is reduced due to high computational power, ensuring minimal power consumption.

6) *Low-level microcontroller programming.* Providing access to the lowest level of microcontroller programming for maximum acceleration of the above requirements.
7) *Setting minimum transmission level and optimizing controller placement.* Configuring the transmitter to the minimum transmission level and placing the controller as close as possible to the unobstructed router for radio wave communication.
8) *Optimizing receiver/transmitter on/off times.* Technologically reducing the time it takes to turn on/off the receiver and transmitter to minimal values.
9) *Minimizing receiver current consumption.* Technologically ensuring minimal receiver current consumption to reduce overall energy consumption.
10) *Use of supercapacitors for powering.* Applying supercapacitors for powering the controller with slow charging (from 5 mA to 50 mA) from weak batteries for pulse-powering the transmitter at a level of 300 mA.

Wi-Fi controllers for IoT devices exhibit high power consumption, limiting their applicability in battery-powered devices [4]. In transmit mode, the average current of Wi-Fi controllers ranges from 120 mA to 270 mA [5], rendering the use of batteries impractical for extended periods. For standard IoT controllers like ESP8266 [6] and ESP32 [7], the hardware implementation of real-time methods is absent. Attempts to optimize performance through low-level register code are constrained due to limited access to the internal architecture of these controllers, provided in a closed form [8]. This imposes restrictions on significant improvements in response time and operation of these devices in IoT mode.

In this context, the DA16200 controller stands out as it is proclaimed to be a device originally designed to support sub-second response time in the IoT domain. It is capable of maintaining a constant connection with the router and achieving a power consumption level that enables it to be powered by batteries for a minimum of one year and even longer.

The objective of this article is to compare the energy efficiency of three Wi-Fi controllers (ESP8266, ESP32, and DA16200) for IoT devices.

3 POWER CONSUMPTION CHARACTERIZATION OF DA16200 CONTROLLER

3.1 Analysis of the DA16200 Controller's Pulse Current Consumption

For the current consumption investigation, an experiment was conducted to measure the current when breaking the P2 contacts. To achieve this, a shunt with a resistance of 0.5 ohms was connected to the P2 contacts, and a 1:1 probe of the Hantek DSO5102P oscilloscope with a bandwidth of 100 MHz was connected to the shunt contacts, as shown in Figures 1 and 2. The measured voltage drop across the shunt at a current of 250 mA was 0.125 V, which had no significant impact on the controller's operation. To reduce interference during measurement, the DA16200 Module Evaluation Kit (EVK) was powered from a power bank via USB.

3.2 Calculation of Average Current Consumption

Another crucial indicator of energy efficiency is the calculation of the controller's average current consumption. Average current consumption (I_{avg}) is the amount of energy consumed by a system in a unit of time. It is calculated as the ratio of the total amount of energy consumed by the system over a given time period to that time period [9].

There are several methods for calculating the average current consumption, such as the geometric and current integration methods. In this study, the geometric method was chosen and calculated using (1). This method is based on the average current (I_{avg}) being equal to the area under the consumption pulse (A) divided by the pulse period (T):

$$I_{avg} = \frac{\mathrm{A}}{\mathrm{T}}. \quad (1)$$

To calculate the area under the consumption pulse, data from the oscilloscope measurement results, as shown in Figures 1 and 2, were used. The area of the consumption pulses is equal to the sum of the areas of all pulse shapes, as indicated in (2):

$$\mathrm{A} = \mathrm{A}_r + \mathrm{A}_{r.t.} + \mathrm{A}_{i.t.}. \quad (2)$$

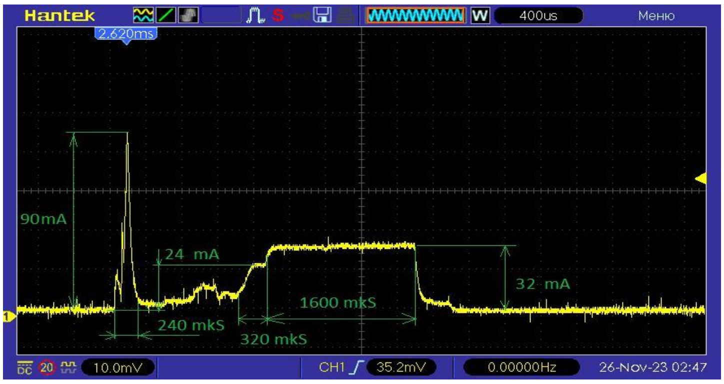

Figure 1: Pulse current consumption of the DA16200 in reception mode.

