Implementation of an adaptive data logging algorithm in low-cost IoT nodes for supply chain transport monitoring

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***Abstract*— In IoT-based supply chain transportation, low rates for data loss, minimizing time to destination, and optimizing energy consumption are paramount. These factors can be influenced by variable parameters, data volume, logging procedures, positioning complexities, and communication hiccups during transit. This study introduces an adaptive data logging algorithm for a cost-effective IoT node, addressing these challenges. This innovation enables real-time data acquisition and remote display via a web interface. Experimental tests demonstrate the prototype's reliability in both controlled indoor and dynamic outdoor environments, particularly in environmental and GPS data collection. Results reveal 5.24% data loss indoors and 23.24% via the web interface. Outdoors, data loss peaks at 55.34%, increasing to 82.76% with the web interface. However, the obtained information is adequate for prototype validation. The algorithm reduces data by 74%, leading to lower data processing and power transmission needs. Moreover, determining the distance from GPS coordinates is essential for predicting travel times and monitoring vehicle velocity to maximize efficiency. The results from this prototype are expected to enhance the development of advanced models, thus enriching future scientific research initiatives that aim to incorporate IoT technology into transportation systems.**

***Index Terms*— adaptive data logging, data reduction, internet of things, smart transportation.**

I. Introduction

The "Internet of Things" (IoT) refers to a system where physical objects are interconnected via the internet using sensors, enabling autonomous functionality [1]. IoT envisions an interconnected world, establishing relationships between objects, environments, and people [2]. Smart cities, driven by embedded systems and advancements in Information and Communications Technology (ICT), are gaining global traction. This paradigm integrates ICT, including IoT, cloud computing, big data, and spatial information, to enhance urban planning and management. IoT's crucial aspect lies in remote monitoring, vital in industries necessitating continuous oversight of products or services during storage, transportation, and retail [3]. Control over environmental factors can significantly reduce perishable goods losses, ensuring optimal delivery to customers [4]. Conventional systems with such capabilities are often costly and complex, involving hardware, software, applications, interfaces, storage, and more [5]. Thus, a cost-effective, reliable platform is urgently needed for low-complexity data acquisition while optimizing energy consumption.

This work aims to propose a cost-effective prototype for remote data monitoring, featuring an adaptive approach geared towards optimizing data acquisition efficiency within the supply chain transportation of products. Additionally, the study includes an analysis involving the calculation of positions based on latitude and longitude coordinates, with the specific aim of estimating transit times for the products.

Problem statement and justification

This research explores enhancing smart transport algorithms by leveraging IoT resources to improve performance and cost-effectiveness. It introduces an adaptive data logging algorithm within an affordable IoT node prototype for efficient processing and storage of GPS georeferenced temperature and humidity data, crucial for supply chain transport monitoring. By reducing data transmission and losses, the algorithm enhances computing efficiency and battery life, making it viable for both indoor and outdoor use, even in resource-constrained environments. This approach also promotes technological innovation, energy efficiency, and economic development in Latin America where, as in other emerging economies, the availability of sophisticated electronic devices and ICT infrastructure may be limited, aligning with the United Nations Sustainable Development Goal 9: Industry, Innovation, and Infrastructure [6].

Hypothesis and goal

This study hypothesizes that current smart transportation models can be made more cost-effective by using adaptive data logging algorithms and off-the-shelf electronic components. The goal is to assess this approach's performance by employing microcontrollers, sensors, and GPS devices at the edge to collect, process, and validate data with low loss during transmission, supported by basic back-end and front-end infrastructure for an end-to-end IoT platform in real-world scenarios like transportation.

Scope and delimitation

This study details the development and tests of a prototype that implements an adaptive data logging algorithm in

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affordable IoT nodes, aimed at efficient data collection and processing for supply chain transport monitoring. The research evaluates the algorithm's ability to reduce data transmission without significant loss of information, thereby enhancing computing efficiency and battery life. Although detailed energy consumption analysis is beyond this work's scope, the study theoretically demonstrates that reduced data transmission suggests potential energy optimization. Future research should address industrial scaling and cybersecurity, as well as evaluate performance and power consumption in more complex environments.

Literature review

IoT technology encompasses a broad spectrum of subjects, presenting challenges for standardization. It is crucial to identify relevant studies and surveys that provide valuable insights to define and scope our experimental setup for monitoring supply chain transportation effectively. Basaure et al. [7] emphasize IoT's potential for innovation, particularly in critical sectors like transportation, agriculture, healthcare, and environmental management. Safar and Halgurd [8] highlight the prevalence of indoor and outdoor localization services as versatile IoT applications. Argyriou [9] explores the smart city concept, highlighting how it integrates technologies such as IoT, cloud computing, big data, and spatial information for improved urban planning. Quian [10] underscores the socioeconomic benefits of IoT in emerging economies, particularly in countries like China, which have made substantial investments in technological zones. GSMA's analysis [11] demonstrates exponential IoT growth in China while noting global market immaturity due to ad-hoc solutions and a lack of standardized components. Craigen [12] defines cybersecurity as resources, processes, and structures safeguarding cyberspace and systems. Various standards, protocols, and rules are in place to mitigate risks to information and infrastructure. Karen Rose and Scott Eldridge [1] provide a comprehensive overview of four prevalent IoT models, outlining their respective pros and cons and shedding light on how networked devices enhance user experiences. IoT platforms often grapple with managing extensive data volumes.

