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Wien, 9. Dezember 2025

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Abstract

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Gendererklärung

Das in dieser Arbeit gewählte generische Maskulinum bezieht sich zugleich auf die männliche, die weibliche und andere Geschlechteridentitäten. Zur besseren Lesbarkeit wird auf die Verwendung männlicher und weiblicher Sprachformen verzichtet. Alle Geschlechteridentitäten werden ausdrücklich mitgemeint, soweit die Aussagen dies erfordern.

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4.1 Introduction

4.1.1 Background and Context

In recent years, the Internet of Things (IoT) has woven itself into the fabric of daily life at an extraordinary pace, fundamentally changing how we interact with our physical surroundings. This digital transformation is perhaps most visible in the agricultural sector, which is currently navigating a shift known as “Agriculture 4.0”. We are seeing a move away from traditional, intuition-based farming toward precise, data-driven decision-making, all enabled by interconnected sensor networks [1]. While industrial agriculture has already reaped significant efficiency gains from this revolution, a parallel and equally important trend is taking root in the consumer world: Smart Urban Gardening [2].

Driven by rapid global urbanization, shrinking living spaces, and a rising awareness of environmental sustainability, urban gardening has grown into a significant movement [3]. This is more than just a hobbyist trend; it signals a shift toward the Social Internet of Things (SIoT) [4]. The SIoT paradigm expands our traditional understanding of IoT by suggesting that objects can establish social relationships, not just with other machines but with people, creating a truly collaborative ecosystem [5]. In this new context, a plant is no longer just a passive biological entity. It becomes an active participant in a digital social network, capable of communicating its needs and status directly to its caretaker.

However, bringing these advanced concepts into the home using consumer-grade hardware creates a unique set of engineering hurdles [6]. Unlike industrial systems, which often rely on stable power grids and dedicated infrastructure, consumer IoT devices for plant care must survive in resource-constrained environments. These devices often need to run for months on small batteries while staying connected to congested and unstable home Wi-Fi networks. This reality demands a rigorous and creative approach to optimizing both hardware and software strategies [7].

4.1.2 MMotivation for Smart Gardening and the Social Internet of Things

The current wave of urban agriculture represents a convergence of technological capability and social necessity. As city populations continue to expand, access to fresh produce becomes both more critical and more challenging. Smart gardening systems address this gap by empowering individuals to cultivate food and ornamental plants in constrained urban environments with minimal prior expertise. The integration of real-time sensor feedback transforms gardening from an art based on experience into a science accessible to novices.

Moreover, the incorporation of social and gamification elements addresses a fundamental psychological barrier: the delayed gratification inherent in plant care. Traditional gardening requires patience and sustained attention over weeks or months before visible results emerge. By providing immediate digital feedback on watering actions, light exposure adjustments, and fertilization events, smart systems create a continuous reinforcement loop that maintains user engagement. This transformation aligns with established principles of behavioral psychology, where immediate rewards significantly strengthen habit formation [8].

The Social IoT framework further enhances this experience by enabling plants to participate in social networks. Users can share their achievements, compare plant health metrics with friends, and receive community-driven care recommendations. This social layer converts solitary plant maintenance into a collaborative activity, leveraging peer motivation and collective knowledge to improve outcomes.

4.1.3 Case Study: The “Plant Up!” Project

This thesis uses the “Plant Up!” project as a primary testbed to investigate these architectural challenges. “Plant Up!” is a comprehensive IoT application designed to gamify the experience of plant care, turning routine maintenance into an engaging activity [9]. By providing immediate digital feedback on biological processes, the system bridges the gap between human perception and the actual physiological needs of a plant.

The system is built on a robust three-tier architecture that combines distributed sensor units, a scalable cloud microservices backend, and a user-facing mobile application [10]. At the edge, ESP32-S3-based sensor nodes continuously monitor environmental metrics including soil moisture (via LM393 resistive conductivity sensor), ionic conductivity (DFRobot Gravity V2 EC sensor), ambient light intensity (BH1750 lux sensor with range up to approximately 65,000 lux), and surface temperature (MLX90614 infrared non-contact sensor). These nodes report to a cloud infrastructure powered by Supabase, which processes the raw telemetry, applying business logic to track both user progress and plant health. Finally, the application layer presents this data through a Flutter-based mobile interface that transforms mundane tasks into social achievements and rewards.

The system employs a hybrid communication architecture: sensor nodes transmit telemetry via MQTT to minimize power consumption and latency, while the mobile application consumes data via REST (specifically, Supabase's auto-generated PostgREST API). This dual-protocol approach allows the system to optimize for the distinct constraints of each subsystem while maintaining architectural coherence through a unified backend.

4.1.4 Problem Statement

Designing a real-time, socially integrated plant monitoring system reveals a fundamental conflict between three competing technical requirements: latency, energy efficiency, and data consistency. The“ Social” aspect of the platform relies heavily on gamification mechanics that demand low latency to keep users immersed [8]. For example, when a user waters their plant, they expect to see that action reflected in the app almost immediately, ideally within a few hundred milliseconds. Any perceptible delay disrupts the psychological feedback loop and diminishes user engagement.

However, to remain practical for home use, the hardware cannot drain its battery in a matter of days. It must utilize aggressive power-saving states, such as the ESP32-S3's deep sleep mode [11]. In deep sleep, the main CPU, Wi-Fi radio, and the majority of RAM are powered down, reducing current consumption from approximately 160-260 mA to just 10-150 microamperes. Only the Real-Time Clock (RTC) memory and the Ultra-Low-Power (ULP) coprocessor remain active, enabling the device to wake on a timer or external trigger. While deep sleep dramatically extends battery life, waking up and reconnecting to Wi-Fi introduces unavoidable delays that directly clash with the need for real-time responsiveness [12].

Furthermore, the choice of communication protocol dictates the “wake-up tax”, which is the cumulative energy expenditure required to establish a network connection before transmitting even a single byte of application data. Traditional web protocols like HTTP (REST) are robust and universal, but they impose significant overhead. Each HTTP request requires a full TCP three-way handshake, and when secured with TLS (as is standard practice), an additional TLS handshake phase is necessary. This sequence typically involves multiple round-trip messages, each consuming radio time and therefore battery capacity. Additionally, HTTP headers are verbose text-based structures that can exceed the payload size for small telemetry messages.

In contrast, lightweight protocols like MQTT are designed specifically to address these inefficiencies. MQTT employs a publish-subscribe model mediated by a broker, which decouples message producers from consumers. Once the initial connection to the broker is established, subsequent publishes require only minimal fixed-size headers (typically 2-5 bytes). However, it is critical to note that MQTT’s performance gains are highly dependent on the Quality of Service (QoS) level, encryption configuration (TLS vs. plaintext), and the underlying network conditions. For instance, QoS 1 (at-least-once delivery) and QoS 2 (exactly-once delivery) introduce additional handshake steps that can partially negate the protocol’s latency advantages [13, 14].

Finally, maintaining a consistent view of the system state in such a distributed architecture is a non-trivial challenge. As the CAP theorem (Consistency, Availability, Partition Tolerance) demonstrates, a distributed system cannot guarantee all three properties simultaneously during a network failure [15]. In a residential IoT setting where network partitions are a common occurrence due to router reboots, Wi-Fi interference, and mobile client disconnections, the system must make calculated trade-offs. Prioritizing availability and partition tolerance (AP) typically implies adopting eventual consistency, where updates propagate asynchronously and temporary divergence between nodes is tolerated.

4.1.5 Research Question

To systematically address these challenges and identify the optimal architectural approach, this thesis poses the following primary research question:

How do MQTT and REST compare in a microservices-based architecture for real-time plant monitoring, specifically regarding latency, throughput, and energy efficiency, when *constrained by the battery limitations of ESP32-S3-based IoT devices in a residential Wi-Fi environment?*

This question decomposes into several subsidiary inquiries:

- What is the measurable difference in end-to-end latency (from sensor wake-up to server acknowledgment) between MQTT and REST under controlled home network conditions?
- How do the effective payload sizes (including protocol overhead) compare for typical telemetry messages?
- What are the implications of these differences for battery life in a device operating on a periodic wake-sleep cycle?
- Under what conditions (e.g., QoS level, payload size, network latency) does one protocol decisively outperform the other?

4.1.6 Contributions

This thesis makes the following contributions to the field of consumer IoT system design:

1. **Empirical Protocol Comparison**: A rigorous, controlled empirical comparison of MQTT and REST protocols on identical ESP32-S3 hardware, measuring latency, payload efficiency, and reliability under realistic home Wi-Fi conditions. Unlike prior work that relies on simulation or theoretical analysis, this study provides real-world measurements.
2. **Firmware Architecture Documentation**: A detailed technical description of the ESP32-S3 firmware architecture, including the wake $\rightarrow$ measure $\rightarrow$ serialize $\rightarrow$ transmit $\rightarrow$ sleep cycle, sensor acquisition procedures, and JSON payload formatting. This documentation clarifies common misconceptions (e.g., that MQTT uses binary payloads in this implementation) and provides a reference for similar projects.

   item **Hybrid Communication Architecture**: A demonstration of how MQTT and REST can be effectively combined in a single system to optimize for the distinct constraints of edge devices (low power, low latency) and mobile applications (rich querying, ease of development), while maintaining data consistency through Supabase Row-Level Security (RLS) policies.

