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A ZigBee Based Reliable and Efficient Power Metering System for Energy Management and Controlling

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***Abstract*—Planning and management of energy are among the most important topics nowadays due to the fact that the existing power plants and systems fail to satisfy the energy demand and keep up with the daily developing technologies. To maintain the energy need of the existing systems, researchers are aiming to improve usage and savings of available resources and systems. For example, power metering system has been proposed to decrease the energy wasting. The purpose of this system can be explained as limiting the energy consumption in some cases like stand-by or while switching programs or devices which the system is installed on. By blocking the unnecessary consumption of energy, profits and savings are targeted. In this work, a new power meter system based on ZigBee technology is designed and implemented to obtain a more efficient structure and reduce the number of disadvantages of the existing technologies. In SmartPlug, the MCU was moved into the plug from outer environment and shifting the host to a spectator to eliminate user based faults and/or problems. Moreover, the proposed structure enhances the safety by detecting the sudden voltage fluctuations and preventing the possible damages of end-devices. In addition to these, we prove that cutting of stand-by powers and limiting the energy consumption by arranging the working hours of devices based on energy unit prices provide efficient, right and cheap usage of the energy.**

I. Introduction

Existing home automation systems are not able to serve cheap and flexible solutions. The embedded structure of these technologies makes the system not upgradable. Besides, they need to be done before the completion of the construction which means that it is hard to implement them into the old buildings. These systems are stable, and this immobile environment restricts the user's opportunities. Another drawback can be defined as having limited applications and scenarios. Power metering and managing systems and in bigger scales Smart Grid applications become the best candidates to overcome these disadvantages of home automation systems.

These power metering and managing systems serve cheaper, more reliable and mobile solutions in contrast with the existing home automation systems. Thanks to their non-embedded structure, the user is able to change the operation place of the plug which helps to manage any targeted devices placed in buildings, offices and/or homes. This benefit of mobility contributes to expand the scenarios and application ranges thus provides a flexible environment for the user. Moreover, the user does not need to invest any extra money for set-up stage, also plug's cheap structure offers economic solutions for energy metering. In order to manage the related devices remotely, wireless communication technologies are integrated both in plugs and the user sides in recent applications. Any protocol can be performed for actualizing the communication between master and slave; however, 2.4 GHz band is preferred frequently and mostly ZigBee Protocol is conducted among these.

ZigBee is a high-reliable, low cost wireless communication protocol which consumes low power during operation and supports generic mesh, star and cluster tree networks for different purposes [1]. Due to the low power consumption, a ZigBee module serves longer process life with tiny batteries preventing the unnecessary usage of external supplies. Therefore, it becomes a cost effective solution for monitoring, managing and controlling duties. Besides the technological improvements, every electronic product becomes a potential energy consumer without any preference of uses. Taking the existing source-demand imbalance or directly shortage of energy into account, it is proved that the importance of energy management and correct use of energy is vital. When it comes to correct usage of energy, controlling and/or monitoring oriented sub-equipments have to be arranged as energy friendly. In this manner, ZigBee Protocol becomes a low power wireless solution for tiny networks with the following characteristics;

- There is no huge data transfer in ZigBee operation,
- It leads into the usage of smaller gadgets which consume less energy,
- It has low duty cycles,
- Power consumption is limited in Binary Phase Shift Keying(BPSK) and Offset-Quadrature Phase Shift Keying (O-QPSK) modulations,
- When it is not in exchanging mode, the whole sections except coordinators and rooters remain in sleep mode.

The mentioned specifications prove that, ZigBee modules provide more economical solutions in contrast with other wireless protocols and also reduce the number of energy induced drawbacks. A detailed comparison can be found in Table I which compares three different wireless communication protocols and justifies why ZigBee is better for communication tasks. In addition to these advantages, fast and easy implementability, flexibility, extra node capability and manufacturer-supplier independence make ZigBee more preferable.

SmartPlug aims to bring a radically different approach in contrast with related existing proposals because of having its own microcontroller which consists read-write, evaluation and control unit inside and works as the brain of the whole circuit.

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This MCU, namely Atmega328 [2] is continuously interacting with the relay, communication, metering and monitoring units. It provides reading and evaluation for the taken data and operates data transfer in the required situations over ZigBee based wireless module which helps remote control of the SmartPlug during operation. In this manner, the MCU takes the user commands over this module and operates it, respectively. This implementation helps to create more reliable and efficient systems and the validity of this structure is proved with the experimental results.

