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Power-Managed Smart Lighting Using a Semantic Interoperability Architecture

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Abstract —We present a power-managed smart lighting system that allows collaboration of Consumer Electronics (CE) lighting-devices and corresponding system architectures provided by different CE suppliers. In the example scenario, the rooms of a building are categorized as low- and high-priority, each category utilizing a different system architecture. The rooms collaborate through a semantic interoperability platform. The overall smart lighting system conforms to a power quota regime and maintains a target power consumption level by automatically adjusting power consumed by luminaries in the building. Experiments with CE devices of different suppliers operating on different networks show that the semantic interoperability architecture allows device collaboration that can lead to lower power cost¹.

Index Terms —priority mechanism, semantic information broker, semantic interoperability architecture, Smart-M3.

I. INTRODUCTION

Electric power usage constitutes an important source of financial outflow for building spaces. Therefore, electricity providers offer various schemes for billing. One model is that a building gets a quota of electric power that it is allowed to use. This way, electricity providers can plan their power generation in a cost effective manner. However, if a building uses more power than its assigned quota, a significantly higher price for electricity is charged, leading to excessive power bills. Hence, power quota overflows must be avoided.

The power usage in a building may vary based on the types of activities happening in the building at different times of the day. Let us take the simple example of an office space with a single coffee machine that is used 12 hours per day to make 200 cups of coffee per week. In this typical setting, according to [1], a single coffee machine would consume around 200 kWh per annum (kWh/a) for actual use (spikes of power use while making coffee), 147 kWh/a for heating water when idle, and 18 kWh/a in stand-by mode. Note that more than half of

the power consumed comes in the form of bursts (i.e. when someone actually presses the button to make coffee), while a rather smaller portion is consumed continuously and constantly due to idle operation. Therefore, in a huge office building with a large number of these machines, coffee break times could cause power consumption peaks, leading to power quota violations, if not handled properly. Thus, it is important to keep power usage just tightly below a given quota taking all power consumption variations into account.

One approach to solve this problem is to purchase more power than the building would actually need on average, creating a power quota margin for times of excessive electricity usage, which is suboptimal. In the near future, it is envisioned that collaborative networks of CE devices (e.g. wireless sensor networks and smart spaces) will be widely deployed [2], offering an alternative solution approach to this problem. This alternative is using power in a controlled way and, therefore, conforming to a power usage quota for the entire building. In this approach, the rooms of the building can be divided into two categories: *i*) high-priority rooms (HiPR) that are allowed to use power according to whatever demand there is at that time, and *ii*) low-priority rooms (LoPR) that are obliged to use the power that is leftover from the quota after the consumption of high-priority rooms. Assuming that the maximum HiPR power consumption by itself cannot exceed the available power quota; quota overflows can be prevented in all cases, while maximizing power utilization by allocating the remaining power budget to LoPRs.

In achieving this, two issues need to be considered. Firstly, individual rooms (either LoPR or HiPR) may contain CE products from various suppliers, possibly forming collaborative networks among themselves. To manage power for the entire building, collaboration of CE products in all rooms is necessary. This is difficult since smart CE products from different suppliers may operate over different system architectures due to lack of standardization. Ideally, a collaborative network that is installed using CE devices of a given supplier should be easily extendable by products of another supplier. Hence, interoperability between architectures of multiple CE suppliers becomes a key challenge. Secondly, a LoPR should only include services that are low-priority by nature, since the functionality of LoPR services depend on the availability of power budget remaining after power allocation to HiPRs. Some examples of such low-priority services are low-priority lighting (e.g. lighting in a parking lot), non-functional (e.g. decorative, artistic) lighting and entertainment

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services (e.g. television, music). Another very common example is deferrable and interruptible services, e.g. the heating system can be momentarily powered-down during a 1-minute power consumption peak and powered back up after the peak.

Hence, one of the key challenges of this paper is *semantic interoperability*, which is defined as the ability of multiple CE devices or systems to exchange high level information and use the information that has been exchanged [3]. This means that the components of such a system have the ability to interpret the information exchanged meaningfully and accurately in order to provide useful services as required by the end users. Achieving joint execution of tasks (or interoperability) is a challenging task for heterogeneous systems consisting of various CE devices with different operating systems and programming languages. The information of a device or a system should be exchangeable with another device to perform a collaborative function. A semantic interoperability architecture provides *not only hardware connectivity at the low level, but also semantic information exchange at a higher abstraction level*.