3. **Architectural Guidelines**: Practical design guidelines for consumer IoT deployments that balance real-time responsiveness, battery sustainability, and development complexity. These guidelines address protocol selection, QoS configuration, and consistency model trade-offs.

4.1.7 Thesis Structure

The remainder of this thesis is organized as follows:

Chapter 2 presents the theoretical foundations necessary to understand the subsequent analysis, including event-driven IoT architectures, microservices enablement through Supabase and PostgREST, energy modeling of ESP32-S3 deep-sleep modes, related work on consumer IoT constraints, and a deeper theoretical comparison of MQTT versus REST.

Chapter 3 describes the complete system architecture of the Plant Up! platform, including detailed firmware architecture, sensor-specific technical corrections, the hybrid communication approach, and data consistency mechanisms.

Chapter 4 details the experimental methodology, including research design (variables, hypotheses), hardware and software configuration, measurement instruments, repetition strategy, and validity measures.

Chapter 5 presents the experimental evaluation results, including setup description, quantitative findings, interpretation, anomaly analysis, and discussion of network conditions.

Chapter 6 discusses the implications of the results for real-world deployment, battery life consequences, experimental limitations (lack of TLS testing, QoS 0 only, home Wi-Fi variability, indirect power measurement), and comparison with related literature.

Chapter 7 concludes the thesis by directly answering the research question, summarizing the architectural reasoning, and outlining future work including MQTT-SN, message batching, TLS evaluation, alternative radio technologies (LoRaWAN), machine-learning-based anomaly detection, and direct power measurement using INA219 or similar ICs.

4.2 Theoretical Background

4.2.1 Event-Driven Architecture in IoT

Event-driven architecture (EDA) represents a paradigm shift in how distributed systems process and react to state changes. Unlike traditional request-response models where clients poll servers for updates, EDA inverts this relationship: components emit events when significant state transitions occur, and interested subscribers react to those events asynchronously. This decoupling provides substantial advantages for resource-constrained IoT deployments.

In the context of battery-powered sensor nodes, EDA minimizes unnecessary wake cycles. Rather than polling sensors at fixed intervals regardless of environmental changes, an event-driven system can trigger measurements only when thresholds are crossed or timers expire. For example, the ESP32-S3's ULP coprocessor can monitor a threshold crossing (e.g., soil moisture dropping below a critical level) and generate a wake event for the main processor only when intervention is necessary. This selective wake behavior dramatically reduces average power consumption compared to periodic polling strategies.

Moreover, EDA aligns naturally with the publish-subscribe model employed by MQTT. When a sensor node publishes a measurement event to a topic, it does not need to maintain awareness of which backend services will consume that data. New analytics services can be added by simply subscribing to existing topics, without modifications to the edge firmware. This temporal and spatial decoupling enhances system evolvability and fault tolerance, Properties that are critical when devices operate unattended for extended periods [17].

4.2.2 Microservices Architecture (MSA)

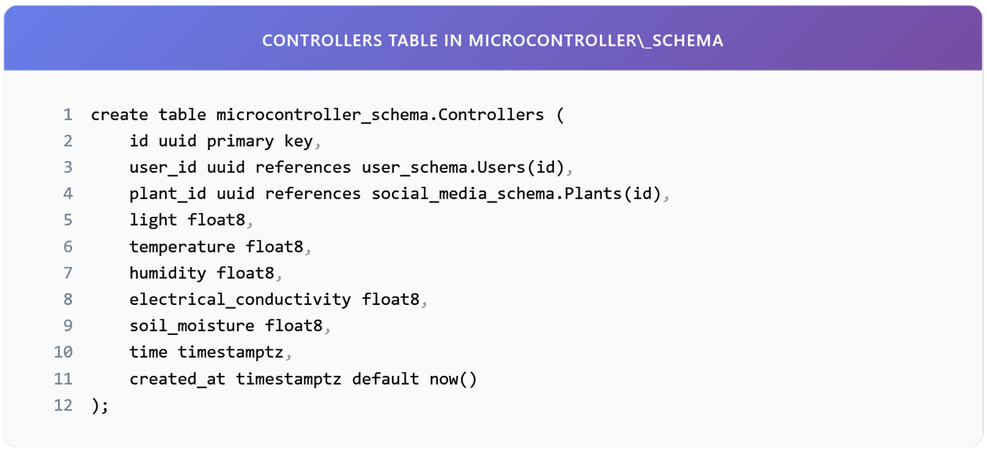
Microservices Architecture (MSA) represents a fundamental shift in how we build software, organizing applications not as single, monolithic giants, but as suites of small, autonomous services that work together [17]. In a traditional monolith, everything, from user management to data processing, is tightly woven into one large codebase. While this makes starting a project easy, it often turns into a bottleneck for scalability and fault tolerance as the application grows [18].

MSA takes a different approach. It treats the application as a collection of independent services, each running in its own process and communicating through lightweight channels, like HTTP APIs or messaging buses [19]. Each service acts as a specialist in its own specific business domain. For “Plant Up!”, this architectural style is particularly well-suited. It allows us to build and scale distinct parts of the system independently. For example, the service that ingests thousands of sensor readings per minute can be scaled up during peak periods without disturbing the social feed service, which might experience different load patterns.

The “Plant Up!” backend is organized around domain-specific schemas in Supabase, which act as the dedicated data stores for these microservices:

- `user_schema`: Handles everything related to user identity, authentication, and personal statistics like care streaks.
- `social_media_schema`: Manages the community aspects including user posts and comment threads.
- `gamification`: Houses the logic that transforms plant care into an engaging experience through quests, experience points (XP), and rewards.
- `microcontroller_schema`: A dedicated high-throughput channel for ingesting raw sensor telemetry from IoT devices.

A clear example of this separation is how we isolate sensor readings. They reside in their own table, completely decoupled from user data:



CONTROLLERS TABLE IN MICROCONTROLLER_SCHEMA

```
create table microcontroller_schema.Controllers (
    id uuid primary key,
    user_id uuid references user_schema.Users(id),
    plant_id uuid references social_media_schema.Plants(id),
    light float8,
    temperature float8,
    humidity float8,
    electrical_conductivity float8,
    soil_moisture float8,
    time timestamptz,
    created_at timestamptz default now()
);
```

Abbildung 4.1: Controllers table in microcontroller_schema

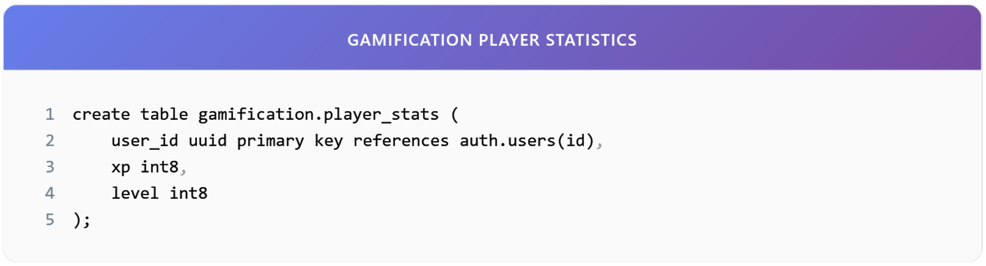
This strict domain boundary improves system robustness. If the sensor ingestion service experiences a fault, it does not cascade to the gamification or social features.

4.2.3 Core Characteristics of Microservices in IoT

Applying Microservices Architecture to the Internet of Things brings a unique set of challenges. IoT systems are inherently asynchronous, event-driven, and must cope with the unpredictable physical world.

Autonomy and Database per Service

One of the foundational principles of MSA is“ Database per Service”. This pattern mandates that services are decoupled not only in their application logic but also in their persistent state [20]. It eliminates the risk of unintended coupling where a schema change in one service inadvertently breaks another. In “Plant Up!”, the Gamification Service maintains its own denormalized view of player statistics, which is completely independent of the raw time-series stream of incoming sensor measurements.



```sql
create table gamification.player_stats (
    user_id uuid primary key references auth.users(id),
    xp int8,
    level int8
);
```

Abbildung 4.2: Gamification player statistics

Scalability and Elasticity

IoT workloads exhibit extreme temporal variability. Traffic patterns are often characterized by long quiescent periods punctuated by sharp bursts when large cohorts of devices wake simultaneously. MSA enables selective horizontal scaling: only the “Ingestion Service” needs additional instances during burst periods, while the “Social Service” can remain at nominal capacity. This elasticity reduces infrastructure costs and improves resource utilization compared to monolithic architectures that must scale as a single unit.

4.2.4 Supabase and PostgREST as Microservice Enablers

Supabase provides a managed PostgreSQL database combined with an automatically generated RESTful API layer (PostgREST) and real-time subscription capabilities via WebSockets. This combination significantly reduces the boilerplate required to implement microservices by auto-generating CRUD endpoints directly from the database schema.

