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Instant-incidental-close-loop scheme to improve battery life in wireless sensor applications

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ABSTRACT

This work presents a simple new idea for implementing algorithms in microcontrollers that govern duty cycle transition settings in wireless sensors in closed-loop circuits that run on batteries. The switching time controlled to get end point and average duty-cycle (STEADY) method is used. Duty cycle regulation algorithms are used by instantaneous incidental closed loop (IICL) schemes to regulate current flow in circuits that serve as power-consuming loads, facilitating quick and seamless transitions from open to closed loop. By using the STEADY algorithm on IICL, the issue of conserving battery energy to increase battery life can be resolved. Additional advantages of the STEADY algorithm include its low memory utilization of 4 Kbytes, or 12.5% of the 32 Kbytes of available memory slot, simplicity, and ease of implementation on microcontroller devices. Final testing using the IICL STEADY algorithm on the VD-2023 wireless DC voltage sensor prototype series shows that 627 mAh is more energy efficient than battery life in the IICL scheme without the STEADY algorithm applied, which is 26 minutes 37 seconds. The wake time is set to one millisecond, and the sleep time is set to one minute, and the battery power is provided by a 280 mAh battery. This results in a battery life of 8 hours 16 minutes 57 seconds.

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1. INTRODUCTION

Significant technological advancements, applications, and integration with the internet of things (IoT) are characteristics of the development of wireless sensor networks (WSN). WSNs are made up of several inexpensive, low-power sensor nodes that can wirelessly sense, analyze, and communicate data, allowing for more thorough environmental monitoring at a reduced cost [1]. WSNs, however, have numerous obstacles that limit their usefulness in a range of applications. Important problems include hardware and software expenses that make deployment more difficult, as well as restricted energy supplies that affect network performance and longevity [2]. Significant obstacles stand in the way of using batteries as an energy source for WSNs, particularly given the short lifespan and low energy capacity of traditional batteries. In distant or industrial settings without power outlets, relying solely on batteries is difficult due to the need for frequent replacement [3], [4]. Furthermore, battery depletion is made worse by the energy-intensive nature of sensor nodes, particularly during data transmission, making effective energy management techniques necessary [5].

Since battery energy efficiency has a direct impact on sensor node operating lifetime, our research focuses on increasing battery energy efficiency. Duty cycle management can be used to drastically cut down on idle energy consumption by allowing nodes to switch between active and sleep modes [6]. As an alternative to the duty cycle approach, which is commonly employed for IoT networks generally, the suggested method to extend battery life is to first examine the duty cycle technique and the maximum amount of energy that the radio can consume [7]. Additionally, the duty cycle method can be used to lower the power consumption of low-power microcontroller transceivers [8], and it uses a decentralized approach to choose its own operational modes, such as transmitting, listening, or sleeping, for each time slot [9]. Energy consumption is greatly decreased by the strategy of implementing a new protocol based on duty cycle methods and energy thresholds to balance traffic between all nodes. By balancing energy use across nodes, this approach prolongs network lifetime and increases energy retention by 28% to 61% across nodes [10]. Furthermore, by minimizing redundant data collection and guaranteeing efficient energy use between sensor nodes, the implementation of optimized sleep scheduling and clustering algorithms can also increase network lifetime by 20% [11]. Significant energy savings can be achieved by optimizing the microcontroller configuration and radio module interface, which can reduce wasted energy by up to 50% [12].

Another option is to incorporate a closed-loop system into the circuit, which can greatly extend battery life using a number of creative techniques. The successful approximation register (SAR) of analog-to-digital converters (ADCs) can save energy by implementing a switching scheme based on the closed-loop charge recycling method, which achieves 100% less switching energy than traditional switching schemes [13]. The pulse width modulation (PWM) technique is used for closed loop control of the interleaved buck converter with soft switching (buck converter) to share load current and minimize switching losses among parallel connected converters [14]. For battery charger applications, use an inductor inductor capacitor (LLC) resonant converter with closed-loop control to maximize battery life without overloading the charger volume by eliminating low and high frequency current ripples in the battery. This will increase efficiency and stability [15]. In addition, any methodology that provides a fast and smooth transition from open loop to closed loop uses a duty cycle regulation algorithm that corresponds to the current flow in the circuit that forms the load. We call this the instant-incidental-close-loop (IICL) scheme [16], [17].

The approach used in earlier study, which we dubbed IICL, nevertheless has drawbacks, including the possibility of stability loss during closed loops due to the use of conventional methods and the inclusion of time-varying parameter estimations [16], [17]. Our research will concentrate on this. Although we still employ traditional techniques to implement the IICL scheme, we pay close attention to the current consumption in a closed loop in the direct interface circuit, which connects the sensor directly to the microcontroller by estimating the average current consumption in active mode [17]. When designing direct interface circuits for battery-powered measuring systems, these estimations are useful [18] other. The analysis's findings will guide the creation of designs that prioritize minimizing energy usage papers [19], [20]. Consequently, it will result in a circuit that uses extremely little energy. Additionally, duty-cycle optimization [21], [22] done to maximize the duty-cycle method's performance level for battery energy efficiency, and a new, easy-to-understand concept for implementing algorithms embedded in hardware. This algorithm regulates the switching circuit to obtain the best stable condition in the shortest possible time, named the “switching time controlled to get end point and average duty-cycle” (STEADY) algorithm.