In this paper, we investigate the example scenario of low- and high-priority lighting to illustrate semantic interoperability for power-managed smart lighting. However, the proposed scheme can be easily generalized. A smart lighting system refers to a system where multiple luminaries with actuators and light sensors are connected in a network, and cooperate to meet the lighting requirements of users' activities. Such a system contributes to home automation by providing intelligent light services for users and power management [4]. In making a power managed smart lighting system based on the proposed semantic interoperability architecture, there are three challenges:

i) Integration of CE devices of different suppliers: Differences in hardware platforms must not jeopardize the interoperability and the overall functionality.

ii) Integration of low capacity distributed networks with Internet Protocol (IP): Traditionally, IP integration of low capacity distributed networks such as Wireless Sensor Networks (WSN) is implemented using two methods. In the first method, the sensor nodes implement the TCP/IP stack or compatible protocols such as 6LoWPAN [5] in IEEE 802.15.4 [6] networks. In the alternative method, one node acts as an application layer gateway to make the lower layer protocols from both networks (e.g. TCP/IP and IEEE 802.15.4) transparent and to route information [7]. We utilize the latter approach since it is lighter-weight.

iii) New light source: Existing systems utilize traditional light sources such as incandescent and fluorescent [8]-[10], whereas we propose to adopt LED luminaries to benefit from power savings and environmental advantages.

The literature work on smart lighting focuses mostly on automatic dimming control based on occupancy detection, user preferences and user activity [11]. We propose a novel *i)* power-managed and *ii)* priority-based smart lighting system on top of a semantic interoperability architecture. The

proposed system is power-managed since it manages power consumption due to lighting in a building with a power quota. It is priority-based since power consumption in every room of the building is managed based on its priority. The interoperability is tested using two different network architectures, each with their own CE devices from different suppliers and their own network protocols. The two architectural solutions are installed in two different rooms with different priorities. CE devices in one room can communicate and collaborate with the CE devices in the other room, exchanging light information over the semantic interoperability platform.

The paper is organized as follows: In Section II, the system architectures used for HiPR and LoPR are described. In Section III, the proposed system with priority mechanism is presented. In Section IV, the implementation of the proposed architecture and the interoperability approach are introduced. In Section V, the example use case scenario is explained along with experimental results. Finally, in Section VI, conclusions are drawn.

II. INTEROPERABILITY ARCHITECTURES

Semantic interoperability across multiple architectures is realized using the Smart-M3 (multi-vendor, multi-device, multi-domain) platform [12], which is a solution for information interoperability. On the other hand, the connection to lower capacity sensor and actuator nodes is realized over the OSAS (Open Service Architecture for Sensors) platform – an architecture for programming a network of sensors and actuators [13], [14].

A. Smart-M3 Architecture

The Smart-M3 architecture is designed to achieve semantic information based interoperability and used in HiPR. Smart-M3 architectural elements are shown in Fig. 1. Information in the Smart-M3 architecture is represented using ontology models [15]. An ontology allows description of the semantic model within a specific knowledge domain by means of an explicit data format. In Smart M3, ontology is useful for representing semantic information and reasoning about it [16], [17]. Entities called Knowledge Processors (KP) and Semantic Information Brokers (SIB) form a Smart-M3 network. A KP is an entity that produces or consumes information according to the ontology relevant to its defined functionality. A SIB is an entity, in which high level information for a smart space is stored and maintained. This information can be used and updated by a KP. For example, a producer-KP can collect raw data (e.g. sensory data) from the physical environment and provide semantically meaningful information to the SIB. Similarly, a consumer-KP can subscribe to such information available at the SIB and make queries. KPs and SIBs run the Smart Space Access Protocol (SSAP), which is a simple set of primitives to insert, remove and access data in a SIB, and can be used on top of transport technologies such as TCP/IP or Network on Terminal Architecture (NoTA) [18]. A KP can use SSAP for several transaction types such as *join*, *leave*, *insert*, *remove*, *update*, *query*, *subscribe*, and *unsubscribe*.