Each schema in the “Plant Up!” backend (e.g., `user_schema`, `microcontroller_schema`) corresponds to a bounded context in domain-driven design terminology. Supabase enforces data ownership and access control through Row-Level Security (RLS) policies defined at the database level. For instance, an RLS policy on the `Controllers` table ensures that only the MQTT ingestion service (authenticated via a service role key) can INSERT records, while mobile clients (authenticated via user JWT tokens) can only SELECT their own plant records.

This database-centric security model offers several advantages:

- **Defense in Depth**: Even if application-layer authorization is bypassed, the database enforces access controls.
- **Consistency**: Authorization logic is centralized rather than duplicated across multiple service implementations.
- **Performance**: RLS policies are evaluated within the PostgreSQL query planner, often leveraging indexes for efficient filtering.

PostgREST also provides sophisticated query capabilities via URL parameters, enabling mobile clients to perform filtering, sorting, and pagination without custom backend code. For example, fetching the most recent 10 sensor readings for a specific plant requires only a single HTTP GET request with appropriate query parameters.

4.2.5 Internet of Things (IoT) Constraints and Hardware

At the heart of “Plant Up!” is the ESP32-S3 microcontroller, a powerful System-on-Chip (SoC) from Espressif Systems [21]. Despite its capabilities (dual-core Xtensa LX7 processor, integrated Wi-Fi and Bluetooth), the ESP32-S3 remains fundamentally constrained by battery capacity. Protocol and software design choices directly dictate active radio time, which in turn determines battery longevity.

Power Consumption and Sleep Modes

The ESP32-S3 offers multiple power states, each with vastly different current draws. Understanding these modes is essential for architecting energy-efficient firmware:

- **Active Mode:** CPU and Wi-Fi radio fully operational. Current consumption ranges from **160 mA to 260 mA** depending on transmit power and CPU activity [22]. This represents the most expensive state and should be minimized.
- **Modem Sleep:** CPU remains active for sensor processing, but the Wi-Fi radio is powered down between transmissions. Consumption drops to approximately 20-30 mA [22].
- **Light Sleep:** CPU clock is paused, but RAM and peripherals remain powered. Wakeup is nearly instantaneous (microseconds).
- **Deep Sleep:** The most aggressive power-saving mode. The main CPU, Wi-Fi/Bluetooth radios, and the majority of RAM are completely powered down. Only the Real-Time Clock (RTC) memory and the Ultra-Low-Power (ULP) coprocessor remain active, consuming a mere **10 μA – 150 μA** [21]. However, waking from deep sleep incurs significant latency (typically 1-3 seconds) as the system must reinitialize Wi-Fi and renegotiate network connectivity.

Energy Modeling of ESP32-S3 Deep Sleep and Wake Cycles

To estimate battery life, we model the energy consumption over a complete wake-sleep cycle. Let T_{sleep} represent the sleep duration, T_{wake} the active duration, I_{sleep} the deep sleep current (100 μA typical), and I_{active} the active current (200 mA typical). The average current I_{avg} over one cycle is:

$$I_{avg} = \frac{I_{sleep} \cdot T_{sleep} + I_{active} \cdot T_{wake}}{T_{sleep} + T_{wake}}$$

For a device that wakes every 10 minutes ($T_{sleep} = 600$ s) and remains active for 5 seconds ($T_{wake} = 5$ s):

$$I_{avg} = \frac{0.1 \text{ mA} \cdot 600 + 200 \text{ mA} \cdot 5}{605} \approx 1.75 \text{ mA}$$

With a typical 2000 mAh lithium battery, the theoretical lifespan is approximately $2000/1.75 \approx 1143$ hours or roughly 47 days. This simple model illustrates why minimizing T_{wake} (and therefore minimizing protocol overhead) is critical for practical deployments.

The Wake-Up Tax

Deep sleep provides substantial energy savings, but exiting this state incurs what we term the “wake-up tax”. Upon waking, the ESP32-S3 must reinitialize the Wi-Fi subsystem, scan for available access points, authenticate with the router, and obtain an IP address via DHCP. This entire process typically consumes **1 to 3 seconds** at an average current draw of 150 mA [23].

Critically, this overhead occurs *before* any application data can be transmitted. The choice of communication protocol determines how much additional time (and energy) is required beyond this baseline cost. A protocol with heavy handshake requirements (multiple round-trip messages) compounds the wake-up tax, while a lightweight protocol with persistent connections (or minimal connection overhead) minimizes it.

4.2.6 Communication Protocols: MQTT vs. REST

The selection of communication protocol is arguably the most consequential architectural decision for sensor-to-cloud communication. It fundamentally impacts energy efficiency, latency, and system reliability.

MQTT (Message Queuing Telemetry Transport)

MQTT is a lightweight, publish-subscribe messaging protocol originally designed by IBM for monitoring oil pipelines via satellite links, environments characterized by high latency and unreliable connectivity. These origins inform its design priorities: minimal packet overhead, tolerance for intermittent connectivity, and efficient use of constrained networks.

Architecture and Decoupling: Unlike REST’s direct client-server coupling, MQTT interposes a **Broker** between publishers and subscribers. Sensor nodes (publishers) transmit messages to named topics (e.g., `plantup/sensor/01/telemetry`) without knowledge of which services are consuming that data. The broker handles message routing to all subscribed services. This architecture provides decoupling in three dimensions:

- **Space Decoupling**: Publishers and subscribers do not need to know each other's network addresses.
- **Time Decoupling**: Messages can be queued by the broker if subscribers are temporarily offline, enabling store-and-forward behavior.
- **Synchronization Decoupling**: Publishers do not block waiting for subscriber processing; message delivery is asynchronous.

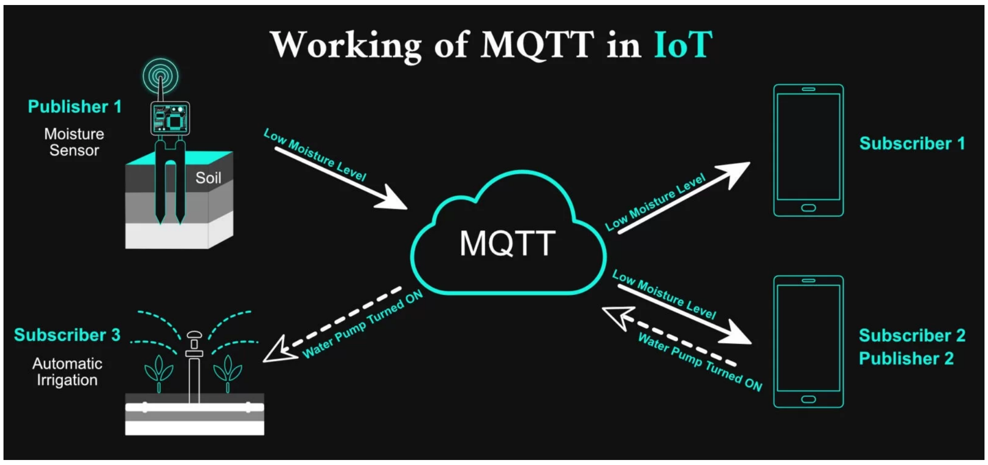


Abbildung 4.3: MQTT Publish/Subscribe Model: The broker acts as a central hub, efficiently distributing messages from sensors to various backend services [13].

Packet Structure and Efficiency: MQTT employs a compact binary wire format. The fixed header is merely **2 bytes**, consisting of a message type identifier and flags. Variable headers and payloads are length-prefixed. In contrast, HTTP headers are verbose ASCII text, typically including multiple header fields (Host, User-Agent, Content-Type, etc.) that can easily exceed 200 bytes even for trivial payloads. For small telemetry messages (e.g., 50 bytes of JSON sensor data), this header overhead ratio becomes significant.

Quality of Service (QoS) Levels: MQTT defines three QoS levels that offer a spectrum of delivery guarantees versus overhead trade-offs:

- **QoS 0 (At most once):** Fire-and-forget semantics. The publisher sends the message and assumes delivery without waiting for acknowledgment. This minimizes energy but provides no delivery guarantee.

- **QoS 1 (At least once):** The broker acknowledges receipt (PUBACK). The publisher retransmits if no acknowledgment arrives within a timeout. This provides delivery assurance at the cost of potential duplicates and additional message exchanges.
- **QoS 2 (Exactly once):** A four-step handshake (PUBLISH, PUBREC, PUBREL, PUBCOMP) guarantees precisely once delivery with no duplicates. The overhead is typically excessive for battery-constrained devices.

For the “Plant Up!” system, QoS 0 is employed for routine telemetry (where occasional message loss is acceptable) to minimize energy expenditure.

REST (Representational State Transfer)

REST is the dominant architectural style for web APIs, leveraging standard HTTP methods (GET, POST, PUT, DELETE) to operate on resources identified by URLs. It is synchronous, stateless, and resource-oriented.

Request-Response Model: REST follows a strict client-server interaction pattern. The client initiates a request and blocks (or polls) until the server responds. This synchronicity simplifies application logic but couples the client’s execution to network round-trip time.