There are numerous important advantages to this research. The development of this scheme will be very helpful in designing future integrated IoT technology that uses batteries, such as smart electric cars, smart electric ships, smart home-scale solar power plants in remote areas [23] and other smart devices. This research is aimed at implementing a wireless sensor node system that will be integrated into a WSN and contribute to minimizing battery energy consumption with conventional methods still used in its implementation, they are more complex than non-conventional methods, which can negatively affect computing algorithms' power consumption because non-conventional methods require large amounts of data for training. Reduced system performance could arise from any circumstance that isn't addressed in the training data [24]. With the right computer program and a microcontroller unit, the STEADY method is simpler to implement just 4 Kbytes, or 12.5% of the 32 Kbytes of available memory slots, are used by the STEADY algorithm. Therefore, this study emphasizes sustainability, usability, and efficiency, while also offering creative technical solutions. In this case, the integration of the STEADY algorithm with IICL has improved battery energy efficiency, primarily by reducing the current flow in a closed-loop system with an ideal duty cycle setting. Future studies will contribute significantly to scientific advancements in WSNs and battery-efficient control systems, which will help create the IoT and other battery-powered technologies such as electric vehicles or air vehicles.

2. METHOD

The integration of the STEADY algorithm on IICL implemented in the research can be applied for various purposes, such as reducing costs by minimizing battery energy consumption settings with a soft-switching algorithm that optimizes the duty cycle, resulting in battery energy savings [25]. In this research, the method applied through several stages, namely; i) IICL design; ii) STEADY algorithm design;

iii) P-Spice software simulation; iv) making a prototype of a VD-2023 type wireless voltage sensor; v) collection of experimental data; and vi) data analysis that will produce conclusions.

2.1. Instantaneous incidental closed loop design

The basic IICL circuit block diagram shows the IICL design in Figure 1. At the top there is a circuit designed as an IICL model where there is a STEADY algorithm embedded in the microcontroller, which will control the switching interface with a DC voltage sensor circuit designed as a voltage divider connected to a battery power source. Next to the circuit is described the ideal waveform in the form of PWM in one period. At the bottom of the ideal waveform there is a waveform due to the influence of the duty cycle setting, switching conditions usually produce suboptimal and non-ideal signal forms such as the occurrence of (rise time, overshoot, ringing, fall, fall time, and undershoot) which were the previous problems.

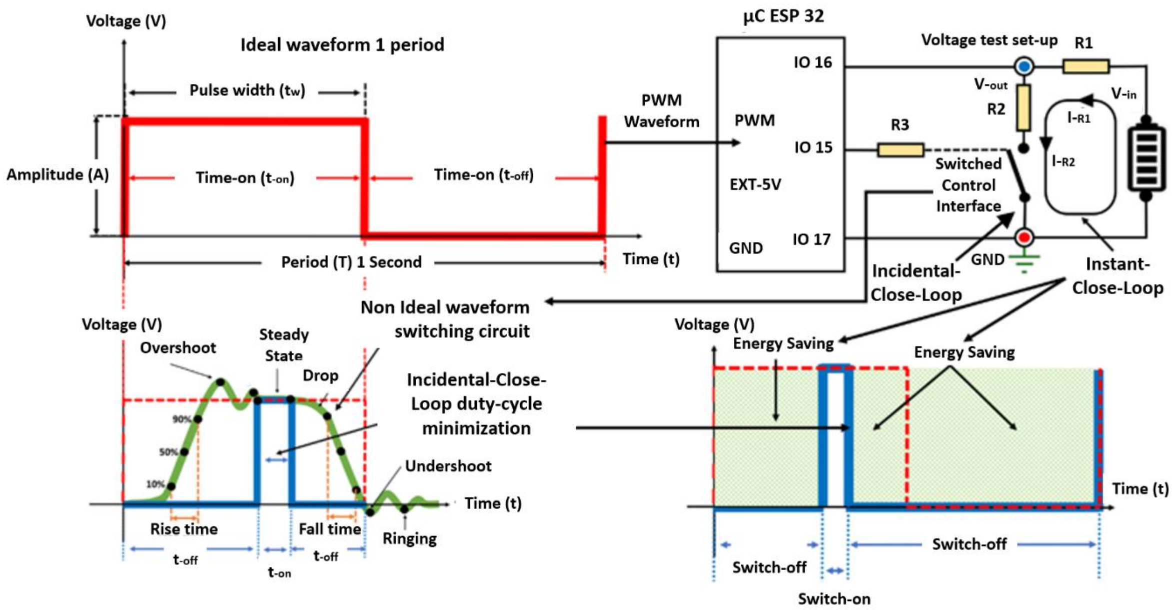

Figure 1. IICL design and illustration of solutions to problems in the instant-closed-loop scheme

