Energy Consumption Management in Smart Homes: an M-Bus Communication System

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***Abstract*—Energy consumption management in Smart Home environments relies on the implementation of systems of cooperative intelligent objects named Smart Meters. In order for devices to cooperate to smart metering applications' execution, they need to make their information available. In this paper we propose a framework that aims at managing energy consumption of controllable appliances in groups of Smart Homes belonging to the same neighbourhood or condominium. We consider not only electric power distribution, but also alternative energy sources such as solar panels. We define a communication paradigm based on M-Bus for the acquisition of relevant data by managing nodes. We also provide a lightweight algorithm for the distribution of the available alternative power among houses. Performance evaluation of experiments in simulation mode prove that the proposed framework does not jeopardise the lifetime of Smart Meters, particularly in typical situations where managed devices do not continuously turn on and off.**

***Index Terms*—M-bus; Smart Home; energy management**

I. Introduction

The last few years have been characterized by the technological revolution of the Internet of Things (IoT) [1]. The aim of this paradigm is to enable the network objects to dynamically cooperate and make their resources available, in order to reach a common goal, i.e. the reduction of energetic consumption in a building. There is an exceptional number of applications that can make use of the IoT. Emerging applications in smart environments such as Smart Homes are often based on smart devices, named Smart Meters, which can create a network and monitor the home energy consumption. Smart Homes are residential buildings equipped with smart devices which cooperate in order to achieve a common set of goals. Some key features characterize many Smart Home environments: i) available node energy is often limited. This is the case, for example, of battery powered nodes, which have limited energy amounts. ii) Smart devices, which give the opportunity to monitor and to remotely control key equipment within homes. iii) Decision-support tools aimed to aid users in making more intelligent decisions and based on maximizing the benefits gained by the end users when they utilize energy services. It is evident that in parallel with the energy management problem, an appropriate communication protocol among smart devices would consistently improve performance of the system. The problem of energy management in Smart Home environments is treated in [2] and [3]. In these studies, the aim is to introduce an home energy control system's design that provides intelligent services for users. The proposed Smart Home energy management systems are based on task assignment, integration of various physical sensing information and control of some devices. However, they do not focus on finding the best communication protocol among devices that corresponds to an improvement of system performance. To the best of authors' knowledge, there are no studies focusing on optimal energy management protocols among Smart Meters.

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In this work, we first describe the characteristics and challenges of Smart Homes and Smart Meter applications that are widely exploited. We then propose a reference framework that supports the optimal distribution of the available energy among controllable appliances belonging to the same neighbourhood or condominium. This framework considers both the electric power distribution and the alternative energy sources that are available to the group of Smart Homes considered. We then propose a communication paradigm among Smart Meters, based on the M-Bus (Meter Bus) standard, which enables the exchange of information to achieve the devices' management. We also define the optimization model characteristics that enable the implementation of this protocol.

The rest of the paper is organised as follows. Section II analyses some past works and how they approached the energy management in Smart Home scenarios using Smart Meters. In Section III, the reference architecture is introduced. Section IV describes the communication protocol and Section V presents the optimization model. Finally, Section VI provides a performance analysis and Section VII draws conclusions.