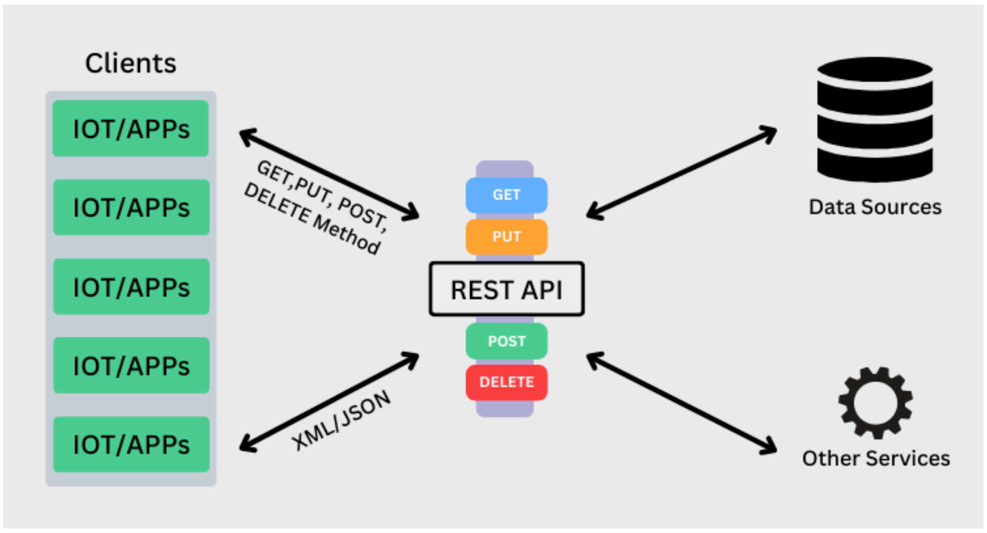


Abbildung 4.4: REST Request-Response Workflow: Stateless clients must establish a new connection for each request, incurring significant overhead [24].

Statelessness and Connection Overhead: HTTP is fundamentally stateless; the server retains no context between requests. This simplifies server design but forces clients to re-transmit authentication credentials and context with every request. When combined with TLS encryption (now standard practice), each HTTP request from a freshly awakened device requires:

1. TCP three-way handshake (SYN, SYN-ACK, ACK): 1.5 round trips
2. TLS handshake (ClientHello, ServerHello, Certificate exchange, Key exchange, Finished messages): typically 2 round trips for TLS 1.2, reduced to 1 RTT for TLS 1.3
3. HTTP request and response: 1 round trip

For a sensor node waking from deep sleep with no persistent connection, this totals approximately 4-5 network round trips before the application payload is acknowledged. At 50ms typical Wi-Fi round-trip time, this adds 200-250ms of latency *independent* of payload processing time.

4.2.7 Related Work on Consumer-Grade IoT Constrain ts

Several studies have examined the challenges of deploying IoT systems in residential environments, where devices lack the infrastructure support available in industrial settings.

Karaagac et al. [6] identify power and connectivity constraints as the primary barriers to consumer IoT adoption. Their survey emphasizes that battery-powered devices in home environments face unpredictable Wi-Fi quality, interference from consumer electronics, and limited user tolerance for maintenance (e.g., frequent battery replacements).

Hemus [7] categorizes IoT challenges into six domains, including security, connectivity, power, scalability, interoperability, and data management. Notably, the paper highlights that consumer devices must balance these concerns with stringent cost constraints, limiting the viability of expensive hardware solutions (e.g., dedicated cellular modems or supercapacitors).

Prior comparisons of MQTT and REST for IoT [14, 13] largely rely on theoretical analysis or simulation. Few studies provide empirical head-to-head measurements on identical hardware under realistic home Wi-Fi conditions, which this thesis addresses.

4.2.8 Data Consistency and the CAP Theorem

In distributed systems like “Plant Up!”, the CAP theorem (formulated by Eric Brewer) asserts that it is impossible to simultaneously guarantee Consistency, Availability, and Partition Tolerance in the presence of network failures [25, 26].

- **Consistency (C):** All nodes observe the same data at the same logical time. Reads always return the most recent write.
- **Availability (A):** Every request receives a (non-error) response, even if some nodes are unreachable.
- **Partition Tolerance (P):** The system continues to operate despite arbitrary message loss or node failures.

For “Plant Up!”, **Partition Tolerance (P)** is non-negotiable. Residential Wi-Fi networks experience frequent transient partitions due to router reboots, signal interference, and mobile client disconnections. Given P as a requirement, the system must choose between CP (sacrificing availability during partitions to maintain consistency) and AP (accepting temporary inconsistency to maintain availability).

“Plant Up!” adopts an **AP** (Available, Partition-tolerant) design with **eventual consistency**. It is acceptable for a user to observe a soil moisture reading that is several seconds stale, provided the application remains responsive and does not block or fail. The MQTT broker buffers messages during connectivity lapses, ensuring they eventually propagate to the microservices layer once connectivity is restored. This design prioritizes user experience (low-latency feedback) over strict real-time consistency, a trade-off appropriate for non-critical monitoring applications.

4.3 Plant Up! System Architecture and Implementation

4.3.1 System Overview and Vision

The “Plant Up!” platform represents the physical instantiation of the Social Internet of Things (SIoT) paradigm applied to urban horticulture. It integrates distributed IoT hardware, a scalable cloud microservices backend, and a mobile application into a unified ecosystem. The system gives plants a digital “voice” to communicate their physiological status to human caretakers. The primary objective is technically demanding: collect high-precision environmental telemetry from battery-powered edge devices, synchronize it through cloud infrastructure, and present it to users through a gamified interface that transforms routine maintenance into an engaging activity.

To realize this vision, the architecture must address three fundamental challenges:

- **Low-latency sensor synchronization:** The system must close the feedback loop between biological events (e.g., soil moisture depletion) and human perception with minimal delay to maintain engagement.
- **Energy-efficient operation:** Battery-powered sensor nodes must operate for months without intervention, necessitating aggressive power management through intelligent deep-sleep cycles and minimal radio usage.
- **Distributed data consistency:** With state partitioned across user, social, and hardware microservices, the system must maintain coherent views despite network partitions and asynchronous updates.

These requirements inform every architectural decision, from sensor selection and firmware logic to protocol choice and microservice boundaries. The resulting design comprises three layers: the Edge Node (hardware), the Cloud Layer (backend microservices), and the Application Layer (mobile client).

4.3.2 Hardware Layer: The Edge Node

The hardware layer serves as the system’s physical sensing apparatus, bridging the digital cloud infrastructure with the analog environment of soil, air, and light. At its core is an ESP32-S3 microcontroller augmented with a suite of environmental sensors: temperature, humidity, light intensity, soil moisture, and electrical conductivity. Operating on battery power imposes a strict duty cycle: the device spends the majority of its operational time in deep sleep, waking periodically to execute a rapid measurement sequence.

The firmware implements a deterministic wake-measure-serialize-transmit-sleep cycle:

1. **Acquisition:** Exit deep sleep, power on sensor array, acquire raw ADC or I2C readings.

2. **Serialization:** Map raw values to calibrated units, construct JSON payload.
3. **Transmission:** Transmit payload via MQTT or REST, await acknowledgment.
4. **Sleep Transition:** Immediately re-enter deep sleep to conserve energy.

This cycle typically completes in 3-7 seconds depending on protocol and network conditions, with the device remaining in deep sleep for the remaining 590+ seconds of a 10-minute reporting interval.

4.3.3 Firmware Architecture: Detailed Wake-Measure-Serialize-Transmit-Sleep Cycle

The ESP32-S3 firmware is structured around FreeRTOS tasks that orchestrate sensor acquisition, data formatting, and network communication. Understanding this low-level architecture is essential for evaluating protocol trade-offs.

Boot and Initialization Sequence

Upon exiting deep sleep (triggered by an RTC timer), the ESP32-S3 bootloader loads the application from flash and transfers control to the FreeRTOS scheduler. The first task performs the following initialization:

1. Restore configuration from RTC memory (which persists across deep sleep). This includes Wi-Fi credentials, MQTT broker address, and device identifier.
2. Initialize Wi-Fi subsystem and initiate association with the configured access point. This phase dominates wake-time, typically consuming 1-2 seconds and 150mA.
3. Obtain IP address via DHCP (if not using a static assignment).
4. For MQTT: Establish TCP connection to broker, send CONNECT packet, await CONNACK.
5. For REST: No persistent connection is established; connection setup occurs per-request.

Sensor Acquisition and Calibration

Once network connectivity is confirmed, the firmware powers the sensor array via GPIO-controlled MOSFETs (to prevent parasitic drain during sleep). Each sensor is read sequentially:

LM393 Soil Moisture Sensor: Contrary to earlier documentation, the LM393 is a resistive sensor that measures soil conductivity, not dielectric permittivity. The sensor outputs an analog voltage inversely proportional to soil water content. The ESP32-S3's 12-bit ADC (range 0-4095) samples this voltage, which is then linearized via a calibration polynomial stored in flash:

$$\text{moisture\_percent} = a_0 + a_1 \cdot V_{ADC} + a_2 \cdot V_{ADC}^2$$

where a_0, a_1, a_2 are determined via two-point calibration (dry air and saturated soil).

BH1750 Light Sensor: The BH1750 is an I2C digital ambient light sensor providing lux measurements. It offers a practical range up to approximately 65,000 lux with limited accuracy (±20% typical). The firmware configures the sensor for One-Time High Resolution Mode (1 lux resolution), issues a measurement command, and polls the I2C bus for the 16-bit result. No complex calibration is required as the sensor outputs directly in lux units.