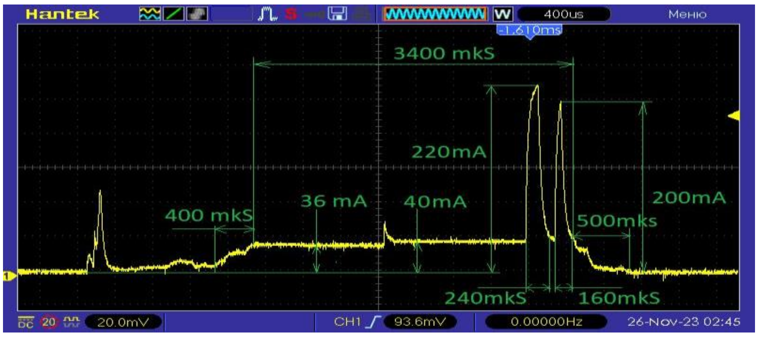

Figure 2: Pulse current consumption of the DA16200 in transmission mode.

The area of rectangular consumption pulses (Ar) was calculated using the method of multiplying the sides, that is, multiplying time (t) by the current amplitude (I_m):

$$A_r = t * I_m.$$

The area of rectangular triangles ($A_{r.t}$), representing the fall and rise of the pulse, is calculated as half the product of the area $A_{r.t} = \frac{t * Im}{2}$, and the area of isosceles triangles *($A_{i.t.}$)*, is calculated as one-third of the product $A_{i.t.} = \frac{t * Im}{3}$. The measurement time *(t)* was chosen to be 30 seconds.

As a result of oscilloscope measurements, we obtained the following picture: 30 reception pulses (pulse shapes) and 1 transmission pulse during the measurement time. During this period, when there is neither transmission nor reception, the controller is in Sleep 1 mode, consuming a current of 0.2 μA.

The area of one session of consumption pulses during reception is equal to:

$$A_t = 1600 * 32 + \frac{320 * 24}{2} + \frac{240 * 90}{3} = 62.240\ (mA \cdot \mu s).$$

The area for 30 sessions is equal to:

$$A_t = 62.240 * 30 = 1\,867\,200\ (mA \cdot \mu s).$$

The average receive current is:

$$I_{avg\_t} = \frac{1\,867\,200}{30\,000\,000} = 62\ (\mu A).$$

The area of consumption pulses during transmission is equal to:

$$A_r = (1400 * 36) + (110 * 40) + \frac{400 * 36}{2} + \\ + \frac{240 * 220}{2} + \frac{160 * 200}{2} + \frac{500 * 40}{3} = 150\,667\ (mA \cdot \mu s).$$

The average current during transmission is:

$$I_{avg\_r} = \frac{150\,667}{30\,000\,000} = 5\ (\mu A).$$

To obtain the overall average current, it is necessary to add the Sleep 1 current to the average reception current and the average transmission current.

$$I_{avg} = 62 + 5 + 0.2 = 67\ (\mu A).$$

It turned out unexpectedly that the receiver contributes the main share (92%) to the current consumption - 62 μA out of 67 μA, indicating the potential for further current reduction while maintaining IoT Wi-Fi responsiveness once per second.

The investigation of the DA16200 controller's current consumption revealed that the receiver contributes the majority, consuming 62 µA out of the total 67 µA. This accounts for 92%. Therefore, there is significant potential to reduce power consumption by optimizing the receiver's operation.

3.3 Battery Operating Time of DA16200

The measurement of the average current consumption of the DA16200 controller showed that it is 67 µA. This figure is exceptionally low for devices of this class. However, to ensure prolonged operation of an IoT device, it is essential to consider that the operating time also depends on the supply voltage and battery capacity. The supply voltage of the DA16200 controller ranges from 2.1 to 3.6 V [10]. This voltage range allows the use of various types of batteries to power the controller, including two AA or AAA batteries, one Li-ion battery, or a single lithium battery.

Table 1: The capacities of different batteries.

Battery Type	CR2032	AAA	AA	18650
Capacity, mAh	240	1000	2000	2500
Pulse discharge current	15 mA	0.7 A	1.5 A	5 A
Operating time, days at 67 µA	149	622	1243	1554

In Table 1, average values of battery capacity and their pulse currents sufficient to operate the DA16200 transmitter with a peak consumption current of ~ 250 mA. The operating time is specified for maintaining a connection to the router with a response time of 1 second. When transmitting data, the operational time decreases proportionally to the increase in the current consumption during transmission.