Numerous data reduction techniques have been explored across various fields [13], including data mining, coordinate measurements [14], and dynamical system simulations [15]. In hardware, Mahindar [16] introduces an IoT-based home appliance control system employing the NodeMCU microcontroller with Wi-Fi. Mamta and Tiwari [17] implement a similar home automation system using HTTP requests, integrating relays for remote switch operation. The platform leverages the NodeMCU (ESP32) microcontroller along with relays for remote electrical switch operation. Khan [18] develops a portable biometric attendance system utilizing the NodeMCU, enabling wireless communication to a web server for data storage in a database. The system captures data from registered students, automatically recording their attendance.

In product management, Abdulahad [19] engineers a system for monitoring and controlling air quality, temperature, and humidity in remote food stores through web servers, enabling automated cooling and contamination removal. Sarkar et al. [20] create a LoRa transceiver system for IoT sensor data storage and monitoring, with a reported cost of approximately 150 USD. This project focuses on connecting cities and suburban areas without relying on conventional communication providers, using Wi-Fi modules and secure cloud-based databases. Finally, significant efforts are devoted to cold chain supply monitoring [21], employing Wireless Sensor Network and RFID technologies, with successful validation in a container port. The authors primarily assess detection capabilities in this context.

Specifically, in relation to adaptive methods for data reduction, Table I highlights how the proposed solution in this work differs from and improves upon existing approaches.

TABLE I
COMPARISON BETWEEN ADAPTIVE METHODS FOR DATA REDUCTION

Approach	Focus	Key metrics	Improvement in the proposed solution
Adaptive Data Reduction for IoT [13]	Data reduction in IoT through dynamic sampling and transmission adjustments.	Data transmission reduction (up to 95%).	Further optimizes data logging intervals and incorporates GPS georeferenced data to enhance IoT monitoring systems.
Implicit & Explicit Adaptive Algorithms [14]	Stability and efficiency in solving ODEs, particularly stiff systems.	Stability, number of steps, computational efficiency.	Focuses on optimizing energy consumption and reducing data transmission needs, tailored for IoT environments.
Adaptive Methods for Numerical Integration [15]	Adaptive numerical integration in dynamical systems.	Error reduction, convergence rate, computational time.	Applies adaptive techniques specifically to IoT systems, improving data logging efficiency in real-time applications.
Proposed solution in this work	Adaptive data logging in low-cost IoT nodes for supply chain monitoring.	Data reduction (up to 74%), file size reduction (up to 75%).	Introduces an algorithm that dynamically adjusts data acquisition intervals based on environmental variables, leading to more efficient data handling and energy use in IoT applications.

Smart transportation

The integration of IoT for real-time monitoring shows great potential in goods transportation. These devices enable continuous tracking of vital parameters like route, velocity, and cargo condition in transit. Thus, there is a need for advanced IoT tracking and monitoring devices to meet evolving supply chain demands. In today's transportation landscape (rail, sea, road, air), each mode poses distinct challenges from environmental conditions, logistical intricacies, and unforeseen events. Failures in refrigeration or mishaps in storage and transportation are not uncommon, heightening spoilage concerns. Fluctuations in environmental factors, like temperature and humidity, can occur abruptly during storage and transit, creating favorable conditions for microorganism proliferation [22].

A. Benefits

Integrating IoT technologies into supply chain-managed vehicles opens a range of potential tasks and benefits [23]:

- Streamlining routes and delivery schedules for optimization;
- Detecting and promptly alerting to abrupt braking or sharp turns during transit;
- Notifying of instances of speeding or extended idle time on the road;
- Real-time monitoring of vehicle geolocation;
- Continuous monitoring of the status of transported goods;
- Enhanced control over vehicle maintenance;
- Gaining insights into drivers' driving habits;
- Reducing the time required for the commercialization of services and products.

Smart transportation concepts can extend across practically every industry and business no matter the size. Applications goes from connecting medical coolers for the transportation of organs and vaccines between hospitals, to smart textiles that can detect changes in temperature or even pallets that can send information regarding cargo, location, and weather [24].

B. Challenges

While IoT monitoring systems offer substantial benefits within the supply chain, they also present notable technical challenges that necessitate careful consideration and resolution for effective development in this domain:

- Mobility: For vehicular applications, bidirectional data transmission is crucial. Interruptions in network access are common during movement. Additionally, outdoor components may face power constraints, requiring optimization for sustainable system lifetime [25];
- Retransmissions: Efficient strategies are needed to address data loss from factors like mobility, low device battery levels, and network congestion or unavailability;
- Big Data: Scalability leads to vast data generation. Minimizing processing and transmission of sensed data is essential, involving the reduction of redundant sensor information to cut down on storage and communication overhead;
- Effective Communication Protocol: HTTP and MQTT are suitable for IoT applications, showing proficiency in low-power computation and aligning with energy constraints in IoT devices;
- Scalability: IoT systems must accommodate varying numbers of sensors and actuators, ensuring stable connections, consistent performance, and the ability to serve numerous coexisting clients in real time;
- Reliable and Secure Data Management: Identity verification, message encryption, and robust authentication protocols are indispensable for safeguarding data during transmission;
- Energy Constraints: IoT platforms require embedded systems with modest computational power and finite energy sources. This is crucial in smart transportation systems designed for tracking abnormal events, necessitating heightened monitoring frequency and increased energy consumption.