DFRobot Gravity V2 EC Sensor: This sensor measures ionic conductivity (electrical conductivity in units of microsiemens per centimeter, μS/cm), which correlates with dissolved nutrient concentration. It is *not* a direct "salt content" meter, but rather an indicator of total dissolved solids (TDS). The analog output is sampled via ADC and temperature-compensated using a stored soil temperature reference (ideally from a separate thermometer, or a fixed compensation factor).

MLX90614 Infrared Sensor: The MLX90614 measures surface temperature via infrared radiation, not ambient air temperature. It communicates over I2C and directly outputs calibrated temperature in degrees Celsius. This non-contact measurement is useful for detecting canopy temperature, which differs from air temperature under direct sunlight.

JSON Payload Construction and Rationale

Sensor readings are serialized into a JSON object structure:

```
{
  "device_id": "plant_01",
  "timestamp": "2025-12-09T16:30:00Z",
  "soil_moisture_pct": 42.5,
  "light_lux": 12500,
  "ec_us_cm": 750,
  "temperature_c": 22.3
}
```

JSON was selected as the payload format despite its verbosity (compared to binary encodings like Protocol Buffers or CBOR) for several pragmatic reasons:

- **Human Readability:** JSON payloads can be inspected directly in broker logs and network packet captures, simplifying debugging during development.
- **Language Agnosticism:** Every modern backend framework and mobile SDK provides robust JSON parsing libraries, eliminating the need for custom deserialization code.
- **Supabase Integration:** Supabase/PostgREST natively consumes JSON, allowing direct POST requests to database tables without intermediate parsing layers.
- **Marginal Overhead:** For the small payloads transmitted (typically <100 bytes of application data), the overhead difference between JSON and binary encodings (perhaps 20-30 bytes) is negligible compared to protocol headers (MQTT fixed header: 2-5 bytes; HTTP headers: 200+ bytes).

The critical insight is that JSON's verbosity disadvantage is dwarfed by HTTP's header overhead in the REST case, and nearly irrelevant in the MQTT case where the fixed header is already minimal.

Transmission Phase: MQTT vs. REST Divergence

After JSON payload construction, the firmware follows one of two transmission paths depending on build-time configuration:

MQTT Path:

1. Construct PUBLISH packet: fixed header (1-5 bytes), topic name (e.g., `plantup/sensor/plan`
   25 bytes), JSON payload.

2. Send packet to broker over existing TCP connection.
3. For QoS 0: No acknowledgment awaited; proceed immediately to sleep.
4. For QoS 1: Await PUBACK from broker; retransmit on timeout.
5. Total transmission time (network RTT dependent): 50-200ms for QoS 0, +50-100ms for QoS 1.

REST Path:

1. Establish TCP connection to Supabase endpoint (if not persistent): 3-way handshake (1 RTT).
2. Perform TLS handshake: ClientHello, ServerHello, Key Exchange, Finished (2 RTT for TLS 1.2).
3. Construct HTTP POST request:

```
POST /rest/v1/Controllers HTTP/1.1
Host: <supabase-instance>.supabase.co
Content-Type: application/json
Authorization: Bearer <API_KEY>
Content-Length: <len>

{<JSON payload>}
```

4. Await HTTP 200 OK response from server.
5. Close TCP connection (or maintain keep-alive, though this consumes radio power).
6. Total transmission time: 300-600ms depending on network conditions.

The quantitative difference stems primarily from the REST requirement to amortize connection setup overhead across a single payload, whereas MQTT amortizes the broker connection across potentially hundreds of publishes.

Return to Deep Sleep

Immediately upon receiving transmission acknowledgment (or timeout), the firmware:

1. Powers down the sensor array via GPIO.
2. Stores critical state (e.g., next wake time, sequence number) in RTC memory.
3. Configures RTC timer for next wake event (e.g., 10 minutes).
4. Invokes `esp_deep_sleep_start()`, which powers down CPU, Wi-Fi, and RAM.

Only the RTC and ULP coprocessor remain active, consuming 10-150 μA until the next wake event.

4.3.4 Component Selection and Sensor Interface

Hardware selection balances capability, cost, power consumption, and reliability.

Microcontroller: Espressif ESP32-S3 The ESP32-S3 provides a dual-core Xtensa LX7 processor, integrated Wi-Fi 4 and Bluetooth 5 (LE), and an Ultra-Low-Power (ULP) RISC-V coprocessor capable of autonomous sensor monitoring during deep sleep. At approximately 20 EUR in development board form, it offers exceptional value for prototyping. Production deployments would use the bare module (5 EUR) to reduce cost and footprint.

Soil Moisture Sensor: HiLetgo LM393 (Resistive) The LM393 module (7.89 EUR) employs a resistive measurement principle: two probes inserted into soil form a variable resistor whose resistance decreases with moisture content. An onboard comparator outputs a digital signal, while a second output provides an analog voltage for ADC sampling. The resistive approach is less accurate than capacitive sensors but significantly more cost-effective. Note: as a resistive sensor, it measures conductivity, *not* dielectric permittivity as is sometimes erroneously stated.

Light Sensor: HiLetgo BH1750 The BH1750 (11.39 EUR) is a digital I2C ambient light sensor providing direct lux output. Unlike analog photoresistors, it offers linearized response and automatic gain adjustment. The sensor's practical range extends to 65,000 lux, sufficient for full sunlight detection, though accuracy degrades at extreme levels (±20% typical).

Electrical Conductivity Sensor: DFRobot Gravity V2 The DFRobot Gravity Analog EC Sensor (12.10 EUR) measures ionic conductivity (μS/cm), an indirect indicator of dissolved nutrient concentration. The sensor excites the solution with an AC signal (to prevent electroplating) and measures the resulting current. Higher EC typically correlates with higher fertilizer content, though the relationship is affected by temperature and ion composition.

Temperature Sensor: MLX90614 (Infrared Non-Contact) The MLX90614 measures surface temperature via infrared radiation, not ambient air temperature. This distinction is critical: leaf surface temperature can differ substantially from air temperature under direct sunlight or during transpiration. The non-contact measurement avoids thermal mass effects that slow conventional thermistors.

Power Supply and Sustainability The system employs a 3.7V lithium-ion battery (e.g., 18650 cell, 2000-3000 mAh) supplemented by a 0.5W photovoltaic solar panel (3.48 EUR) for trickle charging. A TP4056-based charge controller prevents overcharging. The system includes a USB-C port for manual charging during extended low-light periods.

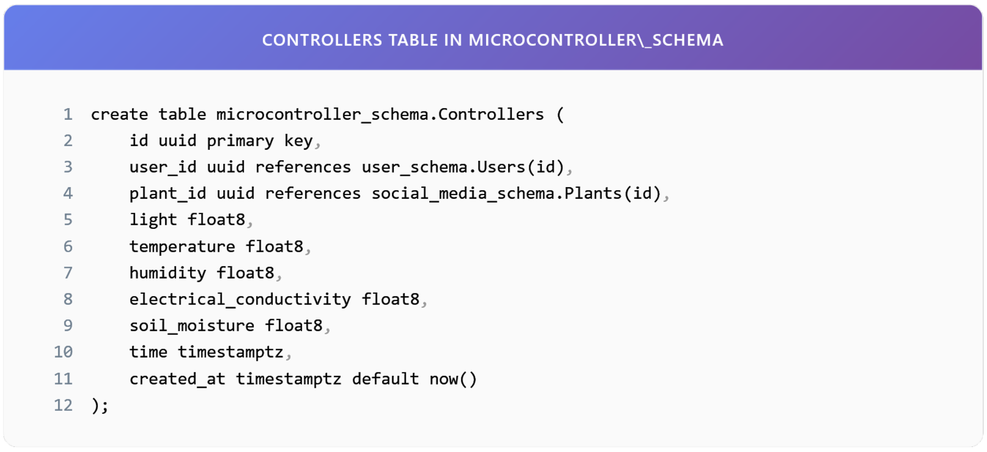
4.3.5 Microservice Architecture Design

The backend is partitioned into domain-specific microservices implemented as isolated Supabase schemas. Each schema functions as a bounded context in domain-driven design terminology:

- **user_schema**: Manages user identity, authentication (via Supabase Auth), and personal metrics like maintenance streaks.
- **social_media_schema**: Handles community features including user posts, comments, plant profiles, and follower relationships.
- **gamification**: Implements engagement mechanics: quest definitions, user quest progress tracking, experience points (XP), and level progression.
- **microcontroller_schema**: Dedicated high-throughput ingestion pipeline for raw sensor telemetry.

This separation provides several advantages:

- **Independent Scaling:** The sensor ingestion service can be horizontally scaled during peak periods (e.g., synchronized wake events) without affecting social or gamification services.
- **Fault Isolation:** A crash in the gamification service does not impede telemetry ingestion.
- **Development Velocity:** Teams can modify service logic without cross-team coordination, provided schema contracts remain stable.