In the section below the IICL circuit related to the explanation of IICL can optimize the duty cycle that can save battery energy. The duty cycle time which is usually in 1 period for 1 second consists of a "high" condition for 500 milliseconds (ms) and a "low" condition for 500 ms, optimized using the STEADY algorithm by breaking the "high" condition incidentally for 1 ms and the remaining "low" condition for 499 ms, so that in 1 period for the "high" condition for 1 ms and the "low" condition for 999 ms. When the condition is "high" then the microcontroller will move incidentally "waking up" the switching interface in the "switch-on" condition so that the circuit becomes a closed loop. The DC voltage sensor works to perform sensing which will consume battery energy for 1 ms. When it returns to the "low" condition, the microcontroller will control the switching interface in the "off" condition so that the circuit becomes an open loop. The DC voltage sensor stops detecting and stops consuming battery power for 999 ms, so that the microcontroller is in a "sleep" condition. In comparison, the previous "wake" state, where one duty cycle consumed 500 ms of battery power, with the IICL scheme, this state only lasted 1 ms. In contrast, during the "sleep" state, which previously saved 500 ms of battery power, the IICL scheme saved 999 ms of battery power.

2.2. STEADY algorithm design

The STEADY algorithm is designed taking into account the capacity of the microcontroller used, namely the ESP-32, which is 4 Kbyte, or 12.5% of the 32 Kbyte available memory slot. The STEADY algorithm is explained through the flowchart presented in Figure 2. Setting the DC input voltage (SetVin), the PWM time-on (SetTon), the PWM time-off (SetToff), and the PWM off time (SetPeriod) are the initial parameter settings that the algorithm begins with the duration of data gathering in a single session, with StarSensing denoting the start of sensing and EndSensing denoting the termination of sensing due to the achievement of a specified value. Initializing the sensor is the next step, assuming that SetVin is 6 volts, StarSensing starts at 100 µs, SetPeriod is 5 minutes, SetSon is 100 ms, and SetSoff is 1 second. In this setup, 300 data points are gathered over the course of 5 minutes of sensing starting at 100 µs. The term "steady state" refers to these data measurements, which are within ±1% of 6 volts (range 5.91 V to 6.09 V). The CntSetSon value will rise and gradually adjust over time until an ideal, steady state value is attained if the data measurement deviates outside of this range. Furthermore, the sensing process is essentially terminated when 300 data points are in a steady condition after 100% of the SetPeriod time, marking the start of the EndSensing phase. Additionally, using IoT principles, the gathered data is sent wirelessly.

