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Technical, Qualitative and Energy Analysis of Wireless Control Modules for Distributed Smart Home Systems

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Abstract: Distributed smart home systems using wireless communication are increasingly installed and operated in households. Their popularity is due to the ease of installation and configuration. This paper presents a comprehensive technical, quality, and energy analysis of several popular smart home modules. Specifically, it focuses on verifying their power consumption levels, both in standby and active mode, to assess their impact on the energy efficiency of building installations. This is an important aspect in the context of their continuous operation, as well as in relation to the relatively lower power of loads popular in buildings, such as LED lighting. The author presents the results of measurements carried out for seven different smart home modules controlling seven different types of loads. The analysis of the results shows a significant share of home automation modules in the energy balance; in particular, the appearance of reactive power consumption due to the installation of smart home modules is noteworthy. Bearing in mind all the threads of the analysis and discussion of the results of measurement experiments, a short SWOT analysis is presented, with an indication of important issues in the context of further development of smart systems and the Internet of Things with wireless communication interfaces, dedicated to home and building applications.

Keywords: smart home; building automation; energy efficiency; internet of things

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1. Introduction

The last decade has been a period of dynamic digitization of building infrastructure objects and common-use devices used in houses, buildings, and industry. Based on these processes, the technology of distributed monitoring and control networks as well as the concepts of the Internet of Things (IoT) are implemented in many areas, one of which is home and building automation systems [1–3]. As a result, numerous technologies, modules, and controllers offering solutions and functions dedicated to smart home systems have appeared on the market. In addition, various research and development works are carried out to develop new, universal system platforms that support the implementation of intelligent solutions and functions at the level of households, flats, apartments, and utility facilities [4–6]. Most of them focus primarily on the possibility of improving the comfort and ease of use of increasingly complex and technically advanced building infrastructure devices. The second important development trend of home and building automation is the possibility of using their devices and functions in the management of electrical energy and other energy media in houses and buildings. They can also be used to control various loads in households to improve the energy efficiency of these facilities, from the perspective of the renewable energy sources' (RES) implementation with mechanisms and solutions for smart grids [7,8].

One of the technical solutions gaining popularity in recent years are the basic modules of the "smart home for everyone" class, available in stores with household appliances and electronics. They are dedicated to easy installation in houses, apartments, and offices, using mostly wireless communication within Wi-Fi networks and parametric configuration using a smartphone or tablet. Products of this class are offered by various manufacturers, and even as "no name", and willingly purchased by users who want to introduce "smartness" to their homes and buildings at a low cost. At the same time, it is an opportunity to popularize the idea of automation and intelligent solutions in buildings, but also a threat to the spread of cheap, uncertified devices affecting the building's power supply network and causing additional power consumption [9–12].

However, in the research and implementation activities related to home and building automation, the issue of the power and energy consumption of the automation modules themselves and the system infrastructure required for them is almost completely ignored. Meanwhile, these devices are characterized by low but constant power consumption during the building operation, which can be significant, especially for large, complex automation systems (scale effect). Therefore, in this paper, the author focuses on these aspects, providing a comprehensive technical, qualitative, and energy analysis of these types of home automation modules, in the context of their use in basic control and switching on and off functions for popular electrical loads used in households.

1.1. Related Work

Research and engineering works on the development and technical verification of smart home modules generally focus on two aspects: (i) analyzing the possibilities of reducing energy consumption by wireless battery-operated modules and (ii) ensuring high comfort of use—safe and reliable data transmission for basic control or monitoring functions. These two aspects are the most important for the effective and safe implementation of intelligent solutions based on the concept of distributed networks and IoT in households. In the organization of smart home systems, many different technical solutions and wireless methods of communication between network nodes, sensors, actuators, and controllers are used.

In [13], Hassan M. et al. point out several technical concepts for smart homes based on different wireless communication techniques, such as the Global System for Mobile (GSM), ZigBee, Bluetooth, and Wi-Fi. Moreover, in [2,3,14], the Bluetooth Low Energy (BLE), Z-Wave, as well as Long-Range Wide-Area Network (LoRaWAN) techniques are added. The authors of these publications discuss the reliability of data communication and the range of the radio signal, ensuring the comfort of using smart home systems. All results indicate the best performance in the case of Wi-Fi (the largest range) and ZigBee, but at the cost of much higher power consumption by the communicating modules. According to the results presented in [2], the power consumption for modules with Wi-Fi communication can be even several times higher than in the case of ZigBee and Z-Wave communication, the range of which is about 30% lower. However, it is the systems based on Wi-Fi technology that are currently gaining the greatest popularity, primarily due to the universality of access to this communication technique in homes and public utility buildings. In this way, the implementation of the smart home system does not require the installation of additional communication infrastructure, and it is possible to easily integrate home and building automation devices with other elements of their infrastructure using a wireless Ethernet/Internet connection.

Therefore, to improve the energy efficiency of smart home modules, while maintaining their ease of integration and operation, the possibilities of organizing hybrid systems are also analyzed, using various techniques and protocols of wireless and wired communication, depending on the needs of the application (communication in one room, in several rooms, communication between building floors, etc.). For instance, in [15], Filho G. et al. propose several different variants of the organization of the communication network for smart home and IoT systems in buildings, along with an indication of the paths of decision-making procedures necessary in the design of the communication network. The procedures should specifically consider: (i) energy efficiency in relation to the dynamics of the wireless network topology and multipath propagation, (ii) the importance and requirements of real-time communication (e.g., in critical applications, security, etc.), and (iii) the standardization of data protocols between wired and wireless devices as well as interoperability with other backbones (multi-level networks in larger buildings). Considering these aspects and innovative topology approaches, an advanced IoT-based electrical consumption measurement system for smart homes has been proposed and analyzed in [9]. The authors focused on integration of the most popular communication techniques based on the TCP/IP protocol, both wireless and wired, using different devices dedicated to smart home systems.

Detailed energy consumption and performance analysis for IoT nodes with both wired and wireless mediums in smart home automation has been performed in [6,16]. In these publications, the possibilities of using single-board microcontrollers and computers (Arduino, Raspberry Pi) and their various operating modes in supporting universal automation functions, along with the possibility of their integration in distributed smart home networks, were verified. It was concluded that the proposed framework extends the existing communication technologies to a new level, introducing edge-based data processing enabling the low-cost computation to the IoT smart networks. The working prototype proposed in [6] is efficient in terms of energy consumption, response time, data processing, and bandwidth use. However, the issue of data security in these types of networks, in particular those with distributed and hybrid architectures, should not be forgotten. Some of them are discussed in [12,17], where innovative methods of data encryption and network attacks' detection are indicated by the authors, considering technical and power consumption aspects to provide secure data transmission among several integrated sensor and actuator nodes in the IoT smart home network over a long convergence range.

There are only a few publications focused on the energy efficiency of smart home systems and their sensors and controllers, both battery-operated as well as main-powered. One of them is in [18], where Krauchi P. et al. discuss the energy consumption of building automation for several real constructed buildings equipped with different designs of building automation systems (BAS) and diverse products. Moreover, the analysis of energy consumption considers different types of building infrastructure subsystems (different loads) controlled by actuators and sensors within the BAS system. Therefore, the BAS energy consumption results presented in the paper assume values from 2 to 5 kWh/m^2 per year. The authors point to this relationship, but they provide only a general discussion of the energy consumption levels for smart home/building automation systems, without a broader analysis of its connection with the type of controlled loads, subsystems.

1.2. Contributions

Bearing in mind the variety of technologies and development trends of smart home modules and IoT network nodes, in this paper, the author decided to conduct and describe a comprehensive technical, energy, and qualitative analysis of the operation of wireless smart home modules offered on the market. Modules performing simple on/off functions of single-phase circuits, supplying loads used in buildings, such as lighting, fans, and heating elements, were selected for the measurements. The experiments considered various technical constructions of smart home modules (different types of microcontrollers, different designs of actuators—relays) with Wi-Fi and ZigBee wireless communication, powered directly from single-phase 230 VAC circuits. Battery-powered modules have not been tested. The energy analysis focused on verifying the levels of active and reactive power consumption by the selected smart home modules. The uniqueness of the analysis, however, lies in the fact that a series of measurements was carried out with various types of loads controlled by the modules, which translated into the changing nature of the electrical circuits controlled by the smart home modules and directly affected the levels of power consumed by them. Therefore, in the next stage of the analysis, a series of measurements of selected energy quality parameters was performed, including the verification of the potential impact of the controlled loads on the quality and parameters of the building's power supply network. The results of the energy and technical analyses also referred to the parameters related to the quality of wireless communication between smart home modules located in different parts of the building and at various distances from each other during the transmission of control signals.