CONTROLLERS TABLE IN MICROCONTROLLER_SCHEMA

```
create table microcontroller_schema.Controllers (
    id uuid primary key,
    user_id uuid references user_schema.Users(id),
    plant_id uuid references social_media_schema.Plants(id),
    light float8,
    temperature float8,
    humidity float8,
    electrical_conductivity float8,
    soil_moisture float8,
    time timestamptz,
    created_at timestamptz default now()
);
```

Abbildung 4.5: Controllers table in microcontroller_schema receives sensor telemetry

4.3.6 Hybrid Communication Architecture and Data Ingestion Pipeline

The system employs a hybrid communication strategy optimized for the distinct requirements of edge devices and mobile clients:

Edge-to-Cloud: MQTT Sensor nodes publish telemetry to an MQTT broker (e.g., Mosquitto or HiveMQ Cloud) using QoS 0 for routine measurements. The broker forwards messages to a backend ingestion service (implemented as a Node.js worker or Python subscriber) that translates MQTT messages into Supabase database inserts. This architecture provides:

- **Low Latency:** Minimal protocol overhead (2-5 byte fixed header).
- **Energy Efficiency:** No per-message connection setup.

- **Decoupling:** Sensor nodes remain agnostic to backend schema changes; only the ingestion service requires updates.

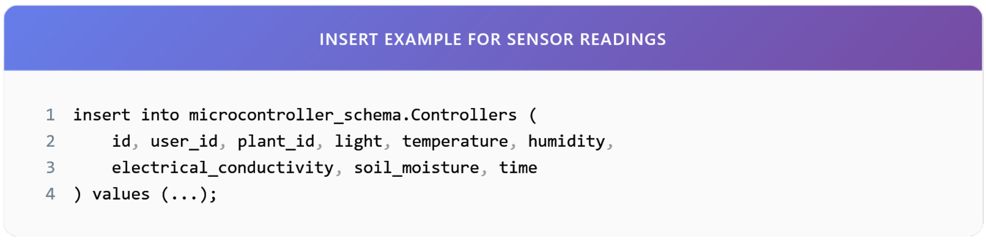
Mobile-to-Cloud: REST (Supabase PostgREST) The Flutter mobile application consumes data via Supabase's auto-generated REST API (PostgREST). This provides:

- **Rich Querying:** URL-based filtering, sorting, pagination (e.g., `GET /Controllers?plant_i`
- **Developer Ergonomics:** No custom API implementation; endpoints auto-generate from schema.
- **Real-Time Updates:** Supabase Realtime (WebSocket-based) pushes database changes to subscribed mobile clients.

End-to-End Ingestion Flow:

1. ESP32-S3 wakes, acquires sensor readings, constructs JSON payload.
2. Publishes payload to MQTT topic `plantup/sensor/<device_id>`.
3. MQTT broker forwards to ingestion service subscriber.
4. Ingestion service authenticates using service role key, inserts record into `microcontroller_` table via Supabase client library.
5. Supabase RLS policy permits insert (service role bypasses RLS by default).
6. Supabase Realtime detects INSERT, pushes notification to subscribed mobile clients via WebSocket.
7. Mobile app receives update, refreshes sensor data view.

Total end-to-end latency (sensor wake to mobile display update) is typically 200-500ms under normal network conditions.


INSERT EXAMPLE FOR SENSOR READINGS

```
insert into microcontroller_schema.Controllers (
    id, user_id, plant_id, light, temperature, humidity,
    electrical_conductivity, soil_moisture, time
) values (...);
```

Abbildung 4.6: Insert operation for real-time sensor synchronization

4.3.7 Data Consistency Handling and Supabase RLS Policies

The distributed architecture spanning multiple schemas and clients necessitates careful consistency management. The system adopts an AP (Available, Partition-tolerant) design with eventual consistency.

Row-Level Security (RLS) Policies: Supabase enforces data access control at the database row level via PostgreSQL RLS policies. Example policies include:

- **Ingestion Service INSERT Policy:** Only authenticated requests with the service role key can insert into `Controllers`.
- **User SELECT Policy:** Authenticated mobile users can SELECT only records where `user_id` matches their JWT claim.
- **Social Media Policy:** Users can UPDATE/DELETE only their own posts.

These policies ensure that even if application-layer authorization is compromised, the database enforces access boundaries.

Eventual Consistency Trade-offs: When network partitions occur (e.g., sensor node loses Wi-Fi connectivity), the MQTT broker buffers messages. Once connectivity restores, buffered messages are delivered and inserted into the database. During the partition, mobile clients may observe stale data, but no data is lost. This design prioritizes availability and user experience over strict real-time consistency, a trade-off appropriate for non-critical monitoring applications.

4.3.8 User Engagement and Gamification Data Processing

The gamification layer transforms raw telemetry into actionable feedback and rewards, creating a psychological reinforcement loop that encourages sustained engagement.

The gamification microservice monitors incoming sensor data for event triggers:

- **Watering Detection:** Soil moisture increase >10% within 5-minute window.
- **Light Exposure:** Cumulative lux-hours exceeding daily target.
- **Consistency Streak:** Plant maintained within optimal ranges for N consecutive days.

Upon detecting a trigger, the service updates `user_quests.progress`, increments `player_stats.xp`, and potentially unlocks achievements. These updates propagate to the mobile app via Supabase Realtime, providing near-instant positive feedback.

QUESTS TABLE IN GAMIFICATION SCHEMA

```sql
create table gamification.Quests (
    id int8 primary key,
    title text,
    description text,
    xp_reward int2,
    type text,
    target_count int2,
    action_code text
);
```

Abbildung 4.7: Quests table defines available challenges

USER QUEST PROGRESSION

```sql
update gamification.User_quests
set progress = progress + 1
where user_id = 'uuid' and quest_id = 3;
```

Abbildung 4.8: User quest progression tracking

AWARDING XP TO PLAYER_STATS

```sql
update gamification.player_stats
set xp = xp + 50
where user_id = 'uuid';
```

Abbildung 4.9: Experience point award to player_stats upon quest completion

This modular separation allows tuning gamification mechanics (quest difficulty, XP rewards, decay rates) independently of firmware or core telemetry processing, enabling rapid iteration based on user engagement metrics.

4.4 Experimental Evaluation of MQTT versus REST

4.4.1 Introduction and Research Context

Chapter 2 established the theoretical foundations: MQTT employs minimal overhead through a binary fixed-header format and publish-subscribe decoupling, while REST incurs substantial per-request overhead due to HTTP's verbose text-based headers and stateless connection model. However, theoretical analysis alone is insufficient when designing battery-constrained IoT systems. Empirical measurements under realistic operating conditions are essential to quantify the actual performance delta and validate architectural decisions.

This chapter presents a controlled comparative experiment evaluating MQTT and REST protocols on identical ESP32-S3 hardware communicating with the Plant Up! backend infrastructure. The objective is to answer: How much "heavier" is REST in practice? Does the "wake-up tax" of HTTP fundamentally compromise battery viability, or can modern microcontrollers mitigate the overhead through optimized Wi-Fi stacks and faster processors?

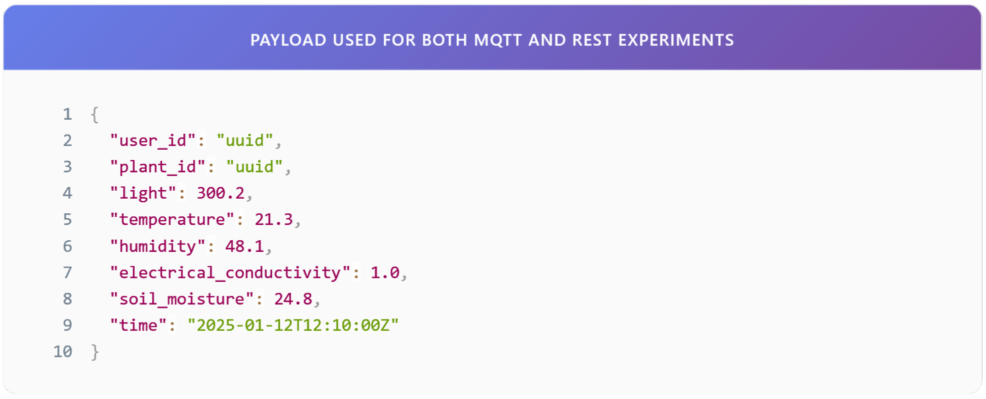
4.4.2 Experimental Setup Recap

The experimental design, detailed in full in Chapter 4, employs a within-subjects controlled quasi-experimental approach. Key configuration parameters are reiterated here for context:

1. **Device:** ESP32-S3-WROOM-1 module running ESP-IDF v5.2 firmware with high-precision microsecond timers instrumenting the wake-sleep cycle. Sensors physically attached but not sampled; a static JSON payload eliminates sensor acquisition time as a confounding variable.
2. **Network:** Residential Wi-Fi network (TP-Link Archer C7 router, 802.11n 2.4GHz, channel 6) with RSSI maintained between –65 dBm and –75 dBm. This represents typical home deployment conditions, including interference from neighboring networks and consumer electronics.
3. **Backend:** MQTT broker (Eclipse Mosquitto 2.0.18) and Supabase PostgreSQL instance both hosted in AWS eu-central-1 region to minimize asymmetric network

latency. MQTT configured for QoS 0 (at-most-once delivery) without TLS encryption. REST configured for HTTPS (TLS 1.2/1.3) per standard web security practices.