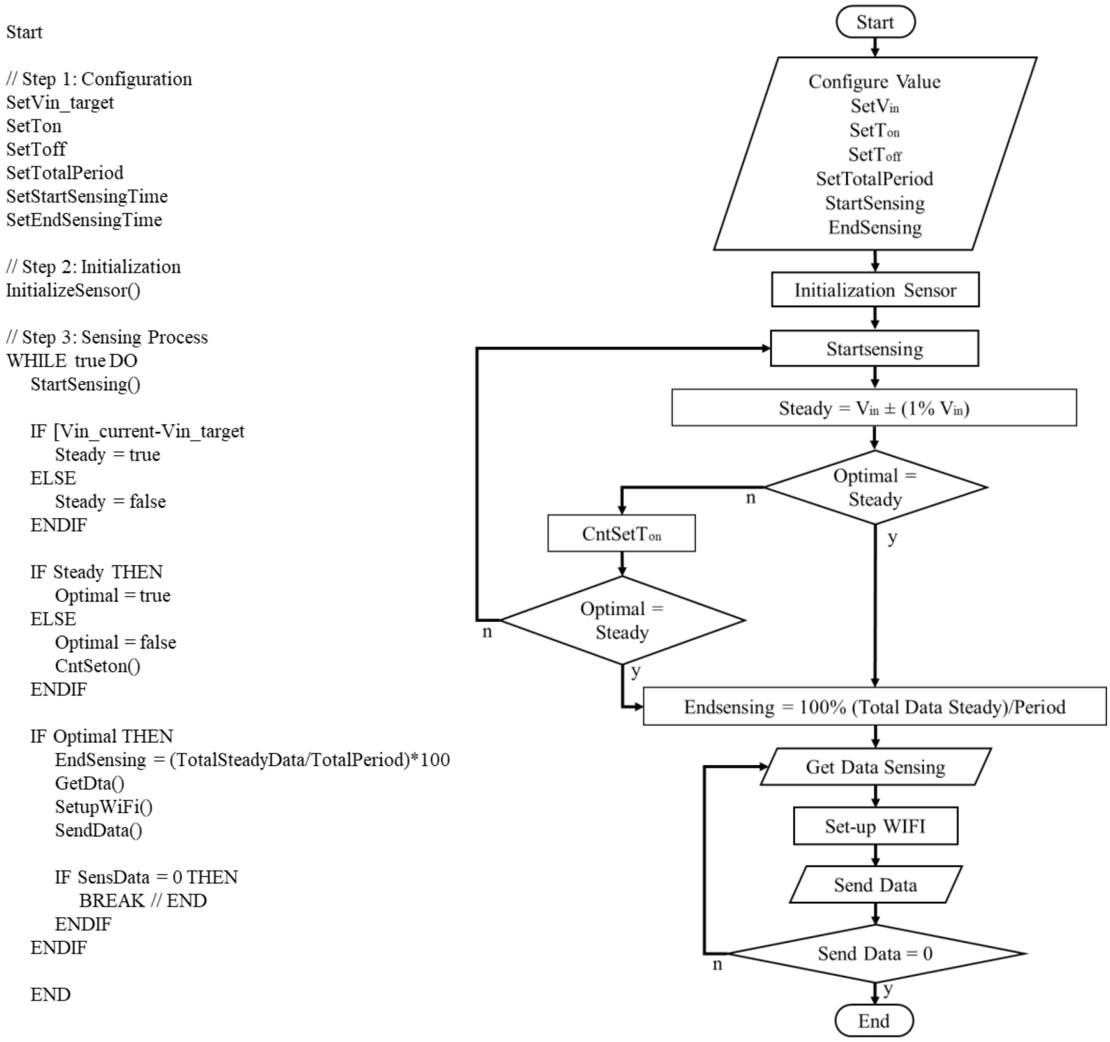

Figure 2. STEADY algorithm flowchart

2.3. P-Spice software simulation and real hardware switching testing

The experiment was conducted through simulation and also conducted hardware experiments in the real world. Simulations were conducted using P-Spice software. This simulation was conducted to obtain suitable components for soft-switching circuits that work optimally and can minimize rise time, overshoot, ringing, fall, fall time, and undershoot factors. P-Spice simulations can also determine the ideal value and output of the circuit according to the IICL schematic design. To test the simulation results, real hardware experiments were also carried out by creating a PCB which was measured directly using a digital multimeter and oscilloscope. Figure 3 shows the simulation testing activities and real hardware testing.

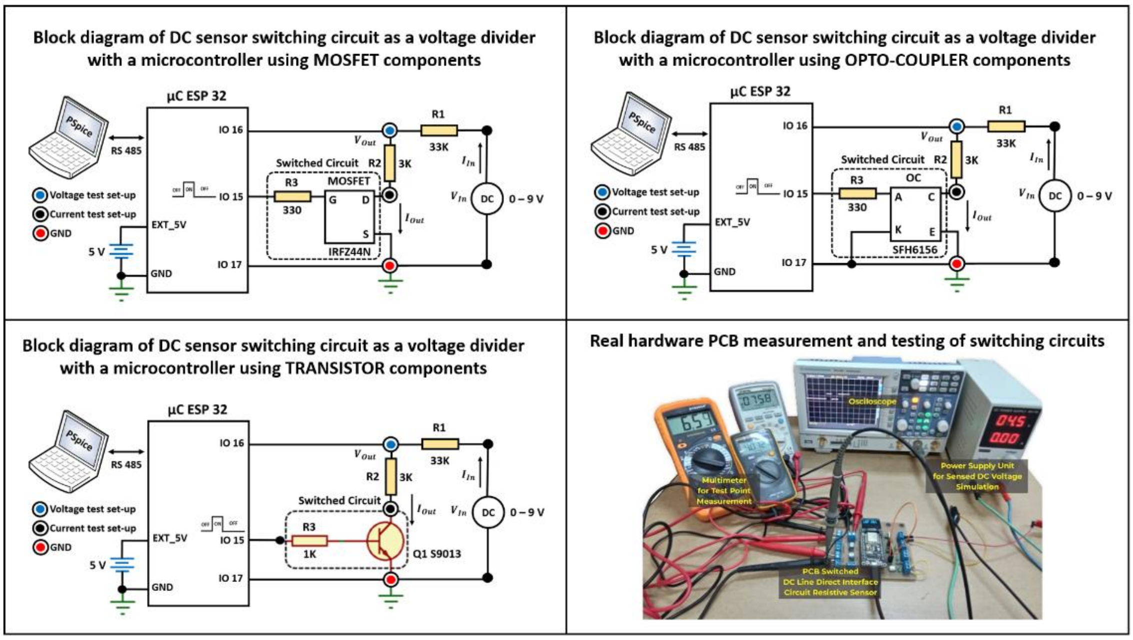

Figure 3. Block diagram of real hardware testing and simulation trial activities using P-Spice software