However, even when addressing the issue of impulse current consumption at a level of 250 mA from a CR2032 battery using a supercapacitor, it is not possible to power the DA16200 for one year. To ensure the operation of the DA16200 transmitter for one year, it is necessary to use batteries with a capacity of at least 600-800 mAh, equivalent to two AAA batteries or more. However, with such initial capacities, the transmitter's runtime for a year will be limited. Increasing the battery capacity will extend the transmission time.

The conducted measurements indicate that DA16200 manufacturers have managed to introduce a high-speed and power-efficient Wi-Fi protocol into the battery-powered IoT domain.

Analysis of the oscillograms depicting the current consumption of the DA16200 has facilitated the elucidation of the underlying success of the new technology. The current consumption in the receiving mode is contingent upon:

- The current consumption of the radio circuits within the Wi-Fi receiver;
- The current consumption of the Wi-Fi protocol processing controller during data reception.;
- The duration of Wi-Fi protocol processing when receiving data.

The current consumption associated with the radio circuits of the Wi-Fi receiver is a nominal few milliamps, contributing insignificantly to the overall consumption of the DA16200. However, the pivotal elements of the technical solution by Renesas reside in the current consumption of the processing controller and the duration of its Wi-Fi protocol processing. Renesas engineers achieved a reduction in the duration of current consumption during reception to 2 milliseconds by employing a proficient and energy-efficient ARM Cortex M4F controller, complemented by the authorship of optimized code for Wi-Fi protocol processing. This reduction is of paramount importance, as the duration of current consumption during reception, particularly for IoT applications requiring response times on the order of several seconds, constitutes the primary (90%) contributor to the total power consumption. After this, the aforementioned metric will be juxtaposed with analogous parameters in competing solutions.

4 COMPARATIVE ANALYSIS OF POWER CONSUMPTION OF DA16200 AND ESP8266/ESP32 CONTROLLERS

In this section, a comparative analysis of the energy consumption of the DA16200 and ESP8266/ESP32 controllers will be conducted. The analysis will utilize data obtained during experimental research, as presented in Tables 2 and 3.

As seen from the provided data, the impulse current consumption during transmission for the DA16200 controller is almost identical to the impulse current of ESP8266/ESP32 controllers. The impulse current consumption during reception is

1.6-2.5 times less than that of ESP8266/ESP32 controllers. This is because the activity time during data exchange with the router for the DA16200 controller is less than 2 ms, while the activity time for ESP8266/ESP32 with the most efficient ESP-NOW algorithm is 130 ms.

Table 2: Comparison of current consumption for DA16200, ESP8266 and ESP32 controllers.

Controller	Pulse current consumption during transmission, mA	Pulse current consumption during reception, mA
DA16200	220	32
ESP8266	200	55
ESP32	240	80

Table 3: Comparison of average current consumption and operating time for DA16200, ESP8266 and ESP32 controllers.

Controller	Average current consumption	Operating time from batteries (2000 mah), days
DA16200	67 µA	1243
ESP8266	4.7 mA	11
ESP32	10.7 mA	7.7

Based on this data, it can be concluded that the DA16200 is the most energy-efficient controller among the mentioned ones. It exhibits lower average current consumption and longer battery runtime. However, it is essential to note that these data are based on nominal values of controller current consumption. Conducting independent measurements is necessary for obtaining more accurate values.

5 CONCLUSIONS

The DA16200 controller, designed for operation within a home environment and connectivity to the internet through standard Wi-Fi routers, represents a significant advancement in the development of the IoT. It addresses a key limitation of existing IoT technologies, such as Bluetooth Low Energy, which require the use of dedicated gateways for internet connectivity. This simplifies and reduces the cost of implementing IoT technologies in household devices, opening up new possibilities for their application.

Based on the research findings, it can be concluded that the DA16200 controller is the most energy-efficient Wi-Fi controller for IoT devices. It is capable of maintaining a constant connection to the router and providing a level of energy consumption that allows it to be powered by batteries for a minimum of one year and even longer.

In the IoTMark®-Wi-Fi test, the DA16200 received a score of 815, equivalent to 815 days of autonomous operation for an IoT sensor powered by two AA batteries. It is anticipated that the smart door lock will last for over three years without recharging, which is 50% longer than what the closest competitor can offer. For the first time in Wi-Fi history, it can provide autonomous operation time comparable to Zigbee and Z-wave.

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