The remainder of this paper is organized as follows. In Section II, some existing proposals regarding power metering, energy management, controlling and monitoring systems are introduced. In Section III, the basic structure of SmartPlug is represented part by part and the detailed specifications and improvements of this system is discussed. Performance evaluation and experimental outcomes are analysed in Section IV. Finally, the concluding remarks are given in Section V.

II. Related Work

There exist several research efforts which have been focused on creating a better system that is flexible, safer, cheaper, easily manageable and more efficient [3], [4], [5]. Decreasing the stand-by power loss can be referred as a way to obtain these desired specifications. Even this loss does not seem very significant in this manner; it affects the system operation and costs, also reduces the efficiency of power supplies and home devices. For realizing these developments, an automatic stand-by power cut-off outlet was developed in the past and thanks to this, the unnecessary costs of home energy were reduced. Further information about the structure of this improved stand-by cut-off can be found in [6]. In order to actualize the communication between the ZigBee Coordinator and a ZigBee RF Module, an MCU was operated with this RF. This model represents star structure features of ZigBee Technology [1]. ZigBee supports peer to peer, star, point to multiple-point, tree and mesh topologies. In star topology, the coordinator takes place in the hub. The other devices communicate with the coordinator from point to point and messaging is done over the coordinator. In tree topology, all the devices communicate to each other in a hierarchical order. The coordinator is located at the highest point of the tree structure. A lower level which resides under the coordinator consists of the rooters, and another rooters and/or end-devices take place at the lowest level in this structure. Mesh topology is the most commonly employed topology for ZigBee applications. In this topology, all devices communicate to each other based on an algorithm. If there is no information about the direction, this algorithm broadcasts a source device route request to the entire network firstly in order to find the location and the direction of the targeted device. Fig. 1 illustrates the scheme of mentioned topologies.

Through the microcontroller measurements, voltage values which lead into power consumption data are calculated and received in the monitoring circuit. Based on these calculated and read information, if the consumption power is lower than the threshold value for a certain time amount, microcontroller changes the plug's situation into stand-by mode and cuts off the energy. To re-energize the plug, a wake-up command must be delivered from the ZigBee Coordinator. This system is basically developed for a simple solution for stand-by power losses by measuring the power and limiting it. Though the structure reaches the goal of loss reduction, it does not offer an adequate solution.

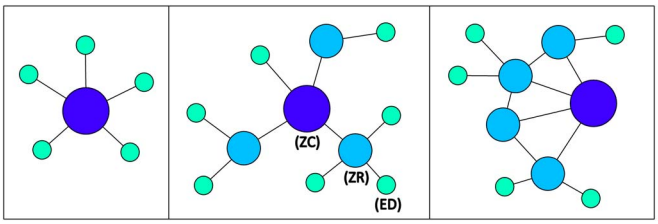

Fig. 1. The star, tree and mesh topologies of ZigBee Protocol, respectively. (ZC: ZigBee Coordinator, ZR: ZigBee Router, ED: End-Device's ZigBee Module)

The equipment of ZigBee Coordinator is required to be adjusted for control and wake-up commands. In [7], Zigbee Coordinator and ZigBee Module based devices were implemented and controlled over a gateway which consists of several switchers for targeted power outlets. These switchers that equipped with IR receivers help to send wake-up commands when pressure is applied to the assigned outlets under the supervision of the ZigBee Coordinator and so, stand-by power efficiency is conducted with a different process.

Home energy management systems (HEMS) offer a good environment to users by arranging the energy usage and managing the plugged devices, and help to reduce the energy consumption [8], [9]. These systems can be equipped with wall screens to display the whole functions and situations of end-devices. Smartphones, tablets, laptops and televisions are also used for monitoring, controlling and optimizing the system so that, internet based applications were conducted recently which provide an online remote control option to its costumers for homes or bigger scale operations.

Although there are several various researches have been devoted to improve energy management systems in home environments, these works are not satisfactory for desired functions and capabilities to the best of our knowledge. Starting from this point, a new energy metering and managing structure is designed, implemented and investigated to heal the drawbacks of related existing proposals which is detailed in Section III.