II. Proposed Prototype Solution

The system prototype proposal has two modules connected via wireless communication, each chosen for specific functionalities in line with proposed requisites. It acquires environmental data (temperature, humidity, and geographical coordinates – latitude and longitude from GPS readings). The architecture follows a Client-Server model (Figure 1), aligned with a Device-To-Gateway Communication model. The client module, functioning as the data acquisition entity, integrates with a microcontroller acting as a gateway. This gateway processes acquired data before sending it to the Server module using HTTP commands. The Server module collects data from the Client module, displaying it on a web interface. Additionally, it archives data for historical review and subsequent analysis.

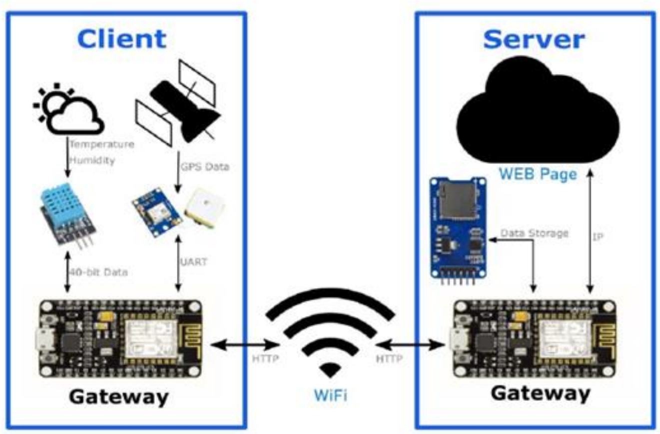

Fig. 1. Communication diagram.

Web page

The web page was created with HTML, CSS, and JavaScript, providing structure, style, and functionality respectively [26]. It displays acquired data from the client to the user, automatically refreshing every 30 s. It is composed of the main sections presented in Figure 2 and listed as follows:

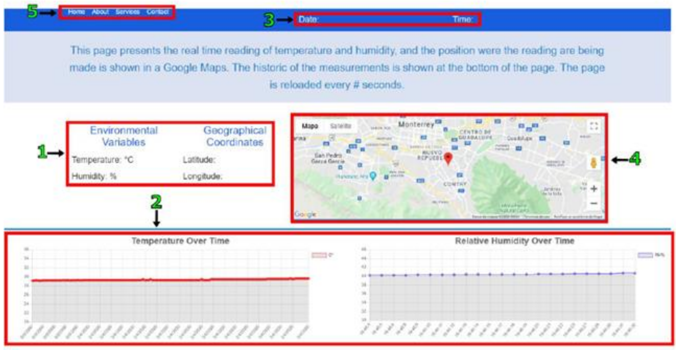

Fig. 2. Web Page main sections.

1. Displays temperature and humidity readings from the DHT sensor, along with latitude and longitude from the GPS.
2. Historic plots show the latest values for temperature and humidity, with time on the horizontal axis and data value on the vertical axis. The vertical axis scale adjusts based on the one hundred data points plotted during each refresh.
3. Presents the date and time obtained from the GPS.
4. Utilizes the Google Maps API to show the location based on latitude and longitude under Geographical Coordinates.
5. Includes a menu bar for potential future development, currently serving a decorative purpose.

The web page employs the Google Maps API, requiring the inclusion of the Maps Javascript API in the HTML5 code. It is important to note that the use of these APIs may incur costs based on request frequency and site visits. Figure 3 displays the JavaScript code for integrating the Google Maps API. To display the client device's current location, the latitude and longitude serve as variables for the API. A marker is added to enhance the visualization of the client device's location.

```
<script type="text/javascript">
function initMap() {
    var location = {lat:-25.363, lng:131.044};
    var map = new google.maps.Map(document.getElementById("map"),
        {zoom:4,center:location});
    var marker = new google.maps.Marker({position:location,map:map});}
</script>
<script async defer src="https://maps.googleapis.com/maps/api/js?key=
AIzaSyDF-1-ZxYLJU6EkG5TRagwtmuWkJAxsLBo&callback=initMap"></script>
```

Fig. 3. Google Maps integration on Web Page.

Prototype price

Prototype cost is a critical consideration alongside scope and time constraints. It is imperative to optimize the electronic platform's affordability without compromising functionalities. Table II provides a breakdown of component costs for the electric platform, facilitating budget estimation for prototype development. Prices are listed in dollars and based on the "Alibaba" company website.

Notably, hardware for visualization was omitted from this table, as information can be accessed through dashboards or cloud platforms. Thus, a comprehensive real-time system with multiple sensors can be implemented for only $13.52.

TABLE II
COMPONENTS AND PRICE OF THE ELECTRONIC PLATFORM

Component	Price
NodeMCU	$2
DHT11 Temperature and Humidity sensor.	$0.77
NEO 6M GPS Sensor.	$3.50
MicroSD Card Adapter.	$3.25
4GB SanDisk MicroSD Card.	$3
Breadboard.	$1
	$13.52

Client components

- NodeMCU: An open-source IoT platform combining firmware compatible with the ESP8266 Wi-Fi System on Chip (SoC) and hardware based on the ESP-12 module [27]. It allows convenient programming using the Arduino IDE, simplifying data capture, processing, and transmission on the edge;
- DHT11 Module: An off-the-shelf component for acquiring temperature and humidity values. It interfaces with the NodeMCU, with an average sensing period of 2 s. It provides a range of 20% - 90% for humidity and 0° - 50°C for temperature;
- NEO6MV2 GPS Module: Known for its compact design and power efficiency, the NEO-6 module is suitable for battery-powered mobile devices with cost and space constraints [28]. It also provides date and time information in Coordinated Universal Time (UTC) zone.