The remainder of this paper Is organized as follows: In Section 2, the measurement stand is described and the technical data for all smart modules verified in the experiments are presented. There is a short section with information about loads as well. Next, Section 3 presents the results of the experiments with short analyses of correlations between them. A discussion of the results is provided in Section 4, and then Section 5 presents the conclusions and future works.

2. Materials and Methods

For the purposes of this paper, the author decided to conduct an energy analysis of the operation of several popular smart home modules dedicated to easily configured wireless installations. These are commercial products, available on the market at affordable prices, addressed to a wide range of users of electrical installations and devices in houses, flats, and apartments [19]. For the measurements of the power and energy consumption of these modules, the classic room of the didactic laboratory was selected, without special environmental conditions. These were the basic assumptions in the organization of the measurement procedures.

2.1. Mesurement Stand

A dedicated test stand was prepared to carry out the measurements, enabling testing of the operation of individual smart home modules (with various types of connections to controlled circuits and devices). In addition, at the stand, it was necessary to provide contacts for connecting the voltage clips and current clamps of the measuring device—the Sonel PQM-711 analyzer (producer Sonel S.A., Świdnica, Poland). Figure 1 shows a diagram of the electrical connections at the measurement stand, with an example of connecting the Sonel PQM-711 analyzer to measure one of the smart home modules—Blebox Switchbox. This module, together with Sonoff ZBMINI, Sonoff Basic R2 (producer Sonoff, Shenzhen, GD, China), and Shelly 1 (producer Shelly Group, Sofia, Bulgaria), was connected to Socket 1, to which the individual loads visible at the bottom of Figure 1 were connected one-by-one during the measurements. In turn, the Sonel PQM-711 analyzer was switched to subsequent circuits supplying the aforementioned modules. Subsequent modules of the controlled sockets—Sonoff, Tplink, and Gosund—were connected to Sockets 2 and 3 during the measurements, and the Sonel PQM-711 analyzer was switched to the circuits supplying those sockets.

Measurements of all other smart home modules visible in the diagram (presented in Section 2.2) were carried out in accordance with the connection of the voltage clips and current clamps of the analyzer indicated in the diagram for the Blebox Switchbox module.

Additionally, the real view of the stand during the measurement of another smart home module—Shelly 1 Switch—is shown in Figure 2.

It should be noted that on the measurement stand itself, as well as in the vicinity of the modules and the stand, no additional shields (separate protections against the impact of external signals and disturbances generated by electrical devices or the modules themselves) were used. Conditions such as those in the real applications in which such modules work in home and building installations were consciously maintained. Measurements were performed in the rooms of the AutBudNet AGH building automation systems laboratory [20].

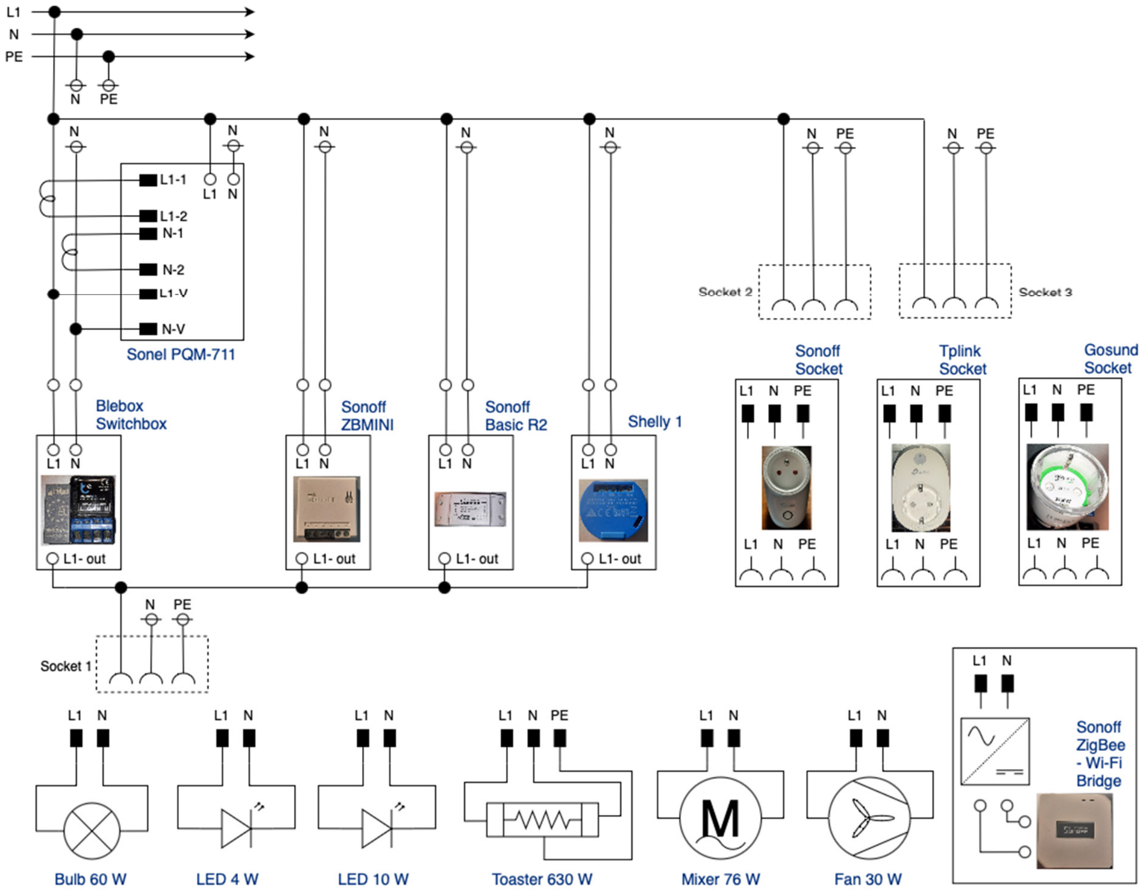


Figure 1. An electrical connection diagram on the measuring stand, with the Sonel PQM-711 analyzer connected to measure one of the smart home modules—Blebox Switchbox.

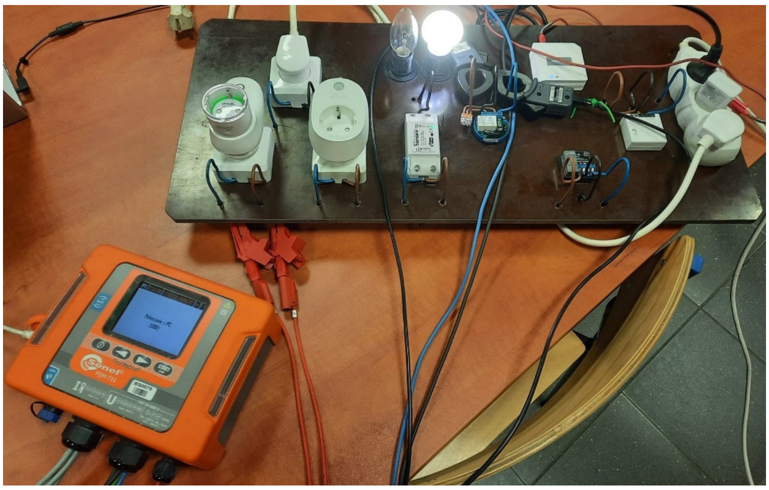


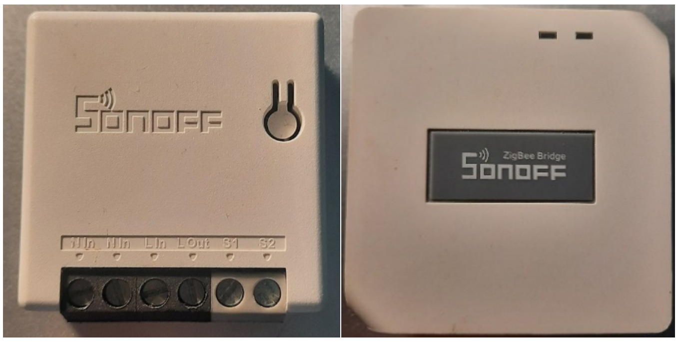
Figure 2. Real view of the measurement stand during the measurement procedure.

