTP requests per second	45
Maximum simultaneous HTTP requests	620
Average event reaction time	33 [ms]

Table 1: Gateway performance measured on a real-life KNX installation running 265 devices

6.2 Discussion

Table 1 summarises the performance of the gateway implemented on a Raspberry Pi as described in Section 5.1. The ETS archive processing time is quite long, mainly due to the XSLT that is extremely resource consuming. However, as this operation has only to be performed during the configuration of the gateway, we can assume that it is not an important issue. The maximum HTTP requests per seconds is actually bottlenecked by the twisted pair of the KNX

network offering only 9600b/s. The maximum simultaneous HTTP requests is limited by the Raspberry Pi. Nonetheless, we believe that the measured value is largely sufficient for common BMS operation. Finally, we observed a fast event response time that would typically allow a BMS to function in reactive mode. We can see that all the results are suitable for such an installation and that the Raspberry Pi has to be considered as an alternative to classical PCs running gateways or serving as middleware.

A potential limitation of our proposition lies in the DNS approach which implies access to the DNS server of the host IP network. Such access may be restricted by security policies in which case a dedicated DNS server has to be made available for the gateway. A second issue is related to the security of our gateway where currently no authentication is implemented. An authentication layer based on access lists could be a solution to this.

Some developers have actually built small applications interacting with the KNX devices through our gateway, this in various languages. Their feedback were positive, showing the benefits of leveraging on standardized and well-accepted protocols to reduce the integration time of KNX devices on a BMS. Some developers asked us to extend the event notification system for recording on the gateway a series of values, and to be notified once the buffer being full or after a period of time elapses. This can be implemented by adding a storage module to the gateway, based on a small database such as SQLite or MySQL.

7 CONCLUSIONS

In this paper, we explored a new way allowing building management systems and information system to interface KNX installations by leveraging on well-known standards like HTTP and RESTful APIs. Instead of having to implement the KNX network protocol on the BMS, developers benefit from the simplicity of use of the WoT, thus facilitate the integration of heterogeneous networks. We believe that BMS will have to dialogue with various networks in near future because of new technologies appearing, like Enocean and others. In addition to this, our results show that the Raspberry Pi is enough powerful to run gateways.

Future works cover security aspects by adding an authentication layer and optional encryption of data to prevent misuse. A centralization of data on the gateway will also be explored, allowing BMS to look for past data used in many scenarios where user behaviour plays a primary key role. Finally, we will investigate the feasibility of building a direct connection to the KNX twisted pair in the gateway to eliminate the need of the KNXnet/IP module. The software running on the gateway can be made available for any scientific research project upon request to the authors.

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