The client device, facilitated by NodeMCU, continuously acquires humidity and temperature values along with the prototype's location status. Its primary function is internet connectivity, initiating data acquisition from modules upon receiving a server response. The time zone is synchronized with the relevant zone of interest, and the remaining data is structured into a URL, which is then transmitted to the designated server via HTTP commands. After each batch transmission, the client checks for server availability for subsequent data transfer.

It is important to mention that the NEO6MV2 GPS module utilizes NMEA protocol to report different metrics, including heading and ground speed (in the $GPVTG message). However, the reason for calculating speed based on the difference between position points in this work is to for cross-verification of speed data, ensuring greater accuracy and robustness in environments where GPS-reported speed might be compromised. Additionally, this method enables the calculation of speed even when the $GPVTG message is not available or when the algorithm needs to account for delays in data transmission that could affect real-time monitoring. This approach also enhances the precision of speed measurements in specific scenarios where the GPS signal might be unstable or when data points are sparse due to connectivity issues.

Server components

The server setup includes the NodeMCU and a Micro-SD card module, enabling communication and data read/write operations.

- Micro-SD card: It is compatible with the Arduino environment and supports both SD and Micro-SD cards with larger storage capacity compared to EEPROM memory. It utilizes the Sdfatlib library for FAT16 and FAT32 file systems [29].

The function of the server is to receive and process data sent by the client via HTTP commands, providing it when requested by the web page. Data is stored on the Micro-SD card for analysis and further processing. The server is accessed via a web browser using the designated IP. The firmware starts by declaring variables like SSID, password, IP address, gateway, mask, and global variables. It then sets up the Wi-Fi with the designated IP, initializes the Micro-SD card module, and begins listening for client requests. The handleURL function retrieves the URL generated by the client, extracts data, and stores it in designated variables. Information storage in the Micro-SD card is managed by this function. Additionally, HTML code for the web page is included in this function and assigned to the variable htmlPage, which is sent by the server upon browser request. The main routine waits for a client to connect, and once connected, the program restarts.

Communication between the card and microcontroller occurs through SPI via pins CSK, MOSI, MISO, and the activation pin CS (set as GPIO15). The Server device processes the received URL, reads parameters, and stores values in firmware-declared variables. These values are stored in the Micro-SD card in CSV format.

Figure 4 shows the data stored in the Micro-SD card. To enable communication between the Client and the Server, knowledge of the server's IP address is essential. The server device is assigned this IP through firmware configuration using the ESP8266 libraries. It functions within a local Wi-Fi network and is inaccessible from outside the network due to the confidential nature of the provided information. External access to the server can be achieved through a VPN or by implementing a public IP address.

It is important to highlight that the use of a Wi-Fi access point and a mobile server, although widely available in remote regions, is only a temporary measure for the prototype testing phase of this work, whose main objective is to evaluate the performance of the adaptive data logging algorithm and its impact on computational efficiency and battery life, particularly in dynamic and resource-limited environments. The need to implement a more robust and secure Wireless Wide Area Network (WWAN) protocol, such as Long-Term Evolution (LTE), Long Range Wide Area Network (LoRaWAN) or Narrowband (NB)-IoT, is also recognized for practical deployment in wide-area transportation scenarios.

```
ID, DATE, TIME, TEMPERATURE, HUMIDITY, LATITUDE, LONGITUDE
1, 24/3/2020, 19:46:18, 40.40, 36.00, 25.699120, -100.154167
1, 24/3/2020, 19:46:19, 40.40, 36.00, 25.699121, -100.154175
1, 24/3/2020, 19:46:20, 40.50, 35.00, 25.699125, -100.154175
1, 24/3/2020, 19:46:21, 40.50, 35.00, 25.699131, -100.154182
1, 24/3/2020, 19:46:22, 40.50, 35.00, 25.699141, -100.154190
1, 24/3/2020, 19:46:23, 40.60, 34.00, 25.699146, -100.154198
1, 24/3/2020, 19:46:27, 40.60, 34.00, 25.699144, -100.154190
1, 24/3/2020, 19:46:28, 40.60, 36.00, 25.699135, -100.154182
1, 24/3/2020, 19:46:30, 40.60, 36.00, 25.699137, -100.154182
1, 24/3/2020, 19:46:31, 40.70, 34.00, 25.699137, -100.154175
```

Fig. 4. The data is stored in the Micro-SD card every second.

III. Prototype Testing

Tests were categorized into two classes, detailed in Table III: indoor static environments (3^{rd} and 5^{th} tests) and outdoor dynamic environments (4^{th} and 6^{th} tests). Each category was further subdivided to evaluate hardware system performance (tests 3^{rd} and 4^{th}) and system performance with the mobile server (tests 5^{th} and 6^{th}). The initial test validated sensor connections and readings. The subsequent test assessed functionality of client and server devices, along with their intercommunication. Additionally, in an Indoor Static Environment, a seventh test with the adaptive data reduction method was executed. Tests were thoroughly debugged using the Arduino IDE, and information was displayed on the serial monitor. The tests adhere to established methodologies described in [30, 31, 32, 33].