The Smart-M3 architecture also contains the notion of Ontology Application Interface (OAI) - an ontology specific interface allowing developers of smart applications to program using ontology concepts relevant to the application area.

Fig. 1. Smart-M3 architecture.

B. OSAS Architecture

The OSAS architecture is used for the wireless network of sensors and actuators in LoPRs. OSAS has been developed as a framework for programming networks of very low capacity nodes. It is based on publish-subscribe communication style and on event-based programming. An OSAS network consists of nodes equipped with a specific run-time system. Instead of programming individual nodes one by one, a single piece of program code is employed for the entire network. Sensors and actuators can be (re)programmed over the network by translating the program into a set of configuration messages that are interpretable by the run-time system. The programming model allows the application developer to define a service-oriented program for a collection of low capacity nodes by means of an Application Programming Interface (API). A service generates events through event generators, which are periodically triggered according to event-condition-action rules. The triggering period is specified by subscribers and can differ per subscriber/application. In addition, a service can process incoming messages generated by event through event-handlers, also called actions. A subscription is required to link the event generator of one service to the event-handler of another service. A single service can be defined and installed for a group of nodes or for the entire network and multiple subscriptions are possible for a single service. For each service, the developer indicates by a content based address (CBA) under what conditions a node installs and runs that service.

This framework enables dynamic reconfiguration of the network, providing communication to the nodes running on OSAS-runtime as shown in Fig. 2. The network program is written in a domain specific language that supports the mentioned concepts. The compiler translates the services and subscriptions into instructions to be interpreted by the OSAS run-time system on the nodes. The loader node's task is to upload configuration messages to smart nodes. The loader sends the CBA definitions and the compiled services into the sensor/actuator network, representing a dynamic installation. The format of these messages is independent of the sensor-

actuator hardware. The end points of a subscription are also specified by CBAs, such that a program is free of node specific information.

Fig. 2. OSAS Architecture functionalities

III. PROPOSED SYSTEM WITH PRIORITY MECHANISM

In the smart lighting with power management scenario, HiPRs are deployed with power measuring luminaries, light sensors, motion sensors and a switch for dimming. The system uses state machines that are capable of adjusting luminary light levels to pre-sets defined by the user, maintaining illumination depending on environmental light (e.g. daylight) and turning off luminaries in case no one is present. Different user activities require different light levels and thus cause different levels of power consumption. The luminaries in HiPRs are also capable of measuring power consumed by them as a result of changes in the user activity.

Fig. 3. System architecture of power managed smart lighting. HiPR: All KPs in HiPR individually and periodically update their power consumption values at the SIB. The luminaries in HiPR can utilize almost the entire power when necessary. LoPR: GWKP translates lighting information between the ontology language used in Smart-M3 and the OSAS message format that is readable by OSAS sensors and actuators.

The architecture of the proposed power-managed smart lighting system is shown in Fig. 3. The luminaries and sensors in LoPR communicate with the SIB through a gateway-KP (GWKP), whereas the power measuring luminaries and sensors in the HiPR are individual KPs. The GWKP is a gateway node that exchanges lighting information with the Smart-M3 SIB on behalf of the OSAS sub-network of sensors and actuators. The lighting information in each room is stored at the SIB in the form of Resource Description Framework (RDF). RDF is a graphical ontology language [19] used for representing resource information on the Internet. The KPs in HiPR and the GWKP in LoPR can read and update this information over SSAP as described in Section II. The lighting information in a system consists of the basic features of light such as ‘illumination’, ‘light output’ levels and power used by luminaries. When the power quota is large enough to support all activities in HiPR and LoPR, the sensor readings in these rooms are used to set and maintain the illumination based on user preferences for the activity performed (e.g. individual reading, meeting, presentation). If the illumination measured differs from the desired illumination, the light outputs of the luminaries are automatically adjusted by the KPs in each room till the desired illumination is achieved.