2.4. Experimental data collection

This experiment served as a last step in which we evaluated the effectiveness of the IICL scheme and the use of the STEADY algorithm in three distinct scenarios: the first involved treating a number of IICL schemes without the use of the STEADY algorithm, the second involved treating a number of IICL schemes using The STEADY algorithm is configured in duty-cycle mode with wake-time of 1 millisecond and sleep-time of 1 second. The third scenario involves treating the IICL scheme circuit with the STEADY algorithm, which is configured in duty-cycle mode with wake-time of 1 millisecond and sleep-time of 60 seconds. An ACS-71 current sensor, a DC voltage sensor that is already available on the market, types INA-219 and PZEM-017, and three wireless DC voltage sensors that were manufactured as prototype models VD-2023 were also used in the experiments. Three wireless sensors based on DC voltage are created for the IoT. In Figure 4, the test and experimental design is displayed. Table 1 displays the specifications of the circuit's components.

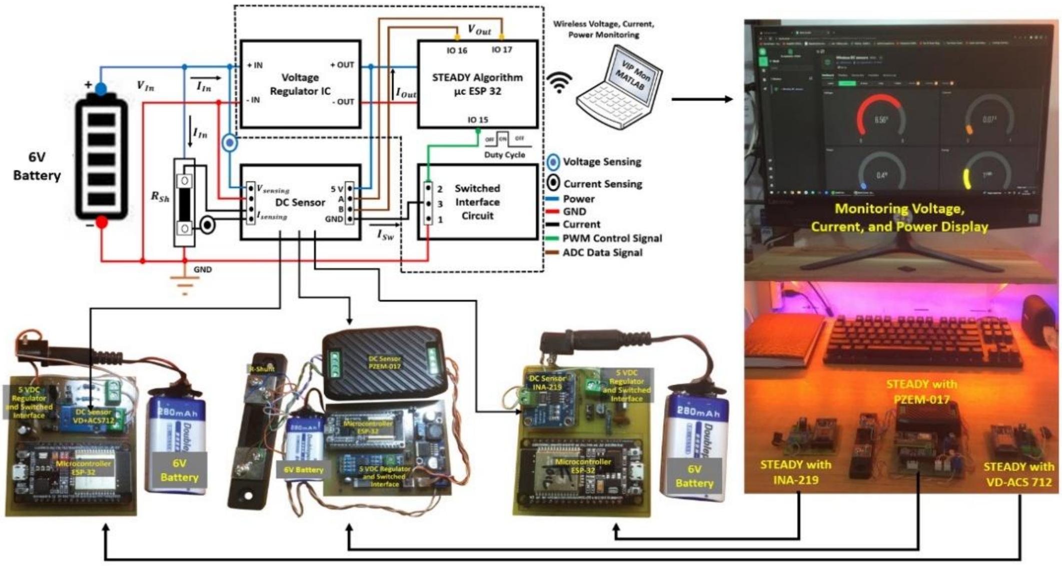

Figure 4. Block diagram of experiments and test data collection

A block diagram of the experiment is shown in Figure 4, where all PCB components have actual hardware mounted on them, the battery serves as the power supply, and the sensing data findings are transmitted and shown on web-based IoT monitoring. Table 1 displays the specifications for every component.

Table 1. Hardware component specifications

Name	Specifications
Microcontroller type ESP-35	The device features a 32-bit dual-core processor. It possesses a memory capacity of 520 KB SRAM
LM7805 IC	The device requires an input voltage ranging from 7.5 V to 30 V, with a precision level of 3%
MOSFET type IRLZ44N	The device exhibits a maximum power dissipation of 150 W, gate-source voltage threshold at 10 V
Opto-coupler type SFH6156	The device tolerates a reverse voltage input of 6 V and operates a DC forward current of 60 mA
Transistors type S9013	The device showcases a breakdown voltage of 40 V for the collector-base, 20 V for collector-emitter
Battery	The battery is Ni-MH type, featuring a voltage rating of 6 V and a battery capacity of 280 mAh
Sensor ACS71	The output rise time is 5 μs, with an output error margin 1.5%
Sensor INA-219	The sensor's measurement highest attainable current being 3.2 A
Sensor PZEM-017	The device is suitable for measuring current across a range of 0 to 300 A, accuracy level of ±1%

Overhead is the additional resources required to run an application. Sampling and computational overhead of algorithms affect the optimization of the duty cycle associated with functions during the sensing and controlling process of power consumption in a device or system. In (1) for the overhead relationship between energy efficiency (η) and duty cycle (D) is:

$$\eta = D/(1 + \alpha * D) \quad (1)$$

In (1) shows that overhead has an effect on increasing duty cycle and energy efficiency, but there is a point where increasing duty cycle will not result in significant improvements.

A battery served as the experiment's energy supply. As long as the battery is still powering the circuit, the data will be suppressed until the circuit fails. In one test cycle, the circuit uses a sensor to sense voltage and current. The sensing data is then sent to a database that has been set up in Firebase and displayed via a web-based voltage and current monitoring application. can transmit information to the database once more, indicating that the circuit can no longer be powered by the battery. The amount of time that passes between the beginning of the circuit's ability to convey data and its inability to do so will be noted and computed as the battery's energy efficiency and savings. Until more precise data was obtained, the experiment was conducted several times. The average data processing results are the data that was processed using the STATCAL application and are shown. Table 2 shows the outcomes of the data processing.