TABLE III
Tests categories

Category	Subcategory	Test number
Indoor static environments	Performance on hardware system	3^{rd}
	Performance on system using mobile server	5^{th}
	Using an adaptive method	7^{th}
Outdoor dynamic environments	Performance on hardware system	4^{th}
	Performance on system using mobile server	6^{th}

Tests in Indoors static environments

The third and fifth tests confirmed seamless integration of client device components, communication with the Server device, and flawless Mobile Server operation. Upon successful Wi-Fi connection, the serial monitor promptly displayed variable updates. Crucial information, including IP address, data transmissions, and URLs, was sent through this interface. The third test lasted 42 min and 56 s (2,576 s total), resulting in a data file of 2,576 rows, inclusive of server firmware waiting time. The fifth test (Figure 5) evaluated system performance with the mobile server and followed a similar protocol but incorporated the Mobile Server for data visualization. This test concluded in 46 min and 20 s (2,780 s total).

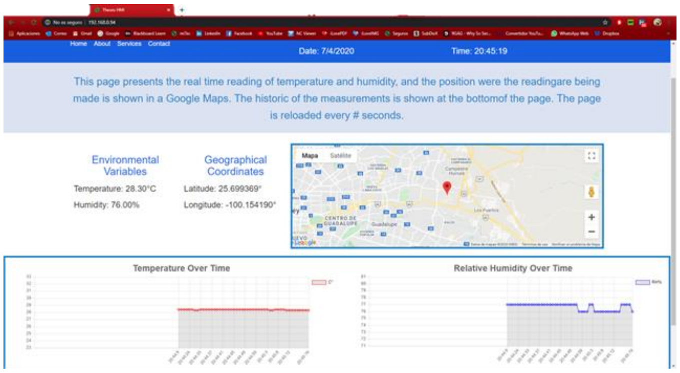

Fig. 5. Web page display during the fifth test.

Adaptive method in indoor static environment

The primary objective of the adaptive method was to enhance the efficiency of data acquisition, tailored to specific project characteristics. In the devised system, pivotal variables encompass temperature, humidity, longitude, and latitude. The proposed adaptive approach entailed modifying the time interval, denoted as h, which represents the acquisition time, and adjusting it by $h = 2$ or $2h$ contingent on the result of equation 1:

$$\varepsilon = |Y_b - Y_a| \quad (1)$$

Equation 1 yields the absolute difference between $Y_a = Y_n+1$, representing the subsequent data point to be acquired, and Y_b, the data point acquired after the time interval h. Should $e < tolerance$ then $h_{new} = h/2$; conversely, if $e > tolerance$ then $h_{new} = 2h$. The specified tolerance must align with the minimum discernible changes essential in measurements.

To validate the implementation of the adaptive method, an indoor test was conducted, with temperature selected as the variable determining the time interval for data storage on the micro-SD card. The algorithm was executed under the following parameters and constraints: Tolerance of 0.2 °C, h is set to 1 s, minimum acquisition time of 1 s, maximum acquisition time of 16 s.

Test in Outdoors static environments

The fourth test assessed hardware system performance in an outdoor dynamic environment using Wi-Fi communication through a Redmi A8 cellphone hotspot, which was configured with specific SSID and password in its firmware. This test lasted 28 min and 2 s (1,683 s total). Using latitude and longitude data, the test route was mapped on Google Maps (Figure 6), yielding 920 data points in a separate CSV file for map generation.

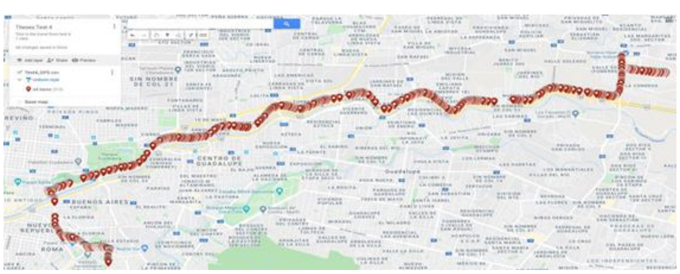

Fig. 6. Fourth field test for outdoor route.

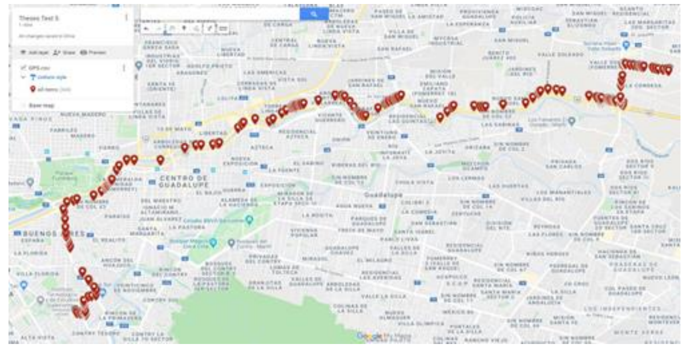

Fig. 7. Sixth field test for outdoor route.

The sixth test aimed to evaluate the system's performance in an outdoor dynamic setting, utilizing the mobile server. It followed a similar protocol to the fourth test, with modifications to specific route paths. This time, the Mobile Server was incorporated to validate real-time data display. The test ran for 22 min and 20 s (1,340 s total), and the route is depicted in Figure 7.

Getting distance from GPS coordinates

The acquired data can be analyzed more comprehensively by calculating the distance between two points on the designated route. This allows for the computation of an average velocity, providing insights into the vehicle's speed. Using latitude and longitude coordinates, this distance can be determined using the Haversine formula [34]. This formula, crucial in navigation, enables the calculation of great-circle distances on a spherical surface based on the respective longitudes and latitudes. To ensure accurate calculations, it is essential to express the angles in radians before applying them in trigonometric functions.