II. Past works

The reduction of energy consumption using ICT has been extensively studied in the last years. In the field of Smart Home technology a lot of works focus their studies to define smart systems which avoid wasting of resources. The system does not simply turn devices on and off, it can monitor the internal environment and the activities that are being undertaken or that it predicts that will be undertaken. The result is that a Smart Home can monitor the activities of the occupant of a home, generate a user profile and independently manage devices using patterns aligned with the user profile [4]. In the literature is clear that a big effort has been put into management of energy consumption using smart devices to create a smart metering applications. In [5] the authors propose an Advanced Metering Infrastructure (AMI). This architecture is defined by the smart metering concept. By the AMI the researchers demonstrate the improvement of the Real Time Pricing (RTP) control and so the improvement of the reduction of the peak demand, the stabilization of wasting resource in the system and the decrement of the electricity cost. In the work [6] the authors use the AMI to approach the problem of electric management using smart metering concept. They propose an hardware architecture and software of the smart controller for use as the platform in smart grid system. The smart controller is installed on the electric plug of the electric appliance. The smart controller grasps the electricity amount used in the electric appliance and delivers to an Electric Management Server (EMS). In addition, according to the RTP of energy, the use of energy of the electric appliance is limited for efficiently controlling the electric energy consumption. The concept of smart metering is used by the authors of [7] to implement a mathematical model for an optimal and automatic residential energy consumption scheduling framework which attempts to achieve a desired trade-off between minimizing the electricity payment and minimizing the waiting time for the operation of each appliance in household in presence of a RTP and inclining block rate (i.e. if people uses more energy, it tends to pay more per unit of energy). In the paper [8], the researchers propose a Real-Time Demand Response Model. They implement a model to optimize the hourly load level of a given consumer in response to hourly electricity prices. The goal of the model is to maximize the utility of the consumer subject to a minimum daily energy-consumption level, maximum and minimum hourly load levels, and ramping limits on such load levels. As far as energy management using Smart Meters is concerned, it is an open issue, because the problem has not been extensively studied yet. Most of the existing works that study energetic management using a cooperative approach among Smart Meters are focused only on the optimization problem, such as in [9] in which the Tabu search algorithm is used, and in [10] in which the game theory is used. None of the works found in the literature proposes a framework that provides: the management of the communication among nodes to collect relevant data and send them to the nodes that are in charge of managing the network; an algorithm that optimally distributes the available energy to the group of Smart Homes considered.

III. Reference Architecture

In this work we consider a Smart Home scenario where the aim is to achieve an optimal distribution of the available energy among controllable appliances. We refer to controllable appliances as to those appliances whose start can be delayed, provided that they are executed before a given deadline. Our reference scenario is that of a group of houses such as a block or a condominium.

Inside each house there are appliances (e.g. electric oven, fridge, boiler, battery charger) and lights that consume energy. On the other hand, power supplies such as electric grid, solar panels, micro wind turbine provide energy that can be used to run appliances. Smart Meters and actuators are associated to these devices to monitor their energy consumption/production.

The devices are subdivided into 4 groups, based on their characteristics and requirements:

- Group 1: small loads such as lights, battery chargers;
- Group 2: not controllable high loads such as ovens, heaters;
- Group 3: controllable loads such as washing machines, dryers, electric cars;
- Group 4: supplies such as solar panels, micro wind turbines.

One or more tasks are associated to each consuming device (e.g. turning on/off the lights, running an oven program). A power consumption amount is associated to each task. At first, information related to involved device characteristics, and tasks that they are able to perform, will be detected and sent to a *Central Unit*. Users' habits, i.e. how family members usually use devices, are monitored and sent to the Central Unit as well. Based on these information, a profile of their energy consumption habits, namely user profile, will be associated to users. If, for example, the house is empty during working hours, it is unlikely that devices such as TV or lights are turned on during this span of time. At a later stage, information acquired and processed by the Central Unit is delivered to the appropriate Virtual Objects (VO). As depicted in Figure 1, each VO is responsible for managing the communication of all the devices inside a house. More precisely, each VO acts as an interface between a house's devices and the central unit. The role of VO can be taken by any Smart Meter that monitors the house devices.

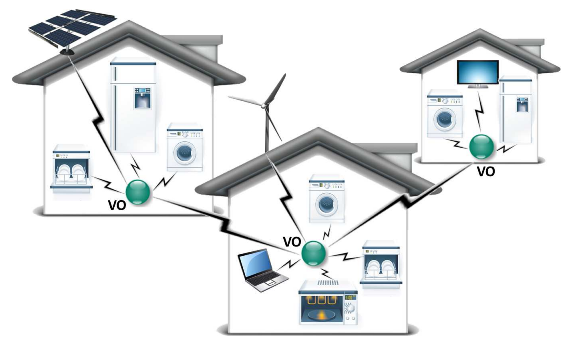


Fig. 1. Reference scenario

Considering a house of $\{1, \ldots, j, \ldots, J\}$ devices, its VO stores the following information for each device:

- Group 1: condition $j \in G_1$, where G_1 is the set of devices of Group 1; state (on/off) $x_{jk}(t)$ for device j related to task k, at time t; power P_{jk}^{cons} consumed by device j to compute task k; probability $Pr_{jk}(t)$ that device j performs task k at time t, as indicated by the user profile. Since power consumption for devices of this Group is negligible, we suppose a fixed energy consumption when they are on. Therefore, information about power consumption is delivered by the Smart Meter only the first time;
- Group 2: condition $j \in G_2$, where G_2 is the set of devices of Group 2; state (on/off) $x_{jk}(t)$ for device j related to task k, at time t; power P_{jk}^{cons} consumed by device j to compute task k; probability $Pr_{jk}(t)$ that device j performs task k at time t, as indicated by the user profile or based on user needs (e.g. if the video

recorder is set to turn on at time t' and turn off at time t'', $Pr_{jk}(t' \leq t \leq t'') = 1$);

Group 3: condition $j \in G_3$, where G_3 is the set of devices of Group 3; state (on/off) $x_{jk}(t)$ for device j related to task k, at time t; power P_{jk}^{cons} consumed by device j to compute task k; time t_{jk}^{exec} needed by device j to perform task k; deadline $t_{jk}^{deadline}$ before which device j needs to perform task k; time t_{jk}^{start} when device j started to perform task k, if task k is running (i.e. $x_{jk}^{3}(t) = 1$);

Group 4: condition $j \in G_4$, where G_4 is the set of devices of Group 4; state (on/off) $x_j(t)$ for device j at time t; power P_j^{prod} produced by device j.

IV. Communication Model

In our scenario, information about energy consumption is collected by Smart Meters. Smart Meters are battery powered, battery that sometimes could be difficult to replace, for instance in the case of Group 4 devices that are typically placed on the rooftop. This entails that their lifetime should be preserved as much as possible. Under these consideration, Wireless M-Bus (Metering Bus) was chosen for our communication model [11][12].

We define two communication phases, which correspond to two different conditions:

- Installation phase, when the Smart Meter is installed in the network and needs to communicate its presence to the VO;
- Working phase, when devices are installed and Smart Meters are monitoring their usage.

These phases will be now described in more detail, defining the communication flows and messages that characterise them.

A. Installation phase

Whenever a new Smart Meter starts to monitor a device, it needs to be installed in the network. The related communication flow is shown in Figure 2.

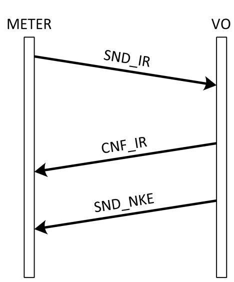
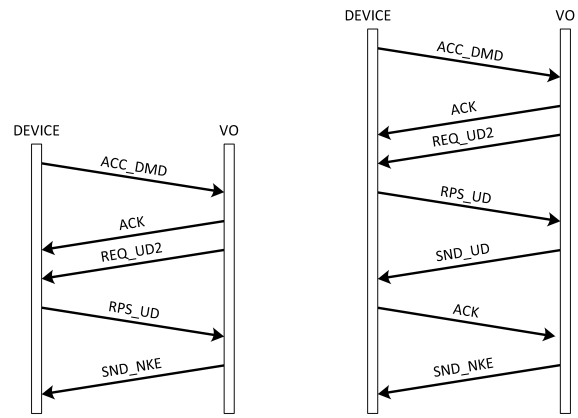


Fig. 2. Installation phase

The Smart Meter sends to the VO a Send Installation Request (SND_IR) message containing all the information needed for its installation. The VO replies with a Confirmation Installation Request (CNF_IR) message, and then resets the communication link with a Send Link Reset (SND_NKE) message.

B. Working phase

In the working phase, information about monitored devices, usage habits and characteristics of the tasks that they perform are sent by Smart Meters to their related VO. These data are then sent by the VO to the Central Unit (using the same communication flow) in order to compute a user profile. Figure 3 summarises these communication flows, that differ depending on the Group the device is part of.



(a) Groups 1, 2 and 4 (b) Group 3

Fig. 3. Working phase

Groups 1*,* 2 *and* 4*:* Communication starts with an Access Demand (ACC_DMD) request message, where the device delivers to the VO its Group ID number and an access number to synchronise the communication. If available, the VO replies with an ACK, and then informs it is ready to receive data with a Request User Data (REQ_UD2) message. Thus, the device replies with a Response of User Data (RSP_UD) containing all its relevant data that will be stored on the VO (see Section III): the state of the device (on if the task is starting, off if the task is ending), the ID number of the task it is performing (for devices of Groups 1 and 2). If it has not been sent before (or if it has changed), this message also contains the power consumption/production value related to the task. For devices of Groups 1 and 2, if the state of the device has changed from off to on, their corresponding probability turns to 1.The communication ends with a SND_NKE message that resets the link.