Table 2. Data from the comparison of testing results

Scenario	Sensor type	Wake-time	Sleep-time	Battery-life	Energy saving
Without the STEADY algorithm	VZEM-017	Real time	Real time	16 m 38 s	-
Without the STEADY algorithm	INA-219	Real time	Real time	19 m 20 s	-
Without the STEADY algorithm	VD-2023	Real time	Real time	26 m 37 s	-
With the STEADY algorithm	VZEM-017	1 ms	1 s	58 m	55 mAh
With the STEADY algorithm	INA-219	1 ms	1 s	1 h 29 m 26 s	93 mAh
With the STEADY algorithm	VD-2023	1 ms	1 s	1 h 40 m 21 s	98 mAh
With the STEADY algorithm	VZEM-017	1 ms	60 s	3 h 57 m 56 s	295 mAh
With the STEADY algorithm	INA-219	1 ms	60 s	6 h 26 m 55 s	490 mAh
With the STEADY algorithm	VD-2023	1 ms	60 s	8 h 16 m 57 s	627 mAh

3. RESULTS AND DISCUSSION

This study expands upon and improves upon earlier research findings by taking into account non-ideal waveform variables that cause components to transition between a on and an off state utilizing P-Spice simulations and real hardware testing. The parameters are then estimated using an improved technique. The effect of employing the IICL scheme with the STEADY algorithm on the size of current, voltage, power, and time so that research findings can be compared to other studies on battery energy efficiency and savings, as well as time on sensor sensitivity and accuracy that were previously not able to be measured optimally, can now be measured in a "steady" state or condition.

3.1. IICL switching based on programming STEADY algorithm

This study demonstrates the benefit of the STEADY algorithm, which has been shown to be reliable in sensing tests of wireless DC voltage sensors related to time parameters when moving from sleep-time to wake-time, by evaluating the data 300 times with repeated test cycles for 10 cycles. The previous duty cycle setup technique, will be improved comprehensively in this research, by adding multiple phases that can produce more accurate values at data points with more stable "STEADY" conditions. The related explanation of the working of the STEADY algorithm in the IICL scheme is explained graphically in Figure 5.