The Haversine formula is delineated as follows:

$$a = sin^2\left(\frac{\Delta\emptyset}{2}\right) + cos\emptyset_1 cos\emptyset_2 sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (2)$$

$$c = arctan2\left(\sqrt{a}, \sqrt{1-a}\ \right) \quad (3)$$

$$d = Rc \quad (4)$$

where $\emptyset$ is latitude, λ is longitude, R is the earth's radius (mean radius = 6372.8 Km), a is the angular distance in radians, and c is the square of half the chord length between the points.

Two specific points along the route were chosen for a comparative analysis using the Haversine formula and distances from Google Maps. The selection considered their linear alignment, ensuring a minimum temporal gap of 30 s, and accessibility on the Google Maps interface. The chosen test points are outlined below:

- Point 1

ID, DATE, TIME, TEMPERATURE, HUMIDITY, LATITUDE, LONGITUDE

1, 24/3/2020, 1 9 : 4 8 : 0 7 , 4 3 . 1, 29 , 25.699780 , -100.15741;

- Point 2

ID, DATE, TIME, TEMPERATURE, HUMIDITY, LATITUDE, LONGITUDE

1, 24/3/2020, 1 9 : 4 8 : 5 7 , 4 3 . 5, 24 , 25.700619 , -100.16375.

Figure 8a visually displays these selected points. A MATLAB script was created for computations of (2), (3), and (4). With the latitude and longitude values of the chosen points as input, the distance was calculated as 0.6422 Km (642.2 meters). These points were carefully chosen on Google Maps to closely align with their real-world counterparts, featuring a gas station and a hardware store as identified landmarks in Figure 8b. In contrast, Google Maps indicated the distance between the two points as 0.650 Km (650 meters). This results in a relative discrepancy of 7.8 meters compared to the distance derived from (2).

Given this established distance, the average velocity for this section of the route can be computed as

$$v = D/T \tag{5}$$

Given that the time intervals are expressed in s, a conversion to h is necessitated to yield the velocity in Km/h. Given that there is a 50 s interval between the two points, this translates to 0.0138889 hours. With 0.6422 Km, the velocity between these points is calculated as $0.6422/0.0138889 \cong 46.2384\, Km/h$.

This method allows for velocity determination within a designated route segment. However, it is crucial to note that the accuracy of distance calculations depends on the linearity of the chosen path. With this method, velocity estimates can be computed for each interval, using the corresponding distances and times in-between. This information is valuable for gaining insights into the average velocity along the route. It is important to mention that intermittent stops along the route will result in velocity readings of zero. The estimated velocities for each interval are depicted in Figure 9.

Fig. 8. A) Route selected points, b) Google Distance Calculation.

Fig. 9. Velocity plot.

The velocity profile, as depicted in Figure 9, displays dynamic fluctuations. It starts with subdued values, transitions into elevated velocities, and eventually subsides. This progression closely aligns with the anticipated behavior along the designated route. The journey initiates in an urban precinct, traversing various neighborhoods, as illustrated in Figure 6. The zenith of velocity is reached upon merging onto the freeway leading from Guadalupe NL to Monterrey NL. Subsequent values represent velocities sustained during the freeway segment. The initial instances of near-zero velocities coincide with entry into another urban expanse, followed by transit along a major thoroughfare. Noteworthy is the second instance of near-zero velocity, occurring when the vehicle halts at a traffic signal. The terminal values reflect passage through additional neighborhoods in proximity to the destination, hence the observed near-complete cessation of motion.

The derivationn of position provides a means to ascertain instantaneous velocity, and further differentiation of velocity yields acceleration. Employing a centered differences approach, it becomes viable to estimate acceleration for each alteration in velocity [35]. This method is executed through the application of (6) and (7):

$$y'(t) \approx \frac{y_{n+1} - y_{n-1}}{2h} \tag{6}$$

$$h = t_{n+1} - t_n \tag{7}$$

where y is the velocity, y' is the acceleration, t is the time, h is the time interval between the next value and the actual value.

Acceleration data, as shown in Figure 10, highlights instances of velocity increase, decrease, or constancy. When the acceleration curve shifts from positive to negative along the time axis, it indicates a decrease in velocity. Conversely, when it shifts from negative to positive, it denotes an increase in velocity. Zero acceleration corresponds to constant velocity. Due to the high data volume in the outdoor test, subtle changes in both graphs may not be immediately discernible. However, an initial visual examination confirms the expected behavior.

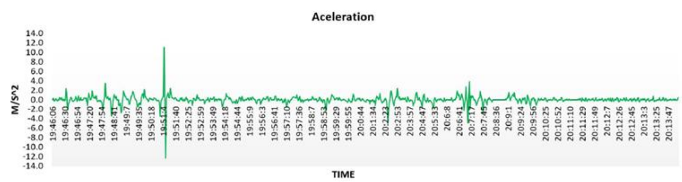

Fig. 10. Acceleration plot.

IV. Results and Conclusions

A. Results

Indoor environment

In the third test, the CSV file contained 2441 rows of information within the selected time interval, resulting in a 5.24% data loss, indicating 135 lines out of the expected 2576 were absent. This discrepancy may be attributed to the following circumstances:

- The client firmware employs two while statements, awaiting the availability of both the server and GPS for data acquisition. The duration for the completion of these statements may vary by ms, potentially leading to slightly prolonged communication with the server.
- The specific indoor test location may have encountered difficulties acquiring a GPS signal. Notably, the maximum data absence duration was approximately 3 s.

Nevertheless, this missing information does not hinder the objectives of the project. In the fifth test, the corresponding CSV file had 2134 rows of data. This test yielded a 23.24% data loss. It is noteworthy that when using the web page, data loss increased. An examination of the CSV file revealed that with each request made by the web page to the server, an average interval of 5 s ensued during which no data was acquired. This accounts for the reduced number of information rows.