Group 3*:* Devices of this Group are controllable devices. Therefore, they do not decide when they are going to perform the task that is required to them: it is the VO that assigns to them a starting time.

The communication is started exactly as described in Section IV-B: the device sends an ACC_DMD request message containing the ID number of its Group. The VO, if available, replies with an ACK and a REQ_UD2 message. Once the device has received these messages, it sends its data inside a RSP_UD message. As described in Section III, these data are: the ID number of the task it needs to perform and its deadline. In case it has not been sent before (or if it has changed), this message also contains the power consumption and the execution time that are expected for this task. In this case, this message is delivered by the VO to the Central Unit.

The VO, which has complete knowledge of the state of the other devices that it manages as well as the user profile, assigns to the device the most convenient starting time for the task, on the basis of an optimization that takes into account the other tasks scheduled inside the house (and their power consumption/production). If any produced power should become available, the VO dynamically decides whether to commit to the device to start earlier. Therefore, on equal cost values, the VO initially assigns to the device the starting time that is closest to the deadline, so that, if a more convenient situation arises, the device can start the task before the assigned starting time. The optimization algorithm performed by the VO will be better described in Section V.

The starting time computed by the VO is sent to the device through a Send User Data message, to which the device replies with an ACK. Finally, the VO resets the communication link with a SND_NKE message.

If the device does not receive from the VO any command to start the task earlier, it turns itself on at the assigned time, after notifying it to the VO using a communication flow that is identical to the one described for Groups 1, 2 and 4. Otherwise, the VO initialises a new communication link with an ACC_DMD message. After receiving an ACK from the device, the VO sends the command to start the task through a SND_UD message. If the device is available, it replies with an ACK and turns itself on. The link is reset by the VO.

V. Optimization Model

When a controllable device requests to the VO a starting time to perform a task, the VO start an optimization to choose the more convenient starting time that is closest to the task deadline, so that the available power P^{max} is not exceeded by the simultaneous usage of several devices. Recalling from Section III that $P^{cons}_{jk}(t)$ is the power needed by device j to perform task k at time t, and that $Pr_{jk}(t)$ is the probability that device j performs task k at time t, we define the expected instant total power $P^{TOT}(t)$ that is likely to be consumed at time t by all the devices managed by the VO as

$$\begin{aligned} P^{TOT}(t) = & \sum_{j \in \{G_1, G_2\}} \sum_{k} P^{cons}_{jk}(t) \times Pr_{jk}(t) \\ & + \sum_{j \in G_3} \sum_{k} P^{cons}_{jk} \times x_{jk}(t) \end{aligned} \tag{1}$$

which takes into account the probability that devices of Groups 1 and 2 are on at time t, and the state of Group 3 devices that are already scheduled. Therefore, the optimization problem solved by the VO to assign the starting time t^{start}_{ik} for task k to device i can be written as

$$\begin{aligned} max \quad & t^{start}_{ik} \\ s.t. \quad & P^{TOT}(t) + P^{cons}_{ik}(t) \leq P^{max} \\ & \qquad \forall\ t^{start}_{ik} \leq t \leq t^{start}_{ik} + t^{exec}_{ik} \\ & t^{start}_{ik} \leq t^{deadline}_{ik} - t^{exec}_{ik} \end{aligned} \tag{2}$$

where t^{exec}_{ik} and $t^{deadline}_{ik}$ have already been defined in Section III.