2.2. Selected Smart Home Modules

A representative group of various smart home modules offered by different manufacturers was selected to carry out the measurements. The dominant wireless communication technology of these modules is Wi-Fi, and one of the modules has a ZigBee wireless interface. Below are the brief technical specifications of the modules used in the experiments.

2.2.1. Sonoff ZBMINI Switch

The Sonoff ZBMINI module shown in Figure 3a is powered by 100–240 VAC with a frequency of 50/60 Hz. Device communication is based on the ZigBee IEEE 802.15.4 standard with a frequency of 2.4 GHz. The signal is secured by WPA/WPA2. The module is managed by the microcontroller MCU CC2652P and controls the GOLDEN GN-1A-5L relay with a coil switched on by 5 VDC. The maximum current load of the contacts is 10A at 250 VAC. The contact activation time is 15 ms. The Sonoff ZBMINI module communicates with external servers using the ZigBee–Wi-Fi bridge (Figure 3b). It requires an additional 230 AVC to 5 VDC power supply.



(**a**) (**b**)

Figure 3. The Sonoff devices: (**a**) Sonoff ZBMINI switch module and (**b**) ZigBee–Wi-Fi bridge.

2.2.2. Sonoff Socket

The Sonoff Socket S26R2TPE-FR module shown in Figure 4 is powered by 100–240 VAC with a frequency of 50/60 Hz. Device communication is based on the IEE 802.11 b/g/n Wi-Fi standard with a frequency of 2.4 GHz. The signal is secured by WPA/WPA2. The module is managed by the microcontroller ESP8266EX and controls the GOLDEN GI-1A-5L relay with a coil switched on by 5 VDC. The maximum current load of the contacts is 10 A at 250 VAC. The contact activation time is 10 ms.

(**a**) (**b**)

Figure 4. The Sonoff Socket module: (**a**) front view and (**b**) rear view.

Both Sonoff ZBMINI and Sonoff Socket modules are configured and controlled by the WeLink application for the Sonoff system from a smartphone (Android or iOS).

2.2.3. Sonoff Basic Switch

The Sonoff Basic R2 module shown in Figure 5 is powered by 100–240 VAC with a frequency of 50/60 Hz. Device communication is based on the IEE 802.11 b/g/n Wi-Fi standard with a frequency of 2.4 GHz. The signal is secured by WPA/WPA2. The module is managed by the microcontroller ESP8285 and controls the GOLDEN GI-1A-5L relay with a coil switched on by 5 VDC. The maximum current load of the contacts is 10 A at 250 VAC. The contact activation time is 10 ms. However, the Sonoff Basic R2 module has been loaded with software that is managed via the Supla system [21]. It is a Polish project developed on the principles of open-source software and open hardware. This module is configured and controlled by the Supla application from a smartphone (Android or iOS).

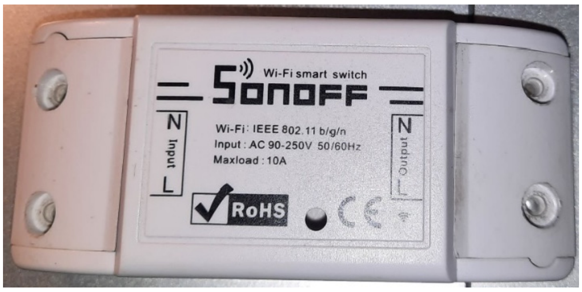


Figure 5. The Sonoff Basic module with the Supla software WiFi Smart Switch DS18B20 v2.0 implemented.

2.2.4. Shelly 1 Switch

The Shelly 1 switch module shown in Figure 6a is powered by 100–240 VAC with a frequency of 50/60 Hz or 24–60 VDC/12 VDC. Device communication is based on the IEE 802.11 b/g/n Wi-Fi standard with a frequency of 2.4 GHz. The module supports the HTTP and UDP protocols. It is managed by the microcontroller ESP8266EX and controls the HF7520 012-HSTP relay with a coil switched on by 5–48 VDC. The maximum current load of the contacts is 16 A at 250 VAC. The contact activation time is 10 ms. This module is configured and controlled by the Shelly Cloud application dedicated to the Shelly smart home system from a smartphone (Android or iOS).

(**a**) (**b**)

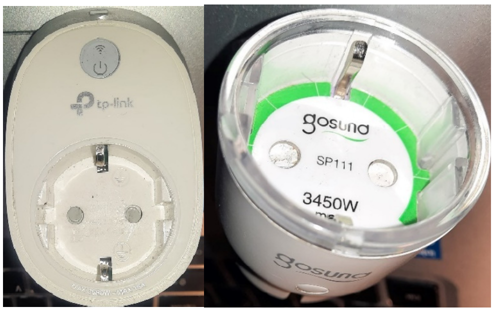
Figure 6. Smart home switch modules: (**a**) Shelly 1 and (**b**) Blebox Switchbox.

2.2.5. Blebox Switchbox

The Blebox Switchbox module shown in Figure 6b is powered by 230 VAC with a frequency of 50 Hz. Device communication is based on the IEE 802.11 b/g/n Wi-Fi standard with a frequency of 2.4 GHz. The signal is secured by WPA/WPA2. It controls the Relpol RM85 relay with a coil switched on by 24 VDC. The maximum current load of the contacts is 16 A at 250 VAC. The contact activation time is 8 ms. This module is configured and controlled by the wBox application for the Blebox system from a smartphone (Android or iOS).

2.2.6. Tplink Socket

The tplink HS110 Socket module shown in Figure 7a is powered by 100–240 VAC with a frequency of 50/60 Hz. Device communication is based on the IEE 802.11 b/g/n Wi-Fi standard with a frequency of 2.4 GHz. The module is managed by the microcontroller Atheros AR9331-AL3A and controls the WRG RB-105DMF5 relay with a coil switched on by 3.85 VDC. The maximum current load of the contacts is 16 A at 250 VAC. The contact activation time is 20 ms. This module is configured and controlled by the Kasa Smart application for the smart home system by tplink from a smartphone (Android or iOS).



(**a**) (**b**)

Figure 7. Smart home socket modules: (**a**) tplink and (**b**) Gosund.

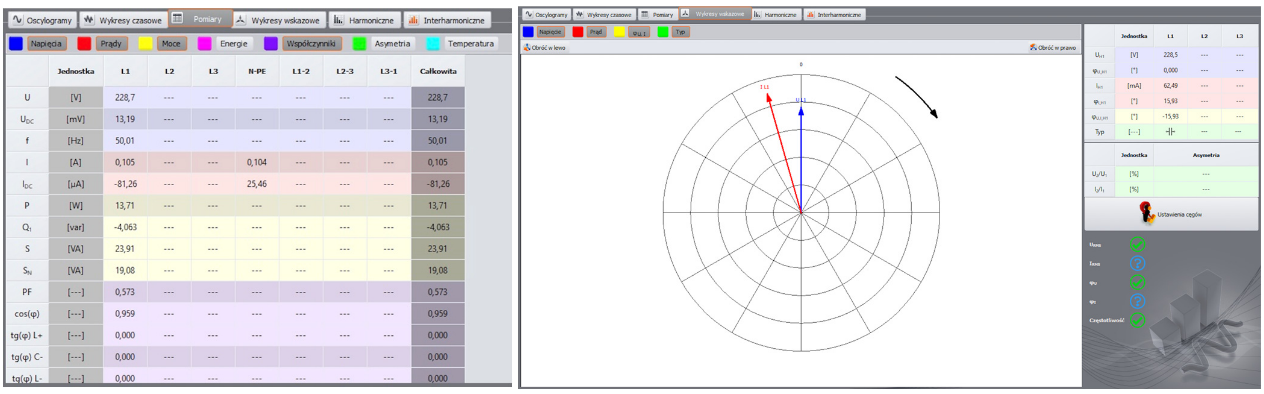
2.2.7. Gosund Socket

The Gosund S111 Socket module shown in Figure 7b is powered by 230 VAC with a frequency of 50 Hz. Device communication is based on the IEE 802.11 b/g/n Wi-Fi standard with a frequency of 2.4 GHz. The module is managed by the microcontroller ESP7285 and controls the HF7520 relay with a coil switched on by 5–48 VDC. The maximum current load of the contacts is 16 A at 250 VAC. The contact activation time is 10 ms. This module is configured and controlled by the Gosund application for the smart home system Gosund from a smartphone (Android or iOS).