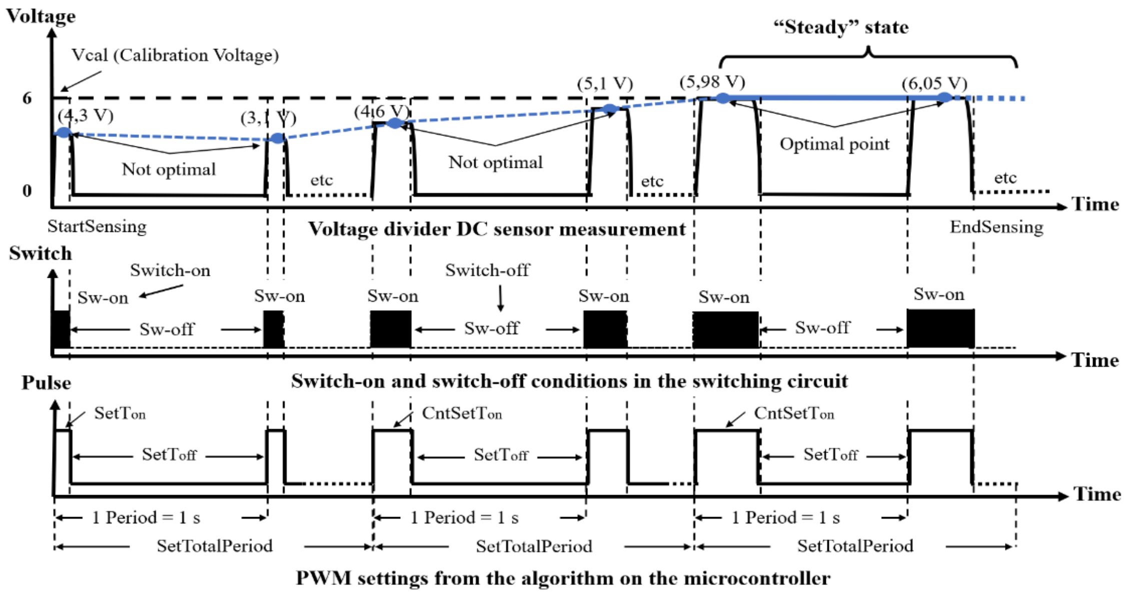

Figure 5. Explanation of testing IICL scheme using the STEADY algorithm

The explanation in Figure 5 focuses on the final test, which yields a "STEADY" state time value. Setting the input voltage calibration (Vin) on the power supply to 6 volts is the first step. A formula for lowering the period time with the Ton value (one second) will then automatically modify the wake-time (SetTon), which ranges from 0.1 milliseconds to one second, and the sleep-time (SetToff). The time period on the resulting PWM is then set for one second. Three hundred testing periods and three hundred data measurements will result from setting the total time period (TotalPeriod) for the testing process at five minutes. StartSensing, the following stage in the process, is what will cause the switching circuit to create PWM in the "high" state, which will cause the "switch-on" status to be triggered as a wake-time condition. The wireless DC voltage sensor will detect the output voltage using the STEADY algorithm built into the ESP-32 microcontroller. Testing is still in progress, and it will be finished (TotalPeriod) if the measurements indicate that the average voltage from 300 data points is between 5.91 and 6.09 volts, which is the voltage tolerance. The process continues with additional setting adjustments (CntSetTon) if the average voltage reading is still below the 5.91 to 6.09 V range. This will continue until the output reaches the optimal voltage within the designated range, as indicated by the "steady" state being reached 100% of the time or after testing up to 300 data points. Once the following testing cycle has reached the "steady" status ten times, the testing step (EndSensing) will be initiated. The fastest wake-time (Ton) value was found to be in the range of 1 ms, 2 ms, 3 ms, and so on, up to 1 second, based on testing of the STEADY algorithm in the IICL scheme applied using a wireless DC sensor prototype to achieve "STEADY" status after ten rounds of testing.

3.2. Voltage, time, and battery life-time

The final test was conducted through a comparative study of testing in a real experiment with the treatment of three different scenario conditions. In the first scenario, the IICL scheme was treated without using the STEADY algorithm. In the second scenario, the IICL scheme was treated using the STEADY algorithm, which was set in duty cycle mode with a wake-up time of one millisecond and a sleep time of one second. In the third scenario, the IICL scheme was treated using the STEADY algorithm, which was set in duty cycle mode with a wake-up time of one millisecond and a sleep time of 60 seconds. The test results are displayed graphically in Figures 6 and 7.

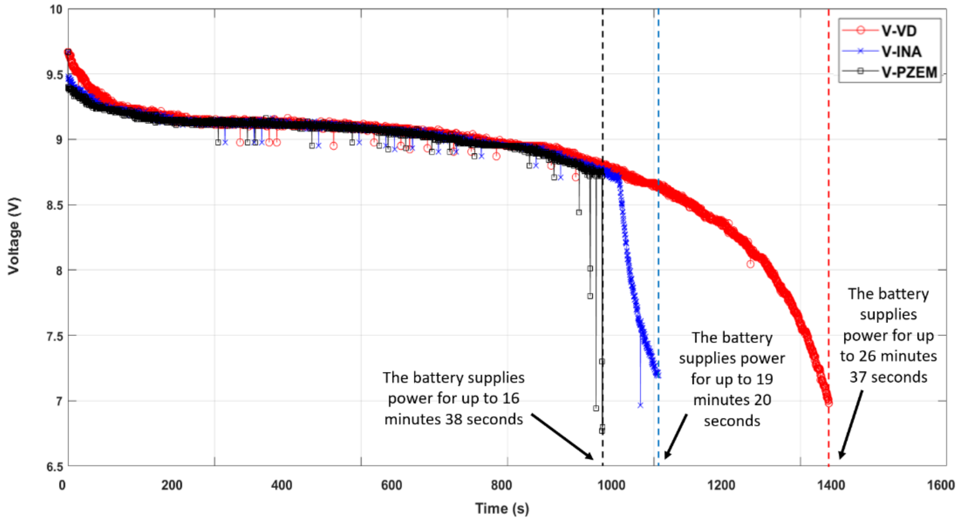

Figure 6. Graph of test results on the IICL scheme without the STEADY algorithm

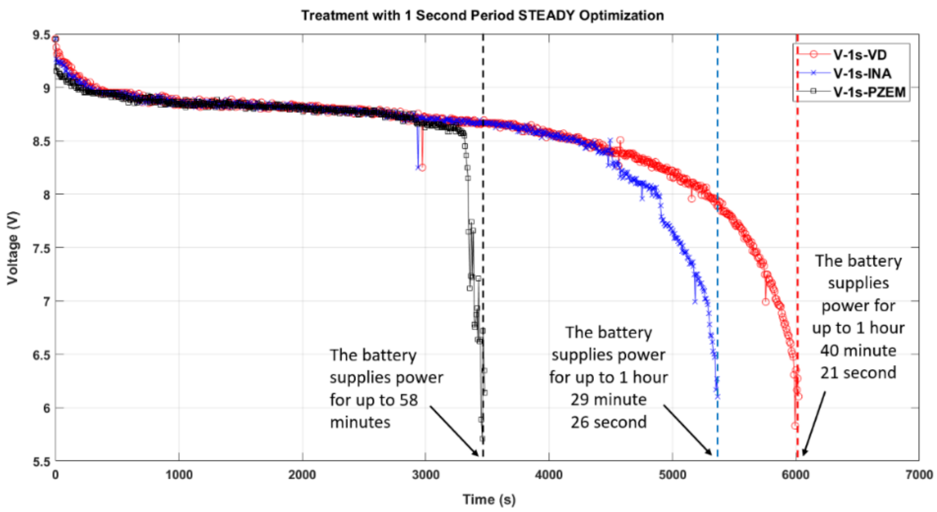

Figure 7. Graph of test results on the IICL scheme which applies the STEADY algorithm