The common drawback of the existing power metering systems can be defined as follows; user induced problems and failures are may occur due to the fact that management units are placed in user side, which let this systems work as just switching and monitoring gadgets. In SmartPlug, management center was transferred directly to the plug, thus human side was changed as a spectator. Therefore, plugs become actually 'smart' and self-managing equipments. Situations like the single connection delays on the running side or faulty management difficulties can be removed with this proposed re-arrangement.

III. SmartPlug Architecture

This section presents the basic architecture, operation flow, requirements and the possible contributions of SmartPlug. In this manner, the basic structure of internal microprocessor power metering system, namely SmartPlug is demonstrated in Fig. 2. It is composed of 5 main sections which are called Power, Monitoring, Energy Metering, Microcontroller, Relay

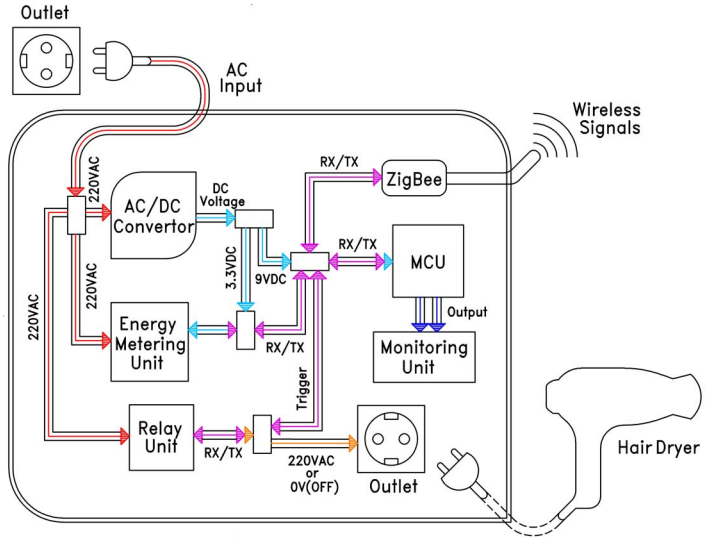

Fig. 2. Connection and flow diagram between main sections of SmartPlug.

and Communication Units.

A. Power and Relay Units

In the first step, Alternating Current (AC) voltage has to be converted into Direct Current (DC). For realizing this goal, Power Unit consists of an AC/DC Converter and sub-equipments inside. Basically, this unit is fed with 220V AC, and the AC/DC Converter converts this voltage into DC to energize the MCU and Energy Metering Unit with 9 and 3.3 voltages, respectively. In this section, there is a transfer connector for sharing 220V AC with Energy Metering Unit and also Relay Unit as shown in Fig. 2. Consequently, Power Unit satisfies energy requirements of the whole circuit.

In Relay Unit, 220V-10A, PCB type single dry contact relay is performed with an opto-isolator, namely MOC3041 which has 6 triac driver outputs that decreases the possible drawbacks of harmonics and high switching currents with the feature of zero crossing. The Relay Unit is triggered with 5V tripping voltage and fed with 15mA. An extra filter is integrated in before the feeding part of the circuit to reduce the voltage rippling and isolation problems. The Relay Unit realizes load switching by following the previously stated orders in software; or in case of instantaneous problems and/or urgent situations, it allows the user to remotely switch devices.

B. Energy Metering Unit

For SmartPlug, a low price energy measurement analog front-end (AFE), namely CS5490 of Cirrus Logic [10] is implemented to perform the measurement duties with a high accuracy. This model has two channels which consist of uncommitted 4^{th} order 24-bit Delta-Sigma Modulators to measure voltage and current values. An EXL signal processing core was placed in the AFE for calculations and measurements of active, reactive and apparent powers, RMS voltage and current, power factor and line frequency, instantaneous power and its constituents. Energy pulses, zero crossing, energy direction and interrupt functions which can be generated for over-currents, voltage sags and swells are provided by an integrated Configurable Digital Output. Another ability of