When the power quota is not sufficient to support LoPR and HiPR simultaneously, the GWKP dims the illumination in LoPR down. Depending on the HiPR power consumption information, retrieved via a subscription/query mechanisms provided by the SIB, the GWKP brings the power consumption in LoPR just below the remaining power budget for LoPR, denoted by Q_l . Therefore, the system never exceeds the total power quota for the building, denoted by Q . Let the power usage due to lighting in HiPR be $P_h \leq Q$.

$$P_h = P_{h,1} + P_{h,2} + \dots + P_{h,n} \quad (1)$$

$$Q_l = Q - P_h \quad (2)$$

where $P_{h,i}$ is the power usage by luminary i and n is the total number of luminaries in HiPR. The value of P_h is updated periodically by HiPR on the SIB and read from the SIB by the GWKP of LoPR. Let P_{lowReq} denote the power required for illumination of a certain user activity in LoPR. The requested power can be provided to rooms in category LoPR only if $Q_l \geq P_{lowReq}$. Otherwise, the smart lighting systems in these rooms must confine their power usage to the leftover power quota, Q_l . The only power constraint that the HiPR systems have is $P_h \leq Q$.

The above priority mechanism regulates power consumption to manage power quota based on power usage in HiPR, while trying to maintain the desired light levels of the users in LoPR. In summary, HiPR is given high priority in the joint power management of both types of rooms.

It is also possible to retrieve semantic information from the proposed system by an entity called Mobile KP (M-KP). The M-KP can make queries and subscriptions to the SIB like any other KP. It can also display the retrieved information on its screen, allowing the user to view a summary of the relevant semantic information on her mobile device.

IV. IMPLEMENTATION

The proposed semantic interoperability architecture is shown in Fig. 4, where the ontology is stored in the SIB. The architecture is divided into three levels: *communication*, *service* and *information*. At the communication level, devices communicate over a communication protocol such as IEEE 802.15.4 [6], ZigBee [20] or IP. At the service level, adaptive

Fig. 4. Semantic Interoperability Architecture for Power-managed Smart Lighting.

or automatic lighting and power measurement models are used to realize lighting services for the system. The information level is utilized to retrieve information from service level and exchange across the networks of HiPR and LoPR. In HiPR, the system consists of one Switch (SW), one sensor-KP (S-KP), and two power-measuring luminary KPs (P-KP). The user preferences are input to the system using the SW, which uses ZigBee to communicate with the P-KP. A user can adjust the light output to achieve the desired illumination for an activity in the room. The S-KP uses IP and Zigbee protocols for the SIB connection and connections to other KPs, respectively. Similarly, the P-KP is connected to the other KPs and the SIB over ZigBee and IP, respectively. The hardware units in HiPR are shown in Fig. 5(a) and (b). The P-KP has a control unit for power measurement and calculates the actual consumed power used by the luminary. After calculating the power consumption in HiPR, all P-KPs update these values in the SIB. The KP interface (KPI) ontology support is used for translating the low level power consumption information into RDF data to be stored in the SIB.

Fig. 5. HiPR hardware components are shown in (a) and (b), where (a) is a power measuring light source P-KP and (b) is an S-KP. LoPR hardware components are shown in (c), (d) and (e), where (c) is a sensor node SN (d) is an LED actuator board for AN and (e) is a 36-LED AN luminary.

On the other hand, the LoPR system consists of a GWKP, sensor nodes (SN) and actuator nodes (AN). The OSAS sensor and actuator network connects to the Smart-M3 through the GWKP. The OSAS interpreter is used for translating RDF data received at the GWKP into OSAS information format. In the reverse direction, from OSAS to Smart-M3, the KPI ontology support is used to translate OSAS information into Smart-M3 contextual information in the RDF format. The lamps and the sensors are connected to the GWKP via Universal Serial Bus (USB) and IEEE 802.15.4, respectively. Furthermore, the GWKP is connected to the SIB via the internet protocol, on top of which the SSAP protocol runs. The LoPR wireless light sensor nodes shown in Fig. 5(c) are designed to measure the intensity of human perceptible light in the range from 1 to 1000 lux. The LED luminaries in LoPR consist of 36 regular LEDs (6x6 square grid shaped) and are attached to the LED actuator board to form an AN. The hardware modules of AN are shown in Fig. 5(d) and (e).