Outdoor environment

In the fourth test, the CSV data file contained 920 lines of information, resulting in 763 unrecorded lines out of the expected 1683. This indicates a data loss of 55.34%, which is significantly above the anticipated value. Figure 11 visually illustrates that a substantial portion of the route has recorded data, mitigating the criticality of the missing information in this context. If there were extensive stretches without recorded data, visualizing the route would have been more challenging. The chosen 1 s interval for data storage appears to have provided sufficient information for validating the system prototype. However, it is crucial to investigate the reasons behind this absence of the expected information, which may be attributed to the following factors:

- The client firmware includes two while statements, awaiting the availability of both the server and GPS for data acquisition. The duration for the completion of these statements may vary by ms, potentially leading to slightly prolonged communication with the server.
- The hotspot generated by the Redmi 8A intermittently experiences connectivity issues with the SIM vendor network.
- The GPS may require additional time to acquire data due to movement.
- In-car Mobile Signal Attenuation [36].

Plots depicting humidity and temperature trends were generated from the acquired data (Figure 11a and Figure 11b, respectively). A clear relationship is observed, where temperature rises alongside a decrease in humidity. This correlation is logically consistent, as elevated temperatures within a car lead to drier interior conditions, given the typically arid urban environment. The data retrieved from the fourth outdoor test was subsequently plotted and analyzed (Figure 11) to assess its accuracy. While no direct correlation between temperature and humidity is discerned, it is crucial to note that relative humidity depends on the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature. With higher temperatures, the likelihood of surface water molecules vaporizing intensifies [37]. Consequently, relative humidity declines with increasing temperature, aligning with the observed behavior in Figure 11. These results affirm the proper functionality of the environmental sensing components within the system prototype.

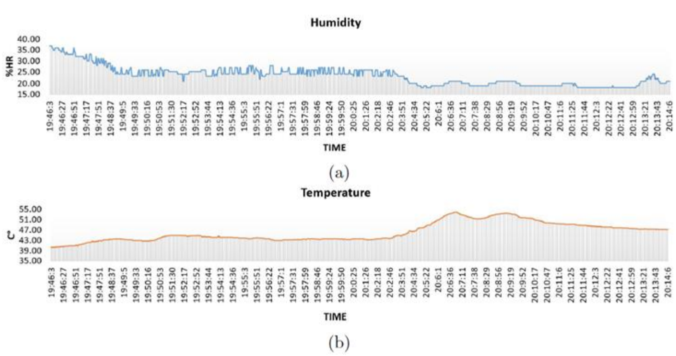

Fig. 11. A) Percentage of relative humidity, b) Temperature in Celsius degrees

The sixth test followed the same protocol as the fourth but employed the web page for data loss assessment. It is important to note that the Google Maps API requires a change in location each time the web page is refreshed. The resulting CSV file contained 231 lines of information, indicating a deficiency of 1109 lines compared to the expected dataset. Despite a higher data loss of 82.76%. Figure 7 shows that this limited dataset is still sufficient for route identification.

Table IV summarizes the loss in row data resulting for each test. It is crucial to note that the default acquisition time is set to 1 s, considering the expected high volume of data points per test. The results from this analysis support the feasibility of extending the acquisition time, given the low variability observed in the primary variables of interest. Throughout testing, the parameters with the most significant fluctuations were latitude and longitude. In contrast, temperature and humidity levels rarely deviated by more than 10%. Therefore, it is essential to explore more efficient methods for data acquisition.

TABLE IV
DATA LOSS OBTAINED IN INDOOR AND OUTDOOR TESTS

	Indoor Test	Outdoor Test
Using Web page	23.24%	82.76%
Without Web page	94.76%	44.66%

Adaptive method

The chosen data acquisition duration occasionally proved insufficient for establishing system connectivity or obtaining complete information from the sensors, particularly the GPS module. This challenge was more pronounced in the outdoor test, where connectivity depended on the device functioning as an internet gateway. To assess the adaptive methodology, an indoor test was conducted, using temperature as the primary variable dictating data storage intervals on the micro-SD card.

The algorithm was executed with defined parameters: a tolerance threshold of 0.2 °C, initial time interval of 1 s, minimum acquisition duration of 1 s, and maximum acquisition duration of 16 s. The test lasted 14 min and 40 s, equivalent to 880 s. At the start, temperatures ranged between 30.80 °C and 30.90 °C, satisfying $\varepsilon <$ tolerance, leading to an increase in h from 1 s to 2 s. The algorithm iterated until it reached an h value of 16 s.

Around 2 min and 21 s into data logging with measurements every 16 s, the temperature sharply rose to 47.6 °C. During these temperature fluctuations, the h value oscillated between 4, 2, and 1 s intervals for 6 min and 53 s before stabilizing, resulting in an h value of 16 s. Figure 12 illustrates the measurements and corresponding timestamps for each acquisition event.

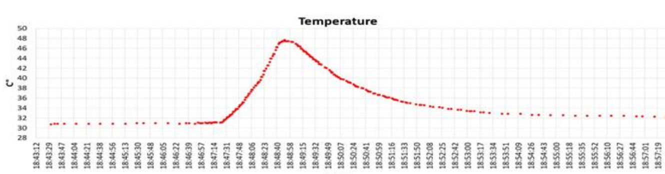

Fig. 12. Temperature from adaptive method.