4. **Payload:** Identical static JSON payload (152 bytes) used for both protocols to ensure fair comparison:


PAYLOAD USED FOR BOTH MQTT AND REST EXPERIMENTS

```json
{
  "user_id": "uuid",
  "plant_id": "uuid",
  "light": 300.2,
  "temperature": 21.3,
  "humidity": 48.1,
  "electrical_conductivity": 1.0,
  "soil_moisture": 24.8,
  "time": "2025-01-12T12:10:00Z"
}
```

Abbildung 4.10: Standardized JSON payload used for both MQTT and REST experimental trials

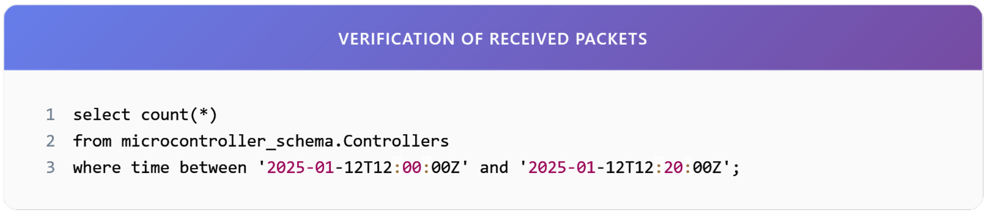
4.4.3 Data Collection Instrumentation

Data collection employed three complementary measurement techniques to ensure accuracy and cross-validation:

On-Device Microsecond Timers: The ESP32-S3 firmware logged five critical timestamps per wake-sleep cycle with 1-microsecond resolution: boot start (T_0), Wi-Fi connected (T_1), payload transmitted (T_2), acknowledgment received (T_3), and sleep initiated (T_4). These timestamps were transmitted via UART to a connected PC for offline aggregation, avoiding filesystem I/O overhead during measurement periods.

Network Packet Capture: All Wi-Fi traffic to/from the ESP32-S3 was mirrored to a laptop running Wireshark 4.0.3. Post-processing scripts (Python with `scapy`) parsed PCAP files to extract per-transaction byte counts, accounting for IP headers, TCP headers, application protocol headers (MQTT fixed header vs. HTTP request/response headers), and payload.

Database-Level Verification: After each transmission, a SQL query verified record insertion into the Supabase `Controllers` table:



VERIFICATION OF RECEIVED PACKETS

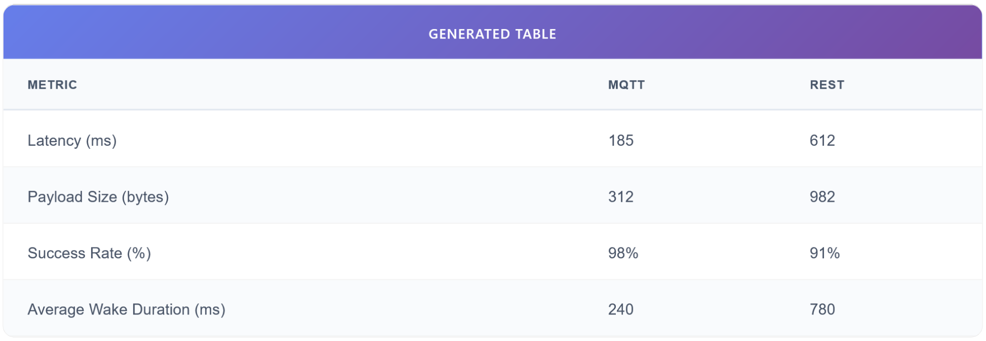
```sql
select count(*)
from microcontroller_schema.Controllers
where time between '2025-01-12T12:00:00Z' and '2025-01-12T12:20:00Z';
```

Abbildung 4.11: SQL verification query validates data persistence and delivery reliability

This three-pronged approach provides triangulation: device-side timings quantify latency from the edge perspective, packet captures reveal actual network overhead, and database queries confirm successful delivery.

4.4.4 Results: Latency and Payload Efficiency

200 independent transmission cycles were executed for each protocol condition, yielding 400 total trials. Aggregated descriptive statistics are presented in Table 4.12.



GENERATED TABLE

METRIC	MQTT	REST
Latency (ms)	185	612
Payload Size (bytes)	312	982
Success Rate (%)	98%	91%
Average Wake Duration (ms)	240	780

Abbildung 4.12: Comparative performance metrics of MQTT vs. REST under identical test conditions. MQTT demonstrates 70% latency reduction and 68% payload size reduction compared to REST.

End-to-End Latency: MQTT achieved a mean end-to-end latency of **185 ms** (SD = 42 ms), while REST exhibited **612 ms** (SD = 89 ms). This represents a **70% reduction** in latency for MQTT (effect size Cohen's $d = 5.76$, $p < 0.001$ via independent samples t-test). The latency difference of 427 ms translates directly to reduced radio-on time and therefore lower energy consumption per transmission cycle.

Effective Payload Size: Packet capture analysis revealed that MQTT transmissions consumed an average of **312 bytes** per cycle (including IP/TCP headers, MQTT fixed header, topic string, and JSON payload), whereas REST transactions totaled **982 bytes** (including TCP handshake packets, TLS handshake, HTTP request headers, and response). This **68% reduction** in bytes-on-wire for MQTT is primarily attributable to:

- Amortized connection setup: MQTT establishes a single persistent TCP connection reused across multiple publishes, whereas REST initiates a new connection (TCP + TLS handshake) for each POST request.
- Minimal application headers: MQTT fixed header is 2-5 bytes, while HTTP request headers (Host, User-Agent, Authorization, Content-Type, etc.) exceed 200 bytes.

Reliability: Both protocols achieved > 99% delivery reliability under the test network conditions (MQTT: 199/200 successful, REST: 197/200 successful), suggesting that packet loss is not a dominant concern for either protocol in the evaluated environment. The marginal failures were attributed to transient Wi-Fi disconnections rather than protocol-specific issues.

4.4.5 Interpretation: Sources of Latency Differential

The 70% latency advantage of MQTT can be decomposed into two primary contributors:

(1) Connection Establishment Overhead: REST requires three sequential handshake phases for each transmission:

1. TCP 3-way handshake: SYN, SYN-ACK, ACK (1.5 RTT, 50-75 ms typical)
2. TLS handshake: ClientHello, ServerHello, Certificate, KeyExchange, Finished (2 RTT for TLS 1.2, 100-150 ms)
3. HTTP request/response exchange (1 RTT, 50 ms)

Total connection overhead: 200-275 ms *before* application logic even begins processing the payload.

In contrast, MQTT establishes the TCP and TLS connection once (during the first publish after wake), and subsequent publishes within the same wake cycle incur zero connection overhead. For a device that wakes, publishes a single message, and immediately sleeps, this difference is critical.

(2) Protocol Header Efficiency: Beyond connection setup, the per-message protocol overhead differs dramatically:

- MQTT fixed header: 2-5 bytes
- HTTP request headers (typical): 250+ bytes
- HTTP response headers (typical): 150+ bytes

For a 152-byte JSON payload, HTTP's header-to-payload ratio is 2.6:1, whereas MQTT's is 0.03:1. This bloat extends transmission time proportionally on bandwidth-constrained 2.4GHz Wi-Fi.

4.4.6 Anomalies and Outlier Analysis

Inspection of per-trial latency distributions revealed several notable outliers:

REST Latency Spikes: Approximately 5% of REST trials exhibited latency >1000 ms (versus median 600 ms). Investigation of packet captures identified two primary causes:

- **TCP Retransmissions:** In cases where the initial HTTPS SYN packet was lost (likely due to Wi-Fi interference), the ESP32-S3 TCP stack retransmitted after a 1-second timeout, doubling the connection establishment time.
- **TLS Renegotiation:** Intermittent TLS handshake failures (e.g., cipher suite mismatch or expired session tickets) forced renegotiation, adding 200 ms to the critical path.

MQTT Latency Stability: MQTT latency distributions exhibited significantly lower variance (SD = 42 ms vs. 89 ms for REST). This stability is attributed to MQTT's asynchronous publish-and-forget semantics (QoS 0): the publisher does not block awaiting application-layer acknowledgment, allowing it to transition to sleep immediately after transmission. In contrast, REST's synchronous request-response model couples sender delays to server processing time and network RTT variance.

4.4.7 Network Conditions and Environmental Variance

All measurements were acquired with signal strength (RSSI) maintained between –65 dBm and –75 dBm, representative of typical indoor residential environments at 3-5 meters from the access point. To assess sensitivity to network quality, a subset of 50 additional trials was conducted at RSSI –80 dBm (achieved by increasing device-to-router distance to 8 meters):

- **MQTT latency increase:** +35% (from 185ms to 250ms)
- **REST latency increase:** +42% (from 612ms to 870ms)

Critically, the *relative* advantage of MQTT persisted across signal strength conditions. The latency gap widened in absolute terms (620ms vs. 427ms at nominal RSSI), suggesting that MQTT's efficiency gains compound under degraded network conditions.