Whenever a VO detects some power surplus $P^{surplus}(t)$, i.e. power produced by Group 4 devices that is either detected directly by the VO or received from other VOs to which it is connected, it start an optimization to distribute this power to the devices that it manages. Let Γ be the set of Group 3 devices to which the VO already assigned a starting time, and that are still waiting to start. First, the VO subtracts from $P^{surplus}(t)$ the expected instant total power. Then, if $P^{surplus}(t)$ is enough for all the devices in Γ, the VO sends to them a command to turn on. Otherwise, it solves the following knapsack optimization problem

$$\begin{aligned} max & \sum_{j \in \Gamma} \sum_{k} b_{jk}(t) \times x_{jk}(t) \\ s.t. & \sum_{j \in \Gamma} \sum_{k} P^{cons}_{jk}(t) \times x_{jk}(t) \leq P^{surplus}(t) - P^{TOT}(t) \end{aligned} \tag{3}$$

where $b_{jk}(t) = \frac{t}{t^{deadline}_{jk} - t^{exec}_{jk}}$ represents the benefit gained if task k is performed in j, and is higher for tasks that are closest to the deadline. The solution expresses which devices the VO needs to contact to turn them on. If residual surplus energy is still remaining, this information is sent by the VO to the next VO to which it is connected. Algorithm 1 summarises the steps executed by the VO.

Algorithm 1

$P^{surplus}(t)$ is detected by the VO
if $P^{surplus}(t) - P^{TOT}(t) \geq \sum_{jin\Gamma} \sum_{k} P^{cons}_{jk}(t)$ **then**
    $x_{jk}(t) = 1\ \forall\ j \in \Gamma$
else
    Solve the optimization problem in Equation 3
end if
If any, send assignments to devices in Γ
Evaluate $P^{surplus}(t') = P^{surplus}(t) - P^{TOT}(t) - \sum_{j \in \Gamma} \sum_{k} P^{cons}_{jk}(t) \times x_{jk}(t)$
if $P^{surplus}(t') \geq 0$ **then**
    Send $P^{surplus}(t')$ value to the next VO
end if

VI. Simulation Results

The communication model proposed in the previous Sections and how it affects the battery charge of Smart Meters has been tested using OPNET Modeler 17.5. For performance evaluation of the radio transceiver we used the characteristic parameters of the Telit ME70−169 module [13], which implements the Wireless M-Bus stack in the N mode (Narrowband VHF mode) at 169 MHz. This operating mode ensures the longest communication range among those defined by the M-Bus standard. The main radio transceiver characteristics, as well as the length of the messages used for the communication flows described in Section IV [12], are listed in Table I.

We analysed the scenario of three Smart Homes with six devices each. We first studied how battery consumption is affected for different frequencies of devices' state changing, i.e. their task frequency. At a later stage we analysed a typical day of usage of these devices. Table II summarises which are the monitored devices, to which Group they belong, to which

TABLE I
SMART METER CHARACTERISTIC PARAMETERS

Tx consumption	475 mA
Rx consumption	34 mA
Stand-by consumption	2 μA
Sleep consumption	1.5 μA
Power supply	3 V
Data rate	2.4 kbps
Bandwidth	12.5 kHz
Frequency	169.4 MHz
Modulation	GMSK
SND_NKE	27 B
ACC_DMD	30 B
ACK	27 B
REQ_UD2	27 B
RPS_UD	128 B

TABLE II
DEVICES OF THE REFERENCE SCENARIO

ID	Type	House ID	Group ID	Task frequency	Task duration
1	Lights	1	1	70/day	20 mins
2	Oven	1	2	2/day	1 hour
3	Air-conditioner	1	2	8/day	30 mins
4	Fridge	1	2	always on	24 hours
5	Washer	1	3	2/day	1.5 hours
6	Solar panel	1	4	3/hour[1]	12 hours
7	Lights	2	1	80/day	20 mins
8	Microwave oven	2	2	6/day	5 mins
9	Fridge	2	2	always on	24 hours
10	Boiler	2	3	4/day	1 hour
11	Dishwasher	2	3	2/day	1 hour
12	Micro wind turbine	2	4	3/hour[1]	16 hours
13	Lights	3	1	60/day	20 mins
14	TV	3	1	4/day	1 hour
15	Fridge	3	2	always on	24 hours
16	Hair drier	3	2	2/day	15 mins
17	Boiler	3	3	3/day	1 hour
18	Washer	3	3	1/day	2 hours

house they belong (1, 2 or 3), how many times they were turned on during a typical day and how long they have been staying on.