By setting the acquisition interval time to 1 second, 880 lines of information were expected. However, when adjusted to the percentage of data loss previously obtained in the third test, 827 lines of information were anticipated. The CSV file that was generated contained 218 lines of information. The changes in temperature, from the initial rise until stabilization, were included in those lines. The most important information for the test was correctly stored. Table V highlights a comparative measuring hardware performance in indoor environments and employing the adaptive method.

TABLE V
COMPARISON BETWEEN THE THIRD AND SEVENTH TESTS

Test number	Test duration	Time Interval	Rows expected	Rows registered
3	2576s	1s	2576	2441
7	880s	1s to 16s	827*	218

*Compared with third test considering data loss and an interval of 1s.

Based on the experimental findings outlined in Tables IV and V, using a 1-second time interval resulted in a 5.24% data loss during the third test conducted without a web page. This percentage represents the expected maximum data loss when using the adaptive method, as the minimum time interval was set at 1 second during the seventh test. The most critical information for the test was correctly stored. A typical CSV file with 880 lines of data has a size of approximately 68 KB, whereas the files generated with 2441 and 218 lines measure 189 and 17 KB, respectively. The adaptive method, therefore, led to a significant 75% reduction in CSV file size for this test. While this method reduces the amount of data stored on the micro-SD card, it is important to note the documented alterations. Specifically, the adaptive algorithm enhances data acquisition efficiency by reducing the volume of stored data.

The power consumption per KB transmitted in a wireless communication system is influenced by multiple factors, including the communication protocol used (HTTP versions), payload size, distance to the server, network conditions, and whether edge or cloud computing is utilized. Additional factors include data transfer patterns, transport layer characteristics, protocol implementation efficiency, device CPU utilization, transceiver power states, and environmental conditions like signal strength. These elements collectively determine the energy efficiency of data transmission. As mentioned at the introduction, a detailed analysis of energy consumption is beyond the scope of this work. However, information on the energy consumption for different payload sizes and communication protocols is available from [38] and [39], leading to an average estimate of 5.1 ± 1.5 mJ/KB. Consequently, the 75% file size reduction obtained with the proposed adaptive algorithm, has the potential to reduce energy consumption associated with data transmission from 240 to 22 mJ for the 189 and 17 KB files generated in test # 3 y #7, respectively; meaning that the reduction percentage on energy consumption between using the proposed adaptive method (#7) and the baseline performance on hardware system (#3) is approximately 90.83%.

B. Conclusions

Data loss, covering maintenance, accuracy, and consistency, was maintained in all system prototype tests. These assessments covered static indoor and dynamic outdoor environments. Results showed low data loss, recording 5.24% in static indoor tests and 23.24% via the web interface under similar conditions. Dynamic outdoor tests achieved a 55.34% data loss, increasing to 82.76% with the web interface, mainly due to network compatibility issues.

These experiments confirm the IoT system’s robustness in accurately monitoring product status, even with partial data capture in indoor and outdoor scenarios. It highlights the potential for optimizing data acquisition intervals, given the stable nature of temperature and humidity compared to variables like latitude and longitude. Implementing an adaptive data collection method resulted in a substantial 74% reduction in data and a 75% reduction in final Comma-Separated Values (CSV) file size.

By using adaptive data collection, the monitoring interval can be extended, reducing energy consumption for data transmission and storage. Additionally, acquired geographical coordinates enable precise position calculations based on latitude and longitude. These coordinates also allow for the computation of velocity and acceleration through a centered differences approach. These calculations form the basis for new routines aimed at ensuring optimal vehicle or equipment use by monitoring velocity. Furthermore, this analysis enables the prediction of time to destination in scenarios where time sensitivity is critical for product preservation.

C. Complementary studies

This article serves as a foundational reference for future IoT platform development with a focus on efficient perishable product management. An area for improvement lies in enabling internet access to the mobile server, expanding beyond local networks. This entails acquiring a public IP address, typically provided by the Internet Service Provider (ISP) [40]. Although associated with costs and privacy considerations, this step is vital for effective remote communication, ultimately enhancing device performance.

Regarding the prototype’s components, there’s potential for augmentation with alternatives featuring advanced features or differing functionalities. For instance, integrating a SIM card module would enable direct internet connectivity through the mobile network, eliminating the need for a separate Wi-Fi router.

Expanding the proposed adaptive method to encompass not only temperature but also humidity and position, based on the relative importance of each parameter, is feasible. A hierarchical decision-making process could be implemented to dynamically adjust data storage duration on the Micro-SD card, prioritizing parameters with the most significant changes or minimal variations. Additionally, a default parameter could govern the adaptive algorithm, potentially focusing initially on position, and later shifting to temperature.

Advanced projects could explore integration with network service providers like Sigfox, offering software-driven communication solutions, or Lora Alliance, dedicated to facilitating Low Power Wide Area Networks (LPWAN) deployment through the LoRaWAN standard [41]. These providers aim to address low data density applications by ensuring device interoperability and managing network complexities in the Cloud, rather than on individual devices. Notably, Sigfox leads in establishing the world's largest IoT ecosystem, catering to diverse sectors including manufacturing, startups, and device manufacturers [42]. In [39], the major versions of the HTTP protocol are evaluated in terms of energy consumption for constrained devices, such as IoT systems. The evaluation shows that for most of the scenarios the energy consumption increments as the payload size increases. In that sense, an actual energy consumption characterization analysis would be beneficial to complement the study of adaptive data logging algorithms for efficient data transmission

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