2.3. Measurement Unit and Measurment Data Aqusition

The Sonel PQM-711 (orange measurement unit shown in Figure 2) versatile power quality analyzer for remote analysis in the A class is a device suitable for use on all types of networks, with a rated voltage range from 110 V to 1000 V either directly or indirectly through transformers. Based on advanced technology, the Sonel PQM-711 power quality analyzer allows comprehensive measurement, analysis, and recording of 50/60 Hz power network parameters and power quality according to the European standard EN 50160 [22].

All data gathered during the experiments were recorded in the form of logs with a time stamp, the required values, and measurement units. Data were observed and recorded using dedicated Sonel Analysis software. This application is delivered as a standard accessory, indispensable for working with PQM-series analyzers. Then, data logs were processed and analyzed in MS Excel sheets, along with the necessary calculations and chart generation. Figure 8 shows exemplary views of the window for the observation and recording of measurement data from the Sonel PQM-711 analyzer.



(**a**) (**b**)

Figure 8. Sonel Analysis 4 software (screenshot with the Polish interface and numbers in European nomenclature): (**a**) measurement data and (**b**) phasor chart.

3. Results

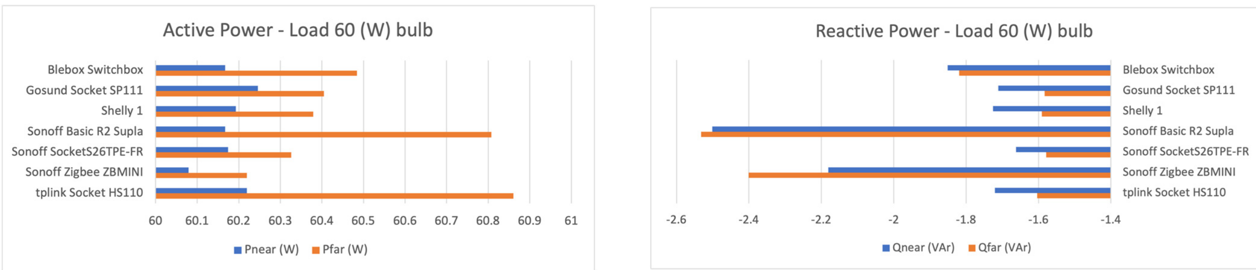
Using the measurement stand described in Section 2, a series of measurements of operating parameters was carried out for all smart home modules indicated in Section 2.2. They were carried out separately for each module, in particular focused on a thorough verification of the levels of instantaneous active and reactive power consumed by smart home modules. Moreover, those measurements were carried out for various types of electrical loads commonly used in electrical installations in houses and buildings and usually desired and considered by their users in load-switching control scenarios. The following electrical loads were used:

- Classic bulb, 60 Watt
- LED lamp, 4 Watt
- LED lamp, 10 Watt
- Room fan, 30 Watt
- Kitchen mixer, 76 Watt (high-speed mode)
- Toaster, 630 Watt

In addition, operating parameters and powers for smart home modules operating without loads were also analyzed. Modules were provided with the required power supply, and the states of switching on (maintaining relay contacts closed) and switching off were successively analyzed to verify the minimum power consumption of these modules during operation, after they were connected to the electrical installation of the house/building.

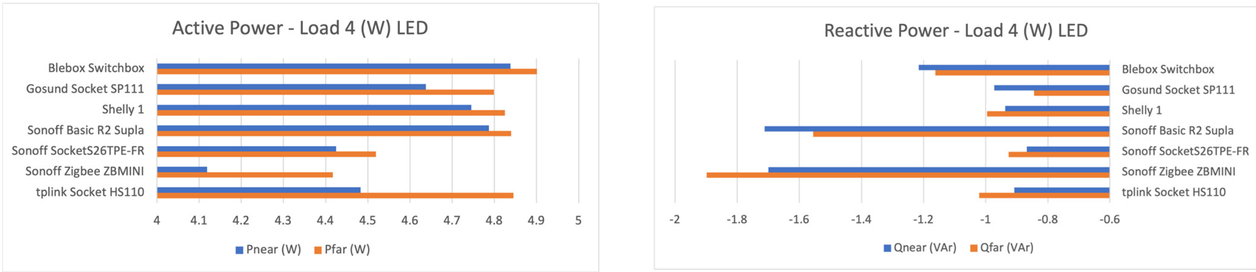
3.1. Active and Reactive Power Measurements

First, for all smart home modules described in Section 2.2, measurements of instantaneous active and reactive power consumption were carried out with the loads switched on. The measured values indicate the total level of active and reactive power consumption, for both the load and the smart home module itself. Measurements were carried out for two cases: (i) the smart module located close to the Wi-Fi access point/router—maximum distance up to 5 m, and (ii) the smart module located far from the Wi-Fi access point/router—distance from 20 m up to a maximum of 22 m. Active and reactive powers are marked P_{near}, P_{far}, Q_{near}, and Q_{far}, respectively. The measurement results in the form of graphs are shown in Figures 9–15.



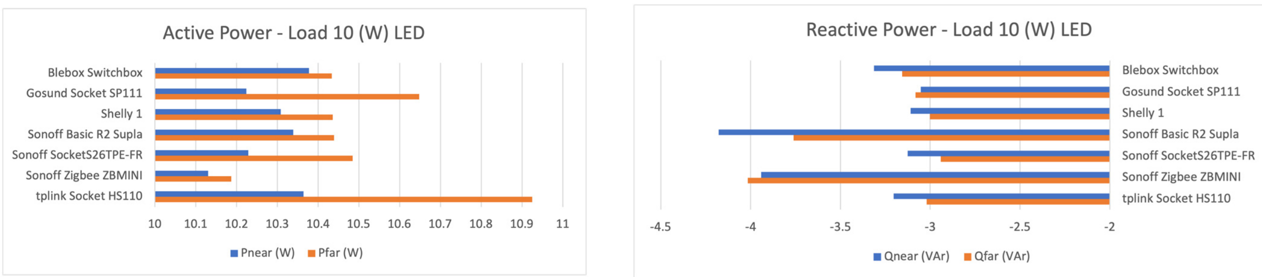
(**a**) (**b**)

Figure 9. Graphs of instantaneous power consumption levels for the classic bulb, 60 Watt load: (**a**) active power of smart home modules + load and (**b**) reactive power of smart home modules + load.



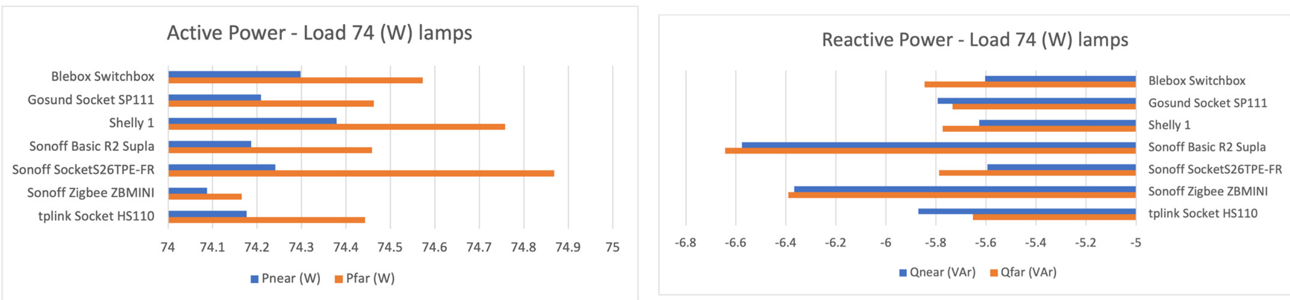
(**a**) (**b**)

Figure 10. Graphs of instantaneous power consumption levels for the LED lamp, 4 Watt load: (**a**) active power of smart home modules + load and (**b**) reactive power of smart home modules + load.