TABLE I. COMPARISON OF WIRELESS PROTOCOLS

Property \ Tech.	Bluetooth 802.15.1	Wi-Fi 802.11.*b*	ZigBee 802.15.4
Frequency Range	2.402-2.482 GHz	2.40-2.50 GHz	.868, .916, 2.4 GHz
Discrete Ch.	3	3	16
Max Channel Bandwidth	$\simeq 8$ MHz	22 MHz	5 MHz
Modulation	GFSK	CCK/QAM64	QPSK
Nominal Data-Rate	1 Mbps	44 Mbps	90 Kbps
Nominal Range(0 dBm)	10 m	25 m	75 m
Alliance	Bluetooth SIG	WiFi Alliance	ZigBee Alliance
Major Proponents	Sony, CSR, Casio	Cisco, Broadcom	Formerly Philips
Protocol Complexity	Complex	Very Complex	Simple
RF Layer Complexity	Low	High	Med
Sleep Power	8 μW	10 μW	4 μW
RX Power	695 mW	21 mW	120 mW
TX Power	360 mW	14 mW	90 mW
Battery Life	$1-7$ (Days)	$0.5-5$ (Days)	$100-1000$ (Days)
Optimized For	Low Cost, Convenience	Speed	Reliability, Low Power, Low Cost
Network Architecture	Star	Star	Star, Cluster Mesh
Nodes/Master	7	32	64000
Security	64, 128 Bit	SSID	128 Bit AES
Ease of Use	Normal	Hard	Easy

CS5490 is to support a wide range of voltage and current sensors, shunt resistors and current transformers which have been employed in this project. Energy Metering Unit is created based on this AFE and for energizing that, a single 3.3V power supply, which is provided from Power Unit, is required, and it consumes less than 13mW in progress. With these unique characteristics, CS5490 stands as the most suitable chip for energy metering unit.

C. Microcontroller and Communication Units

In order to manage the whole circuit in every single step, an MCU needs to be utilized to satisfy project's requirements. In addition to this, having easy to use compiler, programmer and simulator, high current and voltage carrying capabilities, low price, diversity of command sets are also significant features for the performance of microcontroller. Atmega series micro-controllers can satisfy the features what is mentioned above, undoubtedly. In this manner, SmartPlug is developed based on MCU of 8 bits 32k memory Atmega328 [2]. Atmega328 was coded over Arduino platform with using Arduino compiler. For actualizing this, Arduino Uno boot-loader was loaded in the memory of optiboot structured Atmega328. However, the coded MCU was performed independently from Arduino Uno and integrated in managing part of the circuit. Arduino Software was conducted to manage the system and design the human-machine interface for SmartPlug. Atmega328 uses a watch dog timer and a brown out detector to decreases the negative effects of electrical corruptions. This microcontroller is in interact with the relay, communication, metering and monitoring units continuously. It provides reading and evaluation for the taken data and operates this data transfer in required situations over ZigBee based wireless module