3.3. Analysis of testing result data

The experimental and testing datasets were then analyzed using linear regression to evaluate the effect of overhead on the accuracy of sensor readings in measurements controlled by the duty cycle. The linear regression analysis procedure is formulated through as (2):

$$Y = \beta 0 + \beta 1X + \varepsilon \tag{2}$$

In (2), Y is the sensor accuracy, X is the duty cycle, β0 and β1 are the regression coefficients, and ε is the random error. The coefficients β0 and β1 represent the relationship between variables in the linear regression model. Accuracy is assessed by calculating the R-squared value, which indicates the proportion of data variation, for the significance test it is calculated using the t-statistic and p-value. Furthermore, to predict, it is formulated with the absolute deviation sum ADS model which is expressed through (3) and (4):

$$SAD = \frac{\sum|Yt - Ft|}{n} \tag{3}$$

$$Accuracy = 100\% - SAD \tag{4}$$

The results of the analysis processed using the STATCAL application, from in (2)-(4), are described through linearity and normality distributions, as shown in Figure 8 and in addition, the output is summarized in Table 3.

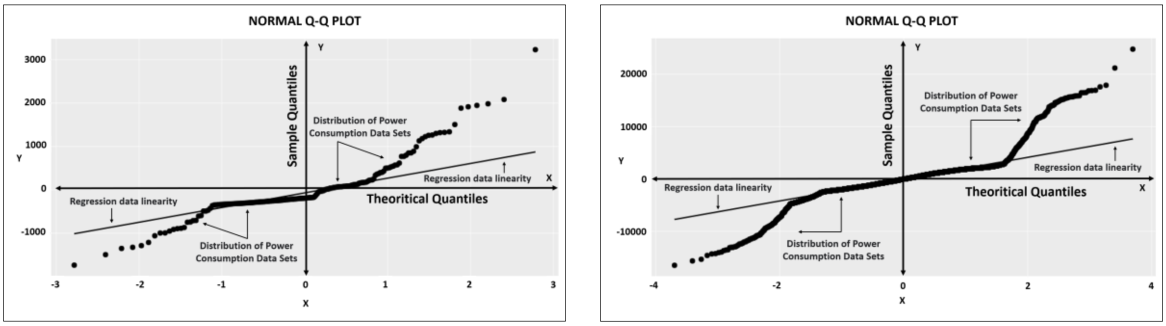

Figure 8. Graph of test results on the IICL scheme which applies the STEADY algorithm

Table 3. Data from the comparison of testing results

Sensor type	β0 and β1	R-squared	t	SAD	Accuracy
VZEM-017	0.702	0.488	-3.06	4.13	95.87
INA-219	0.766	0.551	4.61	2.52	97.47
VD-2023	0.582	0.561	-5.63	1.53	98.47

4. CONCLUSION

This study introduces a duty cycle regulation strategy, called the STEADY algorithm, which aims to minimize the current flow in a closed-loop system to reduce the power consumption of a battery-powered IoT-based wireless sensor load, thereby saving energy and extending battery life. In an instantaneous closed-loop configuration, called the IICL scheme, the STEADY algorithm optimizes the fastest incidental switching time technique. The performance of the proposed method is tested in three different scenarios and with various wireless DC voltage sensor load conditions. Experimental data shows that the system using the STEADY algorithm achieves longer battery life compared to the system without the algorithm. Moreover, when the STEADY algorithm is applied with a 1-second sleep time compared to a 1-minute sleep time, the latter results in a longer battery life, indicating higher efficiency in energy saving with a longer sleep duration. Experiments using the IICL scheme without the STEADY algorithm with real-time wireless DC voltage sensor sensing settings, only resulted in a short battery usage time of 16 m 38 s for the VZEM-017 type DC voltage sensor load, 19 m 20 s for the INA-219 type, and 26 m 37 s for the VD-2023 type. While experiments applying the IICL scheme using the STEADY algorithm with a wake-up time setting of 1 millisecond and a sleep time setting of 1 second for the VZEM-017 type DC voltage sensor load for 58 minutes, for the INA-219 type for 1 hour 29 minutes 26 seconds, and for the VD-2023 type for 1 hour 40 minutes 21 seconds. These results provide definitive evidence that the IICL scheme, which uses the STEADY algorithm, extends battery life, and energy savings are higher because the VD-2023 type wireless DC voltage sensor prototype uses less power.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The author uses or generates research data in this study.

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