(**a**) (**b**)

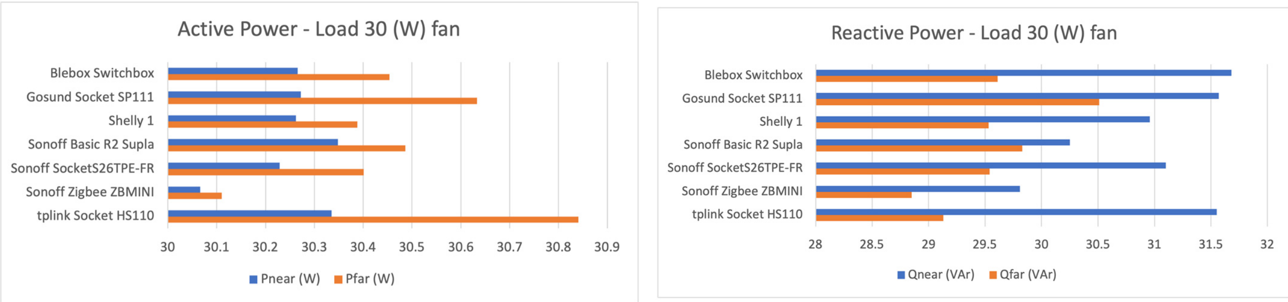
Figure 11. Graphs of instantaneous power consumption levels for the LED lamp, 10 Watt load: (**a**) active power of smart home modules + load and (**b**) reactive power of smart home modules + load.



(**a**) (**b**)

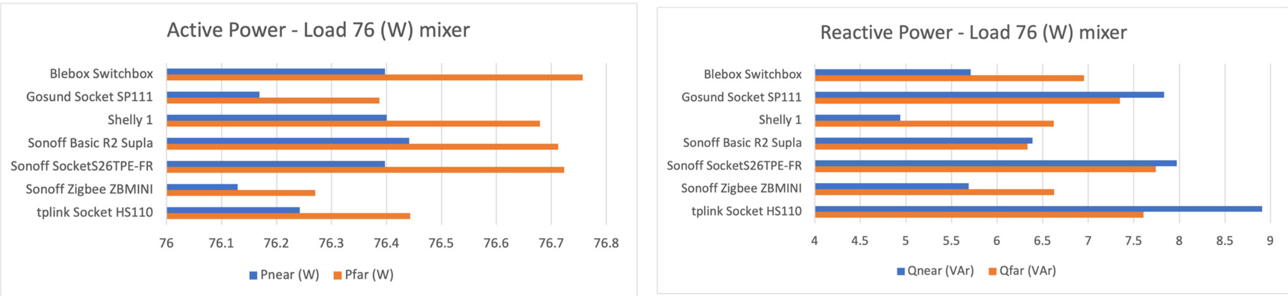
Figure 12. Graphs of instantaneous power consumption levels for series-connected classic bulb 60 Watt + LED lamp 4 Watt + LED lamp 10 Watt: (**a**) active power of smart home modules + loads and (**b**) reactive power of smart home modules + loads.

In turn, the results of instantaneous power measurements for smart home modules without loads are summarized in Tables 1–4. The location of the modules near and far from the Wi-Fi access point/router and the activation and deactivation of the relays were considered during the measurement procedures.



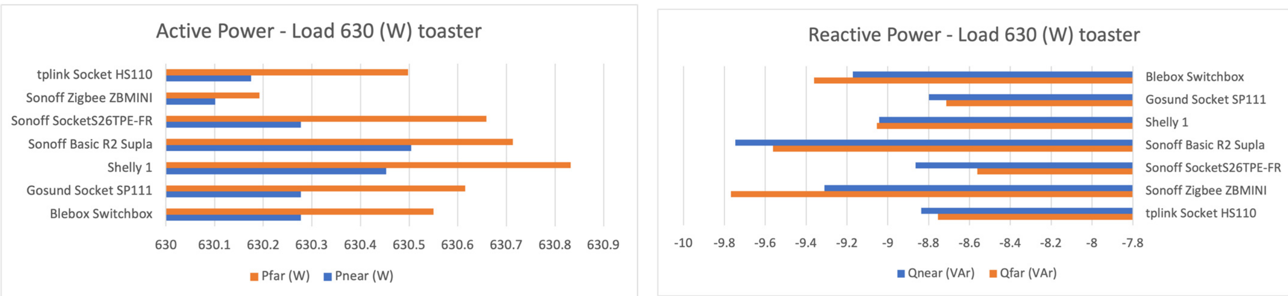
(**a**) (**b**)

Figure 13. Graphs of instantaneous power consumption levels for the 30 Watt room fan load: (**a**) active power of smart home modules + load and (**b**) reactive power of smart home modules + load.



(**a**) (**b**)

Figure 14. Graphs of instantaneous power consumption levels for the kitchen mixer, 76 Watt load: (**a**) active power of smart home modules + load and (**b**) reactive power of smart home modules + load.



(**a**) (**b**)

Figure 15. Graphs of instantaneous power consumption levels for the 630 Watt toaster load: (**a**) active power of smart home modules + load and (**b**) reactive power of smart home modules + load.

Table 1. Instantaneous active and reactive power consumption levels of smart home modules—module located close to the Wi-Fi access point/router, with the relay switched on.

Module	P_{near_ON} (W)	Q_{near_ON} (VAr)
Blebox Switchbox	1.010	−0.259
Gosund Socket S111	0.722	−0.106
Shelly 1	0.744	−0.025
Sonoff Basic R2 Supla	1.172	−0.720
Sonoff Socket S26R2TPE-FR	0.680	0.045
Sonoff ZigBee ZBMINI	0.140	−0.402
tplink Socket HS110	1.094	−0.043

Table 2. Instantaneous active and reactive power consumption levels of smart home modules—module located far from the Wi-Fi access point/router, with the relay switched on.

Module	P_{far_ON} (W)	Q_{far_ON} (VAr)
Blebox Switchbox	1.053	−0.095
Gosund Socket S111	0.750	0.160
Shelly 1	0.846	0.035
Sonoff Basic R2 Supla	1.298	−0.730
Sonoff Socket S26R2TPE-FR	0.821	0.119
Sonoff ZigBee ZBMINI	0.517	−0.692
tplink Socket HS110	1.289	0.030

Table 3. Instantaneous active and reactive power consumption levels of smart home modules—module located close to the Wi-Fi access point/router, with the relay turned off.

Module	P_{near_OFF} (W)	Q_{near_OFF} (VAr)
Blebox Switchbox	0.795	−0.176
Gosund Socket S111	0.427	0.006
Shelly 1	0.535	−0.031
Sonoff Basic R2 Supla	0.578	−0.590
Sonoff Socket S26R2TPE-FR	0.470	−0.017
Sonoff ZigBee ZBMINI	0.069	−0.881
tplink Socket HS110	0.485	0.033

Table 4. Instantaneous active and reactive power consumption levels of smart home modules—module located far from the Wi-Fi access point/router, with the relay turned off.