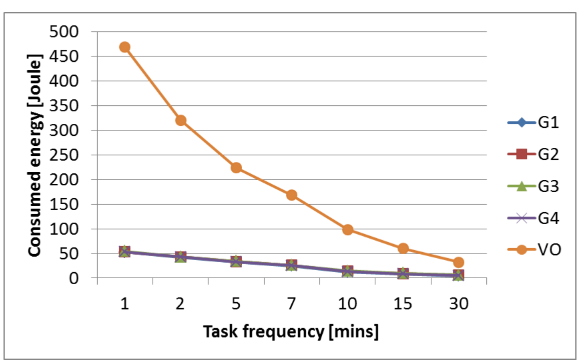


Fig. 4. Mean energy consumption due to communication, for different task frequencies

Figure 4 shows the mean energy consumption for each device Group, for different task frequencies. It is evident that, while energy consumption due to communication is not critical for most of the devices, the VOs suffer a significant decrease of lifetime, particularly when task frequencies are, on average, higher than one each 10 minutes. This result is emphasised in Table III, where the mean lifetime of the VOs for different task frequencies of the devices managed by them is reported. Note that it is unlikely that all the devices in a house send requests more than once every 10 minutes. However, results highlight that particular attention should be paid to devices that frequently turn on and off, which typically are represented by Group 1 devices, or send frequent updates like Group 4 devices. This outcome is confirmed by the typical day analysis, which results are presented in Table IV.

TABLE III
MEAN VO LIFETIME FOR DIFFERENT TASK FREQUENCIES

Task frequency [min]	1	2	5	7	10	15	30
Mean lifetime [years]	0.4	0.5	0.6	0.9	1.6	3.3	7.7

TABLE IV
MEAN ENERGY CONSUMPTION IN A TYPICAL DAY

ID	Type	Consumed energy [J]	Mean lifetime [years]
1	Light	10.5	9.2
2	Oven	0.4	> 20
3	Air-conditioner	1.6	> 20
4	Fridge	0.2	> 20
5	Washer	1.0	> 20
6	Solar panel	7.0	13.7
7	Lights	12.0	8.1
8	Microwave oven	1.2	> 20
9	Fridge	0.2	> 20
10	Boiler	2.0	> 20
11	Dishwasher	1.2	> 20
12	Micro wind turbine	9.4	10.3
13	Lights	9.0	10.7
14	TV	0.6	> 20
15	Fridge	0.2	> 20
16	Hair drier	0.4	> 20
17	Boiler	1.5	> 20
18	Washer	0.5	> 20
VO1	Virtual Object	40.3	2.4
VO2	Virtual Object	48.5	2.0
VO3	Virtual Object	27.6	3.5

Since the VO is a crucial role inside our scenario, it is necessary that its battery life lasts as long as possible. For this reason, frequent updates should be avoided. For example, since energy consumption for Group 1 devices is negligible, monitoring updates could be sent just once every 20 minutes, considering constant the energy consumption between two updates. The same could apply to Group 4 devices, which energy production is supposed to change slowly. Furthermore, since it is not necessary that the VO role is taken by one single node, its role could rotate among the Smart Home nodes, increasing the VO lifetime. However, in case a high task frequency is experienced, the option of supplying the VO through the electric grid should be taken into account.

VII. CONCLUSIONS

In this work we focus on the energy management problem in Smart Home scenarios. We define a architecture aimed at solving the issue of the optimal distribution of the available energy among controllable appliances of a group of Smart Homes, considering also the energy produced by alternative sources. Each appliance is equipped by a Smart Meter, which enables its monitoring and management. We propose a new communication protocol for a smart metering application, which enables the exchange of information to achieve the devices' management. We analyse the communication protocol performance by means of simulations of a Smart Home scenario. In this scenario, Smart Meters communicate using an N mode M-Bus protocol at 169 Mhz.

Simulation results prove that the proposed communication protocol does not jeopardise the battery lifetime of the monitoring devices, even for frequent changes in the device state (from on to off and viceversa). On the other hand, particular attention needs to be paid to the VO, which manages nodes' monitoring, performs the optimization algorithm for the optimal distribution of the available energy, and accomplishes the commissioning of controllable appliances. In fact, its battery is rapidly depleted for extremely frequent updates by nodes. Simulations proved that in typical scenarios it is unlikely to have updates more than once every 10 minutes. However, in cases where a high task frequency is experienced, the role of VO could rotate among Smart Home nodes, so that its lifetime is increased. Another option could be supplying the VO through the electric grid.

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