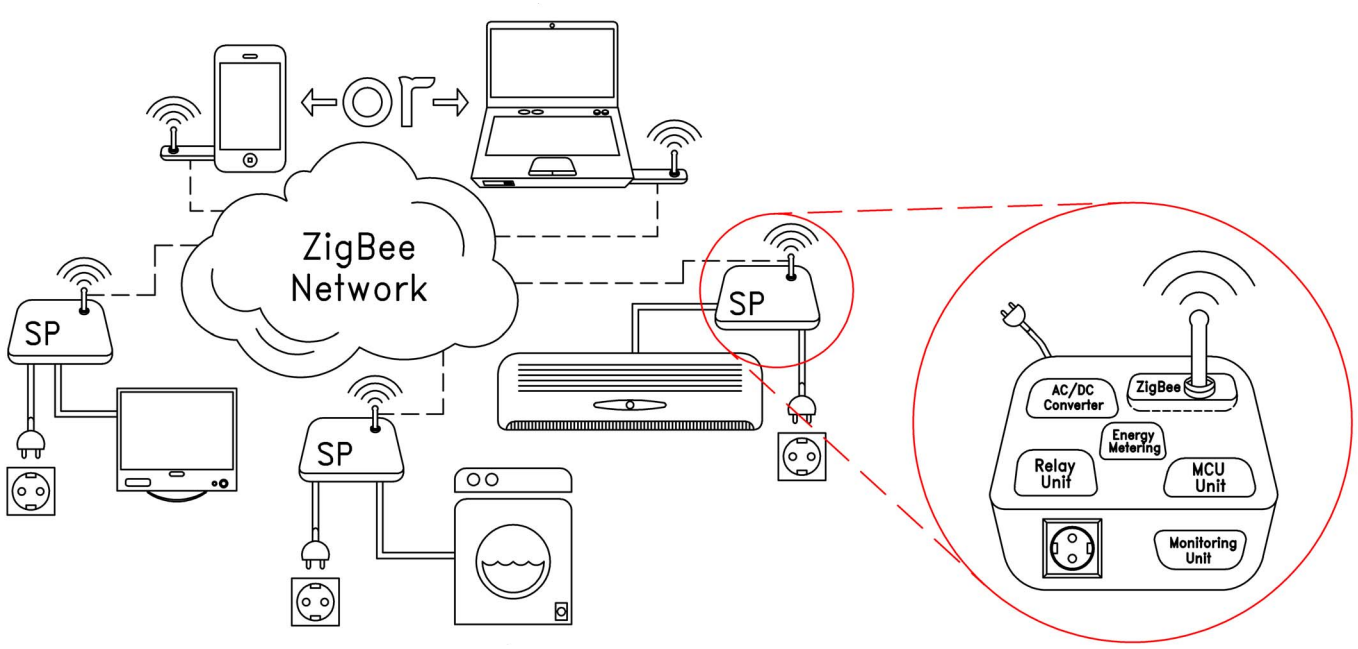

Fig. 3. SmartPlug operation in a ZigBee Network.

which helps remote control of the SmartPlug during operation. In this manner, the MCU takes the user's commands over this module and operates them. ZigBee based this operation scheme is depicted in Fig. 3. Any device that is energized over SmartPlug can be controlled with varied personal gadgets such as laptops and/or smartphones. Unlike the HEMS, the user can take SmartPlugs out of the system and add them into another network. This feature offers a flexible usage opportunity to control targeted devices in desired environments and purposes. On the other hand, the reading and evaluation of energy metering data that are sent from the output ports of the integrated equipment of Cirrus CS5490 are realized again on the Atmega microcontroller. Thus, consumed energy and all energy components are measured. At the same time, the processed data are transferred to user over XBee module under the supervision of Atmega MCU. ZigBee basically uses digital radios that permit the tools communicate with others. A ZigBee Network supports three kind of devices, namely Full Function Device (FFD), Reduced Function Device(RFD) and the Network Coordinator [1]. Every network must contain a network coordinator. The network coordinator bewares of every nodes and their connections, also manages all transmitted or received data in every step of the communication. Several FFDs can be placed in the network and they support the whole 802.15.4 functions. These gadgets serve to every coordinators, rooters or the all endpoints which are connected to the physical world. However, RFDs serve only the end-devices/points.

Another significant function of SmartPlug is to control the relay which provides the user with the opportunity to manage the connected devices. Thanks to the relay unit, end-devices can be switched and controlled based on the user command upon the immediate requirements.

These factors indicate the necessity of an integrated MCU for a better energy metering and control system. So that, Atmega328 is used as an economic and practical solution to perform the desired work.

As seen in Fig. 2, a hair dryer was used as a reagent for testing the basic abilities of SmartPlug. SmartPlug obtained instantaneous current, voltage and active power values in the first attempt. These are the main and desired measurements of performed CS5490 in small areas, and the rest of the abilities can be implemented up to user's request and required applications. Besides these measurements, undesired stand-by powers were cut off thanks to SmartPlug. Preventing this consumption of redundant energy provides a more efficient and cost-effective energy system. Moreover, transferring MCU inside the power meter reduces the number of human-based problems and creates a healthier structure, inevitably. This self-management system helps to decrease the amount of redundant energy which will be used to fix wrong order operations and its results.

Considering that energy is not priced equally for each hour of the day, operation times have to be arranged. With the conducted algorithms, any device with high energy consumption can be energized when the unit price of energy is cheaper. These consumption scheduling and stand-by power cutting off operations contribute to the energy management. Additionally, harmful effects caused by voltage fluctuations, instant drops or raises are prevented, and safer environment is offered to the user.