Module	P_{far_OFF} (W)	Q_{far_OFF} (VAr)
Blebox Switchbox	0.814	−0.027
Gosund Socket S111	0.707	0.155
Shelly 1	0.600	0.137
Sonoff Basic R2 Supla	0.592	−0.701
Sonoff Socket S26R2TPE-FR	0.559	0.148
Sonoff ZigBee ZBMINI	0.252	−0.872
tplink Socket HS110	0.673	0.298

For the collected data, the levels of additional active power, P_{add}, consumed by the modules at their distance from the Wi-Fi access point/router (P_{far}) were calculated in relation to the power consumed in a close location (P_{near}), according to the relation:

$$P_{add} = P_{far} - P_{near} \text{ [W]} \tag{1}$$

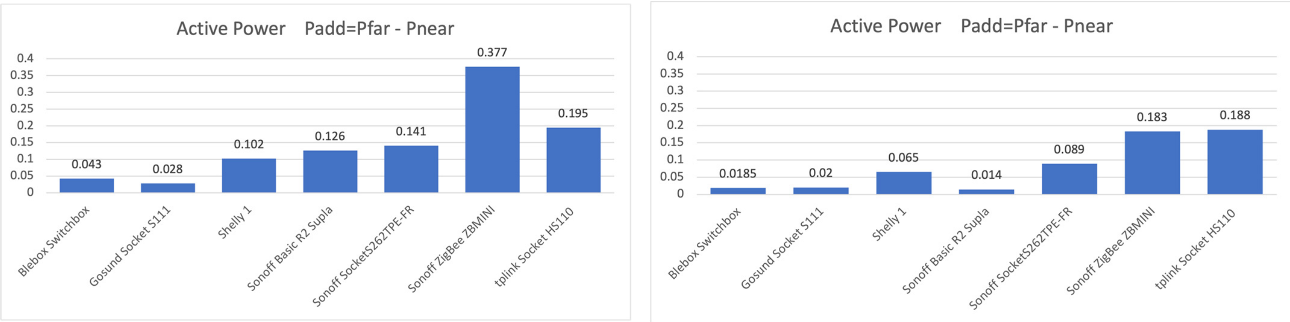
The results, considering the operating status of the smart home modules (relay on and off, respectively), are shown in the form of graphs in Figure 16.

For all modules, there is an increase in the active power level when the relays are turned on. This is especially spectacular for the Sonoff ZigBee ZBMINI module, which may be due to its unusual software loaded into the microcontroller memory directly in the module. Then, the potential levels of consumption of additional active energy by such modules over a period of 1 day (E_{add_day}) and 1 year (E_{add_yr}) were calculated, assuming that one operating state of the smart home module was maintained throughout the entire period (relay on and off, respectively). There were two relations used:

$$E_{add\_day} = P_{add} \times 24 \text{ [Wh]} \tag{2}$$

$$E_{add\_yr} = E_{add\_day} \times \frac{365}{1000} \text{ [k}Wh\text{]} \tag{3}$$

The results are shown in Tables 5 and 6.



(**a**) (**b**)

Figure 16. Graphs of consumption levels of additional instantaneous active power for smart home modules without load: (**a**) with the relay in the module switched on and (**b**) with the relay in the module turned off.

Table 5. Levels of consumption of additional active energy of smart home modules—the module after being away from the Wi-Fi access point/router, with the relay turned on.

Module	$E_{add\_day\_ON}$ (Wh)	$E_{add\_yr\_ON}$ (kWh)
Blebox Switchbox	1.03	0.38
Gosund Socket S111	0.67	0.25
Shelly 1	2.45	0.89
Sonoff Basic R2 Supla	3.02	1.10
Sonoff Socket S26R2TPE-FR	3.38	1.24
Sonoff ZigBee ZBMINI	9.05	3.30
tplink Socket HS110	4.68	1.71

Table 6. Levels of consumption of additional active energy of smart home modules—the module after being away from the Wi-Fi access point/router, with the relay turned off.

Module	$E_{add\_day\_OFF}$ (Wh)	$E_{add\_yr\_OFF}$ (kWh)
Blebox Switchbox	0.44	0.16
Gosund Socket S111	0.48	0.18
Shelly 1	1.56	0.57
Sonoff Basic R2 Supla	0.34	0.12
Sonoff Socket S26R2TPE-FR	2.14	0.78
Sonoff ZigBee ZBMINI	4.39	1.60
tplink Socket HS110	4.51	1.65

3.2. Analysis of Active Energy Consumption of Smart Home Modules

During the measurements, it was noticed that the level of active and reactive power consumption by smart home modules depends on the type of load supported by the module. Therefore, based on the collected measurement data, the average active power consumption of smart home modules (P_m) was calculated, both when working in the immediate vicinity of a Wi-Fi access point/router, and at a distance from it. For this purpose, from the measured active power levels in the circuits with the smart home module and the load switched on ($P_{measured}$), the rated load power (P_{N_load}) was subtracted each time according to the following relation:

$$P_m = P_{measured} - P_{N\_load} \text{ [W]} \tag{4}$$

Then, using a similar relationship as that in (2), the potential levels of active energy consumption by the modules were calculated for a period of 1 day, assuming that one relay state (switched on) was maintained for the entire period and one type of load was operated. The calculated average levels of energy consumption by smart home modules were marked as follows: E_{dman}—24 h energy consumption by the smart home module close to the Wi-Fi access point/router, and E_{mdayf}—24 h energy consumption for the module remote from the Wi-Fi access point/router. The results are shown in the graph in Figure 17.

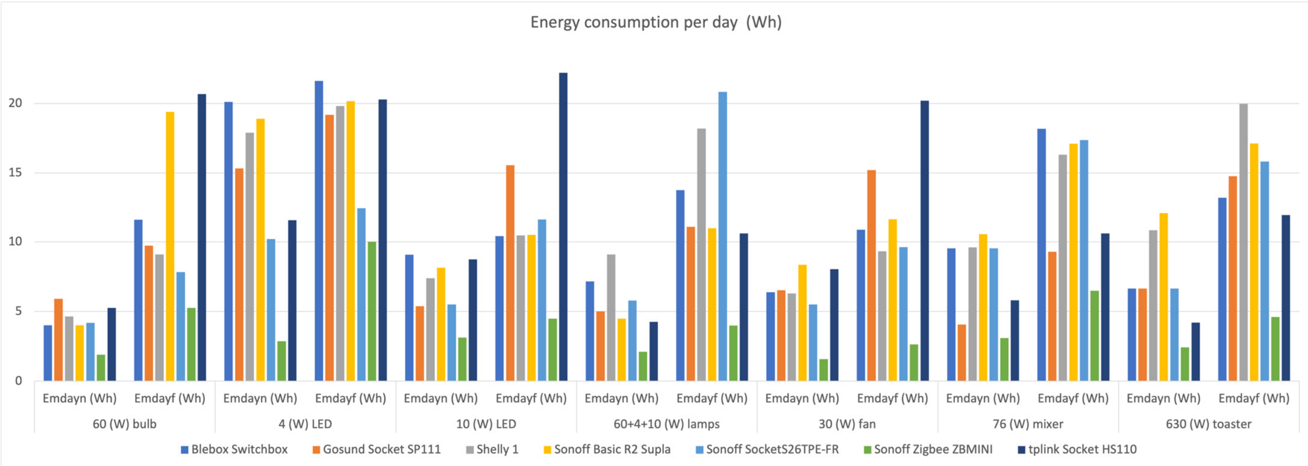


Figure 17. Chart of the levels of daily active energy consumption by smart home modules for the various types of loads they support, with the load constantly switched on (relays of smart home modules switched on).

For comparison, Figure 18 shows the levels of daily active energy consumption by smart home modules without load, respectively, with the relays on and off (No load Switch ON and No load Switch OFF).