The power consumption information received from HiPR is stored in the SIB and is used by the GWKP of LoPR to

regulate its light output. At the same time, the GWKP can change the light information at the SIB for any illumination changes detected in the LoPR environment. The change of light information is performed by means of *insert* and *update* transactions to the SIB. It is possible to regulate power in LoPR such that the illumination in the activity space does not dim down directly. Firstly, the system will dim down the light output of the luminaries that are outside of the activity space (still in the same room). For this purpose, LoPR is divided into grids of square shaped cells. Each grid is equipped with two nodes, i.e. one SN and one AN. The SN in each square grid is responsible for reporting illumination produced by the luminary in the same grid. In practice, most user activities are performed in a limited area of the room. Therefore, a user activity can be scattered over multiple grids depending on the size of a square grid and the luminaries in these grids are automatically adjusted. For example, reading activity can be performed using a reading table area, spread over multiple grids. Based on (2), if the remaining power for LoPR is less than the required power, the following steps are taken:

Step 1: Dim the light output in all grids of LoPR that are outside the activity space such that the remaining power is less than or equal to the required power. Note that, the light output is always greater than or equal to 0.

Step 2: If the light output in the first step is equal to 0 and the remaining power is still less than the required power, dim the light output in LoPR activity grids till LoPR power consumption is less than its power budget, Q_l or equal to 0.

A. Subscription and update links for information exchange

Information exchange between HiPR and LoPR happens over the subscription and update links established in the system as shown in Fig. 6. In HiPR, a subscription is made from the P-KP to the SIB by means of ‘*update_Power*’ subscription link, which updates the consumed power by a luminary. In LoPR, OSAS subscriptions and updates are established by the GWKP. The GWKP uses the ‘*sub_SIBdata*’ subscription of Smart-M3 to subscribe to the information received from HiPR regarding the power usage. It then calculates the Q_l according to (2) for regulating the luminaries in LoPR. Based on these calculations, suitable control commands to the actuators are issued and updates in the lighting conditions are done through a ‘*sub_AdjustLight*’ subscription. The revised light output is updated by a ‘*sub_UpdateLOutput*’ subscription to the GWKP in the OSAS system. In parallel, the illumination is reported to the GWKP by a ‘*sub_UpdateIllumination*’ subscription link. This information is further analyzed at the GWKP for updating the light output in LoPR and stored at SIB by means of a ‘*sub_SIB_store*’ subscription link. The S-KP updates illumination information to the P-KP in HiPR and to the SIB through an ‘*update_Sensor*’ subscription. Furthermore, a user can manually adjust the illumination in HiPR using SW interface by sending commands to the P-KP. The ‘*Light_Command*’ from the SW and the ‘*update_Sensor*’ from the S-KP are the two inputs to the P-KP to adjust the light output levels in HiPR. A mobile device M-KP can enter any room at an arbitrary time and subscribe to the information at

SIB by using ‘*sub_Status*’ subscription. The M-KP can use this information to adapt its services according to the lighting conditions in the room.

Fig. 6. Flow diagram of the subscriptions and updates links of a system architecture for power-managed smart lighting.

B. Information format

Ontology in RDF format is the main data structure that is used to manage information, which can be exchanged between HiPR and LoPR. The RDF format is described in terms of ‘properties’ and ‘property values’ using RDF statements.

Fig. 7. RDF triple query format from M-KP to SIB.

RDF statements are represented as triples, consisting of a Subject (S), Predicate (P) and Object (O), i.e. {S, P, O}. The subscriptions are persistent queries that notify the subscribing KP every time the query results change. An example is shown in Fig. 7, where M-KP is subscribed for all changes at the SIB using the *None* parameter in all fields of the RDF triple, i.e. (\"None\", \"None\", \"None\"). This means that the information in these fields is expected to be filled by the SIB. Upon arrival of the updates 1 and 2 at the SIB (see Fig. 7) from the GWKP and the P-KP, respectively, the subscription results 1 and 2 are sent to the M-KP. Similarly, the GWKP can subscribe to or query a SIB for information regarding the power usage in HiPR. As a result, the power consumption information (i.e. 3500 milliwatts in this example) is received at the GWKP. This means that the SIB fills the *None* field of the triple with the respective information.

V. EXPERIMENTAL SCENARIO AND RESULTS

We consider two different system architectures for high and low-priority rooms as discussed in Section IV, where different types of CE devices and communication protocols are employed to show interoperability.