IV. Performance Evaluation

A ZigBee and integrated MCU based power metering and managing system has been implemented in this SmartPlug. According to the desired design, there is no rear-end processing unit to interfere with the power meter continuously by the user. This unit has been shifted inside the plug to reduce the number of human oriented problems during the operation time. Therefore, the user is not able to code the MCU remotely, and he/she just remotely monitors the plugged device with a ZigBee module that is mounted on a shield. The user's authorities are restricted; however, he/she can switch the plug

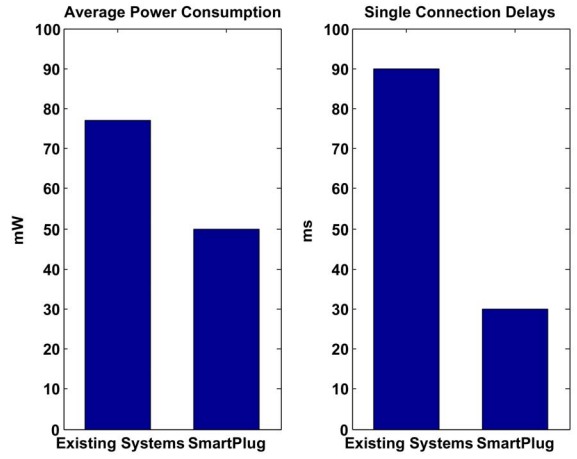

Fig. 4. Comparison of SmartPlug and the existing power metering systems in terms of average power consumption and single connection delay.

in case of sudden and urgent situations, monitor and control the conducted tasks and status informations of the whole system. Thanks to this implementation, a major part of human oriented errors in automation systems are resolved, but unfortunately, there is no way to present a plot of this unmeasurable metric.

At first glance, although the network structure seems like the star topology, it works a bit different because of the relocaiton. Due to the fact that the user side has not an external processing unit, writing commands are conducted by a cable for once before the process, and this reduces the coding and connection delays in operation. Normally, the coordinator and the RF have to be in interaction to send and read data, continuously. These connecting and sharing operations are realized one by one in connected devices by 64-bit addresses. Thus, every end-device needs a processing time for connection, reading-writing and approval before the coordinator leaves and connects to another device. In operation, this causes a chain delay in the network with the addition of writing command faults and the other unexpected matters. Because of these delays, managing process is interrupted and the efficiency of the system is reduced. In order to prevent these delays, the conventional system has been changed, and Fig. 4 represents the improvements of new power meter and managing system in power consumption and single connection delay. Hourly measurements show that, the power consumption is reduced to stand-by levels approximately and delays decreases to one-third of standard values in operation.

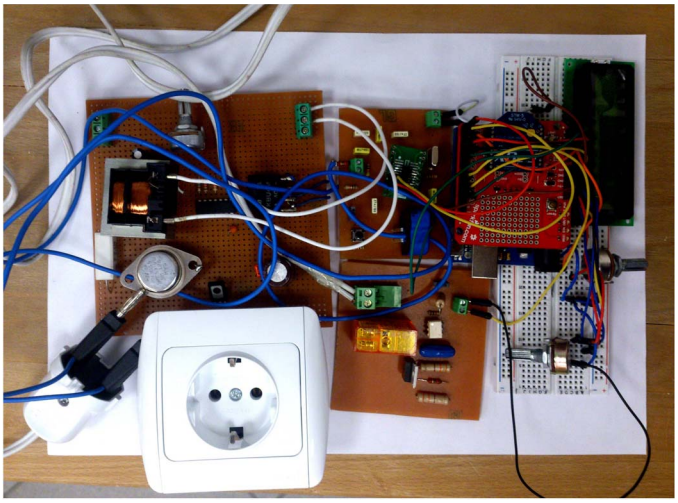

Fig. 5. The demonstration of individual parts of SmartPlug.

V. Conclusion

In this work, a new power meter system based on ZigBee technology has been designed and implemented to obtain a more efficient structure and reduce the number of negative sides of the existing technologies. In this proposed structure, the MCU was moved into the plug from outer environment, and this caused to compose of 'smart' meters that self manage according to previously provided software. With this substitution, the host becomes a spectator, and this allows the user based faults and/or problems are nearly vanished. Bypassing the human factor ensured a better system which is secured from the possible losses and redundant usage of the power. The other security enhancement is that, detecting the sudden voltage fluctuations and preventing the possible damages of end-devices which can be caused by drops and jumps. In addition to these, we validated that cutting of stand-by powers and limiting the energy consumption by arranging the working hours of devices based on energy unit prices provide efficient, right and cheap usage of the energy, consequently. As a result, average power consumption is roughly decreased to stand-by levels and single connection delays reduced to one-third in operation with SmartPlug. Taking all of these into consideration, we believe that the proposed SmartPlug is a efficient solution for energy metering, monitoring and controlling.

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