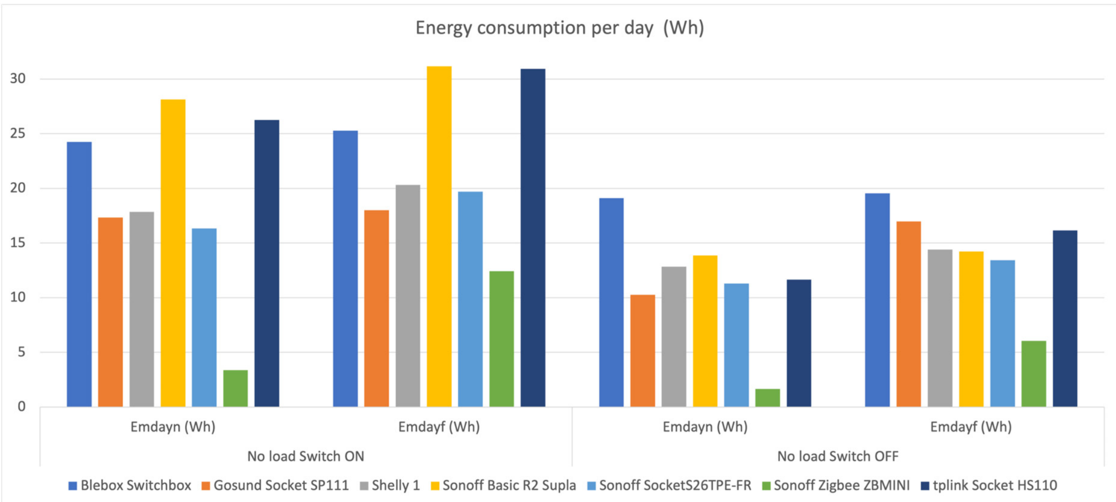


Figure 18. Chart of daily active energy consumption levels by smart home modules without loads, with relays on and off.

There is a visible increase in the level of active energy consumption by unloaded modules, in particular in the case of operation with the relay on. This is because such unloaded modules consume more active power than modules with loads, where, depending on the type of load, there is a consumption of reactive power (and the dependencies resulting from the so-called power triangle in AC electrical installations become more important).

3.3. Verification of the Communication Quality of Smart Home Modules

The measurement results clearly indicate an increase in the levels of active and reactive power consumption by smart home modules when increasing their distance from the Wi-Fi access point/router with which they are to maintain communication during the implementation of load control procedures. To verify the quality of communication and the variability of its conditions when changing the distance of the modules from the access point, measurements of the RSSI (received signal strength indication) indicator and data transmission speed in the communication channel for Wi-Fi radio signals generated by smart home modules as an access point were carried out. The measurements are for illustrative purposes and were carried out using publicly available Wi-Fi monitor applications available for mobile devices, which also operated the smart home modules analyzed in this article. The results are presented in Tables 7 and 8, respectively, for the mobile devices near and far from the module operating as an access point.

Table 7. Wi-Fi signal quality measurements measured close to smart home modules operating as an access point.

Module	Frequency (Mhz)	RSSI (dBm)	Data Throughput (Mbps)	Upload Data Rate (kbps)	Download Data Rate (kbps)
Blebox Switchbox	2437	−48	54	0.8	2.1
Gosund Socket SP111	2412	−44	54	0.9	1.2
Shelly 1	2427	−57	54	0.8	0.5
Sonoff Basic R2 Supla	2437	−51	54	0.6	1.1
Sonoff SocketS26TPE-FR	2442	−51	54	1.1	1.4
Sonoff Zigbee ZBMINI	2442	−28	54	0.7	1.3
tplink Socket HS110	2437	−31	65	0.6	2.0

Table 8. Wi-Fi signal quality measurements measured far from smart home modules operating as an access point.

Module	Frequency (Mhz)	RSSI (dBm)	Data Throughput (Mbps)	Upload Data Rate (kbps)	Download Data Rate (kbps)
Blebox Switchbox	2437	−76	48	0.4	1.6
Gosund Socket SP111	2412	−76	24	0.5	0.7
Shelly 1	2427	−81	36	0.3	0.2
Sonoff Basic R2 Supla	2437	−77	18	0.6	0.7
Sonoff SocketS26TPE-FR	2442	−77	48	0.6	0.7
Sonoff Zigbee ZBMINI	2442	−76	36	0.5	1.0
tplink Socket HS110	2437	−71	58	0.5	1.9

The data clearly indicate a significant decrease in the strength and quality of the Wi-Fi communication signal with the increase of the distance between the communicating devices. Among the analyzed modules with the Wi-Fi communication interface, the tplink Socket HS110 stands out positively in terms of signal quality, but at the same time it is characterized by relatively the most significant levels of active power consumption, in particular to maintain a higher quality of communication when the module is further away from the access point/Wi-Fi router in the rooms. This issue is the subject of separate research currently being conducted by the author. Also noteworthy is the good level of signal strength for the module with ZigBee communication. This is a different technique of radio communication, characterized by low power consumption while maintaining good communication quality parameters [2,23]. Therefore, many manufacturers offer smart home modules with this technology as an alternative to local data communication within rooms or flats at the facility level.

4. Discussion

The results of the energy analysis of popular smart home modules gathered and presented in this paper indicate several important threads, both of a technical and economic nature. First, it should be noted that all smart home modules remain in standby mode 24/7, even when they are not actively used. The collected results (Tables 1–4) show that the modules are constantly consuming low power, to maintain a Wi-Fi connection, for example. This power is negligible, but it loads the supply network all the time. The effect of scale is also important—usually, in home installations with smart home functions, several or a dozen of such modules are installed.

For example, a simple scenario of operation of the selected smart home modules in a daily cycle was analyzed, with an analysis of power and energy consumption in the context of the selected control types of loads. The scenario assumes that the lighting circuit is switched on for 8 h and switched off for 16 h per day. There were selected smart home modules with the lowest power consumption with the relay turned off and the location close to the Wi-Fi access point—Sonoff ZBMINI, with average power consumption—tplink Socket, and with the highest power consumption—Blebox Switchbox (based on Table 3). Energy-saving loads were selected as lighting sources: LED lamp 4 Watt and 10 Watt, commonly used in modern home installations as light sources. The results of the analysis are presented in Table 9.

The analysis of the results indicates that the 24 h power consumption by smart home modules can be significant and contribute to the energy consumption of the electrical installation in a house or building. As can be seen in Table 9, when controlling the 4 Watt LED light source, the energy consumption of the smart home module with the highest power consumption (Blebox Switchbox) can be up to half of the daily consumption of the load itself (8 h on/16 h off). In the case of controlling a larger load, such as the LED lamp 10 Watt, the module's energy consumption slightly increases, but in relation to the energy consumed by the load during 8 h of operation (80 Wh), it is approximately 21%. All these values are for one smart home module and one controlled circuit. Therefore, it is clear that the additional power generated by smart home modules installed so easily and freely in homes should not be underestimated. Hence, certainly the user of the house/building should be aware of it, and especially in the case of larger buildings, the facility manager managing the building infrastructure. At the same time, it should be noted that during communication via Wi-Fi, smart home modules show an increase in power, and thus energy consumption. More intensive communication consumes more energy. Therefore, there is a need to develop a strategy to optimize energy consumption in smart home modules. Research and engineering teams are working on this, especially those related to the manufacturers of such modules [19]. The mechanisms of energy-saving modes or intelligent management of the Wi-Fi connection they are developing can help minimize unnecessary power consumption in standby mode and reduce the time of activity necessary to send/receive control signals.

Table 9. Energy analysis of a simple lighting control scenario for two different LED light sources and several different smart home modules.

Module/Load	Active Power (W)	Operation Time (h)	Energy (Wh)	Module Total Energy Amount (Wh)
LED lamp 4 W	4.00	8	32.0	
Sonoff ZBMINI, relay ON	0.43	8	3.44	
Sonoff ZBMINI, relay OFF	0.07	16	1.12	Total: 4.56
tplink socket, relay ON	0.45	8	3.60	
tplink socket, relay OFF	0.48	16	7.68	Total: 11.28
Blebox Switchbox, relay ON	0.44	8	3.52	
Blebox Switchbox, relay OFF	0.79	16	12.64	Total: 16.16
LED lamp 10 W	10.0	8	80	
Sonoff ZBMINI, relay ON	0.59	8	4.72	
Sonoff ZBMINI, relay OFF	0.07	16	1.12	Total: 5.84
tplink socket, relay ON	0.59	8	4.72	
tplink socket, relay OFF	0.48	16	7.68	Total: 12.4
Blebox Switchbox, relay ON	0.58	8	4.64	
Blebox Switchbox, relay OFF	0.79	16	12.64	Total: 17.28

Another very important conclusion from the measurements carried out using the precise PQM-711 power network analyzer is the observed reactive power consumption, both by the smart home modules themselves (very low levels) and by the smart home modules controlling specific loads. In this case, the level of reactive power consumption strictly depends on the type of load and the nominal power of a given electrical device. Reactive power consumption results from the presence of electronic and power electronic components in smart home modules and loads (especially LED lamps), necessary for their proper operation. In the case of a fan receiver, reactive power is related to the design of the electric motor. The analysis of the level and share of reactive power in the measurements carried out was summarized in the form of data of the power factor value from the analyzer. The results are shown in Figure 19.