The first time a user is in HiPR, the light levels that are preferred for a given activity are input by the user to SW. The preferred light settings (commands) are sent to the P-KP where they are stored. After that, every time the user enters HiPR, her presence is detected and the same settings are automatically used unless the user inputs new preferences. In case the illumination is not at the desired level, the lighting conditions and therefore the consumed power are adjusted to the user preference.

The GWKP in LoPR is responsible to get the power usage information from HiPR and process the required adjustments to the lighting conditions in LoPR.

TABLE I
LED LUMINARY FEATURES IN LOPR AND HiPR

Features	LoPR Luminary	HiPR Luminary
Luminary function	turned on and off, and its brightness controlled	turned on and off, and its brightness controlled
Output update rate	30 updates/second	1 update/second
Number of LEDs in one luminary	36	3
Power source	DC power source	AC 220V
Power conversion	None	LED lighting driver with power measurement
Connection	USB port	ZigBee and Internet
Maximum light output from one LED luminary	360 lumens (maximum 10 lumens per LED)	525 (maximum 175 lumens per LED)
Maximum power used by one LED luminary	6486 milliwatts	4500 milliwatts

Different types of LEDs and LED luminaries are used in LoPR and HiPR and their specifications are given in Table I. The quota of power consumption for the building that houses

these rooms is considered to be 12 watts, which is slightly higher than the maximum total power that can be consumed by LED luminaries in HiPR. This quota is considered to regulate luminaries in LoPR such that the power consumption can vary in the range from 0 to Q as described in Section III.

In our experiments, we used four different user light preference settings for HiPR. The corresponding HiPR power consumption values (P_h) and leftover power quotas for LoPR (Q_l) are as shown in Fig. 8. P_h values are reported to the SIB by P-KP and since the GWKP is subscribed to this information on the SIB, it receives an update. Light sensors in LoPR report their illumination values to the GWKP as well. Based on all this information, the GWKP calculates the light outputs of all luminaries in LoPR according to the priority mechanisms discussed previously.

In Fig. 8, it is clear from tests 1 and 4 that the required power in LoPR is less than the leftover quota for LoPR ($P_{lowReq} < Q_l$), in which case the lighting requirements of both room types are easily satisfied. On the contrary, in tests 2 and 3, the required power in LoPR is higher than its leftover quota ($P_{lowReq} > Q_l$) and the luminaries in LoPR are restricted to use less power than they require to satisfy user preferences.

Fig. 8. Power consumption in HiPR and LoPR based over four tests.

Fig. 9. Comparison of required and regulated power in LoPR.

The comparison of required and regulated power in LoPR is shown in Fig. 9. The priority mechanism maintains the overall power consumption accurately under different lighting preferences from users, conforming to a power quota regime. The high level information that is required by the priority mechanism is exchanged between LoPR and HiPR by means

of the presented Smart-M3 semantic interoperability architecture. The use of different types of CE devices in the system shows device architecture agnostic nature of the proposed solution with the Smart-M3 architecture.

The experiments carried out on the proposed system have shown that the semantic interoperability platform allows lighting products from different CE suppliers and the corresponding system architectures to work together. Power consumption management for smart lighting is accomplished without exceeding a given power quota. When the power quota for lighting is sufficient to support all rooms and all activities in a building, the desired illumination levels in both room types are set and maintained automatically based on the user activity. When the power quota is not able to support LoPR, the luminaries in LoPR are dimmed down to fully utilize the leftover power budget from HiPR.

VI. CONCLUSIONS

We developed a power-managed smart lighting system composed of various types of CE devices with different computing and communication platforms, forming a heterogeneous network. The power management information is exchanged between different networks and devices using an ontology-based semantic interoperability architecture, namely Smart-M3. The proposed priority mechanism ensures accurate maintenance of the overall power consumption levels, always keeping it under a given power quota for the building. This behavior is regardless of changing external lighting conditions as the smart lighting system introduced is capable of adjusting light output levels from individual luminaries as well as their power consumption in both LoPR and HiPR.

In this work we consider power consumption of the smart lighting system as the primary performance indicator of the semantic interoperability architecture. As future work, more performance parameters such as delay, throughput and scalability should be investigated. Furthermore, a study of the tradeoff between such performance parameters can yield interesting results.

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