For the toaster load only, the power factor was 1.0. The worst results in the range of 0.4 to 0.6 were measured for LED lamp loads. This is a very important observation, because this type of load is currently commonly used in building lighting installations, and as can be seen from the measurements, it has a very negative impact on the power supply network. This is an issue for a separate study and publication in the field of electricity quality and it is considered by the author for future works.

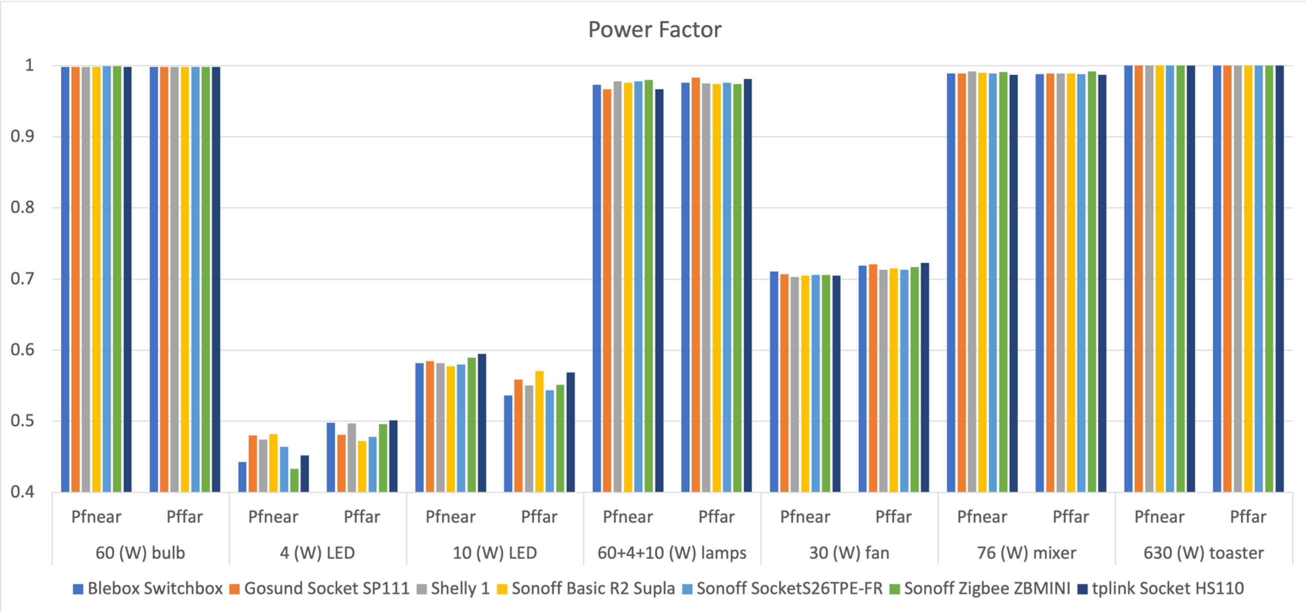


Figure 19. Power factor value for smart home modules with various loads considering near and far distances from the Wi-Fi access point.

A SWOT analysis was carried out regarding the use of smart home modules with wireless communication in installations in houses and buildings.

S—Strengths:

- Convenience and flexibility: wireless communication allows easy integration and control of various smart home modules from anywhere in the building using a smartphone or tablet.
- Fast installation: no need for wiring, and modules can be installed quickly and easily, which is especially beneficial for existing buildings.
- Scalability: wireless systems can be easily expanded with new modules and devices, which allows for gradual modernization and adaptation to changing needs.

W—Weaknesses:

- Interference: wireless communications may be susceptible to interference from other electronic devices or other wireless networks, which may affect signal reliability and quality.
- Range and connectivity: depending on the building and its structure, the range of the wireless network may be limited, which may lead to a loss of communication between modules.
- Dependence on technology: the functioning of smart home systems is most often based on the availability of a stable Internet connection, which may result in problems in the event of a network failure.

O—Opportunities:

- Development of communication standards: the continuous development of wireless technologies, such as Wi-Fi 6 and ZigBee, creates the opportunity to improve the speed and reliability of communication.
- Integration with other technologies: wireless modules can be easily integrated with other technologies, such as the Internet of Things (IoT), allowing for more complex systems.
- Personalization: the development of artificial intelligence can enable more and more personalized experiences for users by adapting systems to their preferences and habits.

T—Threats:

- Network security: wireless communication carries the risk of network attacks and security breaches, which may compromise privacy and system functionality.
- Power dependency: in the event of a power failure or battery problems, wireless modules may stop working, which can be especially critical in terms of safety.
- Privacy and data security: user data related to smart home modules may be exposed to threats related to cybercrime and privacy violations.

5. Conclusions

The modern market of home and building automation systems is flooded with a variety of products that enable control and monitoring of the infrastructure devices of these facilities. Among potential users, solutions that ensure easy configuration, wireless communication—preferably Wi-Fi, popular in homes and buildings, and operation from the level of mobile devices (smartphone, tablet) are very popular. From the perspective of the development of the Internet of Things technology and the possibility of building new, universal smart home modules based on, for example, the open-source electronics Arduino platform and/or Raspberry Pi single-board computers [16], the growing popularity of such solutions offered by various companies should be expected, both recognized on the market and with limited engineering knowledge and experience. Hence, the need for research and experimental verification work for home and building automation modules and controllers introduced and already available on the market arises.

The paper presented the results of experiments carried out on real, commercial smart home modules from various manufacturers, with implemented wireless communication interfaces, dedicated to the implementation of simple on/off control functions for single-phase household appliances. The measurements were conducted using a high-class PQM-711 power quality analyzer. In the qualitative and energy analysis of the obtained measurement data, active and reactive power consumption, the power factor, and other power supply parameters (voltage, current, and frequency) were considered. However, since voltage, current, and frequency did not differ from the norm, they were not discussed in this paper. The collected results indicate significant power consumption by smart home modules, especially in the context of the currently raised issues of energy saving in houses and buildings, as discussed in Section 4. During the experiments, active and reactive power consumption were recorded for all modules. In addition, it was shown that the levels of these powers for AC circuits depend on the type of controlled load. Based on the data, a more detailed analysis and discussion were carried out for loads popular in houses and buildings, such as LED light sources, equipped with additional electronic and power electronic components that negatively affect the parameters of the power supply network in buildings. In the context of the inevitable development of the Internet of Things technology and its integration in smart solutions dedicated to home and building automation, a SWOT analysis was carried out, indicating the most important factors and conditions that should be considered both in decisions on the purchase and installation of such solutions, as well as in the development of their technical and implementation concepts.

In future research, verification tests and energy analyses of modules and controllers used in building automation systems, usually powered from dedicated power supplies and even through communication buses (LonWorks, KNX networks, Loxone technology), will be carried out. In addition, for both smart home modules and Internet of Things network nodes, with the functions of controlling and monitoring the usable parameters of rooms in buildings (lighting, heating, air quality), comprehensive energy analyses and energy quality impact studies will be carried out, considering the operation and control of various load types. Moreover, experiments and in-depth analyses will be carried out regarding changes in the signal strength of the radio communication of modules depending on their distance from access points (signaled in Section 3.3) and the connection with the power levels of smart home modules. Additionally, it is planned to measure signals and analyze the layout of Wi-Fi networks in buildings in the context of the functional potential for building automation systems. Research in this area is currently being conducted by the author.

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Data Availability Statement: The data and datasheets presented in the tables and figures in this study are available upon request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The author declares no conflict of interest.

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