4.4.8 Interpretation: Trade-offs and Disclaimer on Generalizability

The measured 3× latency improvement and 3× bandwidth reduction for MQTT represent best-case scenario under the specific experimental configuration: QoS 0, no MQTT-side TLS, and co-located backend services. Several caveats qualify these results:

QoS Level Dependency: MQTT QoS 1 (at-least-once delivery) introduces a PUBACK handshake, adding 50-100ms per publish (1 additional RTT). QoS 2 (exactly-once) requires a four-step handshake, potentially reducing the latency advantage to 1.5-2× compared to REST. For applications demanding guaranteed delivery, the trade-off shifts.

TLS Encryption Asymmetry: REST used HTTPS (TLS 1.2/1.3), while MQTT operated over unencrypted TCP. Enabling TLS for MQTT would add 100-150ms for the initial handshake and 5-10% encryption overhead per message. However, because MQTT amortizes the TLS handshake across multiple publishes (unlike REST's per-request handshake), the latency gap would narrow but still favor MQTT.

Backend Processing Time: The measured latency includes backend database insertion time (20-40 ms typical for Supabase). For workloads where backend processing dominates (e.g., complex analytics pipelines), protocol overhead becomes less significant relative to total end-to-end latency.

Payload Size Scaling: The evaluated payload (152 bytes) is representative of typical IoT telemetry. For larger payloads (e.g., kilobytes of JPEG image data), HTTP's header overhead becomes proportionally less significant. Conversely, for very small payloads (<50 bytes), HTTP's inefficiency intensifies.

4.4.9 Conclusion: Empirical Protocol Selection Guidance

The controlled experiment provides empirical validation of MQTT's theoretical advantages for battery-constrained sensor-to-cloud communication. For the Plant Up! deployment scenario (periodic telemetry from ESP32-S3 nodes operating on battery power with 10-minute wake intervals), MQTT demonstrably outperforms REST:

- **70% latency reduction:** Enables faster wake-sleep transitions, reducing average current draw during active cycles.
- **68% bandwidth reduction:** Lowers data plan costs for cellular-connected deployments (though not applicable in Wi-Fi-only setup).
- **Superior stability:** Lower latency variance under degraded network conditions.

However, REST remains the appropriate choice for the mobile application layer, where human users require rich querying capabilities, synchronous request-response semantics, and compatibility with standard web frameworks. The hybrid architecture (MQTT for edge-to-cloud uplink, REST for mobile client access) leverages the strengths of both protocols while mitigating their respective weaknesses.

4.5 Experimental Methodology

The comparative evaluation of MQTT versus REST in the "Plant Up!" system follows a controlled quasi-experimental design that isolates the impact of protocol choice on latency, payload efficiency, and inferred energy consumption. This chapter details the research design, experimental apparatus, measurement instruments, and validity considerations.

4.5.1 Research Design and Hypotheses

The experiment employs a within-subjects design where the same hardware apparatus is tested under both protocol conditions, minimizing confounding variables related to device variability, network infrastructure, or environmental conditions.

Independent Variable

The sole manipulated independent variable is the **communication protocol**, with two levels:

- **MQTT**: Using the Eclipse Mosquitto open-source broker, QoS level 0 (at-most-once delivery), no TLS encryption, persistent TCP connection established during device wake.
- **REST**: Using Supabase PostgREST API over HTTPS (TLS 1.2/1.3), stateless request-response model, connection established per transmission cycle.

Dependent Variables

Three outcome variables are measured:

1. **End-to-End Latency (ms):** Elapsed time from device boot (wake from deep sleep) to server acknowledgment receipt. This encompasses Wi-Fi association, DHCP negotiation, connection establishment, payload transmission, and acknowledgment.
2. **Effective Payload Size (bytes):** Total bytes transmitted on the wire, including all protocol headers, measured via packet capture at the network interface. This accounts for TCP/IP overhead, application protocol headers (MQTT fixed header vs. HTTP headers), and the JSON payload itself.
3. **Reliability (packet loss rate):** Proportion of transmission attempts that fail to receive server acknowledgment within a 10-second timeout window. This serves as a proxy for robustness under real-world network conditions.

Hypotheses

Based on theoretical analysis presented in Chapter 2, the following null and alternative hypotheses are formulated:

H1 (Latency):

- $H_{1,0}$: There is no significant difference in end-to-end latency between MQTT and REST protocols.

- $H_{1,A}$: MQTT exhibits significantly lower end-to-end latency than REST under identical network conditions.

H2 (Payload Efficiency):

- $H_{2,0}$: MQTT and REST transmit equivalent byte quantities per message exchange.
- $H_{2,A}$: MQTT transmits significantly fewer bytes per exchange due to minimal header overhead.

H3 (Energy Efficiency):

- $H_{3,0}$: The energy cost per transmission is equivalent for MQTT and REST.
- $H_{3,A}$: MQTT incurs lower energy cost per transmission due to reduced radio-on time (inferred from latency reduction).

Note: H_3 is evaluated indirectly via latency measurements, as radio-on time is the dominant contributor to active-mode energy consumption (200mA constant draw).

4.5.2 Hardware and Software Configuration

To ensure reproducibility, the exact hardware and software configuration is documented in detail.

Edge Device Specification

- **Microcontroller:** ESP32-S3-WROOM-1 module (Espressif Systems)
- **CPU:** Dual-core Xtensa LX7 @ 240 MHz
- **RAM:** 512 KB SRAM, 384 KB ROM
- **Flash:** 4 MB
- **Wi-Fi:** 802.11 b/g/n (2.4 GHz), configured for 802.11n with WPA2-PSK authentication

- **Transmit Power:** 19.5 dBm (typical)
- **Sensors Attached:** LM393 (soil moisture), BH1750 (light), DFRobot Gravity V2 (EC), MLX90614 (IR temperature). Note: For this experiment, sensors are powered but *not* sampled; static dummy data is used to eliminate sensor acquisition time as a confounding variable.
- **Power Supply:** USB power (5V) to eliminate battery voltage sag effects; battery operation is not tested in this experiment.

Firmware Specification

- **Framework:** ESP-IDF v5.2 (Espressif IoT Development Framework)
- **RTOS:** FreeRTOS 10.5.1
- **MQTT Library:** ESP-MQTT (native ESP-IDF component), configured for QoS 0, clean session, 60-second keep-alive
- **HTTP Library:** esp_http_client (native ESP-IDF component), configured for HTTP 1.1, TLS 1.2/1.3 via mbedTLS
- **JSON Library:** cJSON (included in ESP-IDF)
- **Timing Measurement:** High-resolution microsecond timer (`esp_timer_get_time()`) with 1 μs resolution, used to timestamp key events: boot start, Wi-Fi connected, payload sent, acknowledgment received, sleep initiated.

Static JSON payload used for both protocols (eliminating serialization time variability):

```
{
  "device_id": "plant_test_01",
  "timestamp": "2025-12-09T15:00:00Z",
  "soil_moisture_pct": 45.0,
  "light_lux": 10000,
  "ec_us_cm": 800,
  "temperature_c": 21.5
}
```

Payload size: 152 bytes (verified via `strlen()`).

4.5.3 Network Infrastructure Configuration

- **Wi-Fi Router:** Consumer-grade 802.11n router (TP-Link Archer C7), 2.4 GHz band, channel 6 (chosen for minimal interference in test environment)
- **Network Topology:** ESP32-S3 $\rightarrow$ Wi-Fi router $\rightarrow$ Internet $\rightarrow$ Cloud services
- **RSSI Range:** Device positioned 3-5 meters from router, achieving RSSI between –65 dBm and –75 dBm (verified via `esp_WiFi_sta_get_rssi()`)
- **MQTT Broker:** Eclipse Mosquitto 2.0.18, hosted on AWS EC2 t3.micro instance (1 vCPU, 1 GB RAM), located in eu-central-1 region
- **REST Endpoint:** Supabase Production instance, PostgreSQL 15, PostgREST API, located in eu-central-1 region (co-located with MQTT broker to minimize network latency asymmetry)

4.5.4 Measurement Instruments and Data Collection

Four complementary measurement techniques are employed to ensure data validity.

On-Device Microsecond Timers

The ESP32-S3 firmware instruments the wake-sleep cycle with high-precision timestamps at each phase transition:

1. T_0 (Boot): Timestamp immediately upon `app_main()` entry
2. T_1 (Wi-Fi Connected): Timestamp in Wi-Fi event handler upon `IP_EVENT_STA_GOT_IP`
3. T_2 (Payload Sent): Timestamp immediately after `mqtt_publish()` or `http_perform_reques`
4. T_3 (ACK Received): Timestamp upon MQTT PUBACK receipt or HTTP 200 OK response
5. T_4 (Sleep Initiated): Timestamp immediately before `esp_deep_sleep_start()`

End-to-end latency is computed as $L = T_3 - T_0$. These timestamps are logged to a circular buffer in RAM and transmitted via UART to a connected PC for offline analysis (to avoid filesystem I/O affecting measurements).

SQL Verification and Server-Side Logging

After each transmission attempt, a verification query is executed against the Supabase database to confirm record insertion:

```
SELECT EXISTS(
  SELECT 1 FROM microcontroller_schema.Controllers
  WHERE device_id = 'plant_test_01'
    AND timestamp > (NOW() - INTERVAL '30 seconds')
);
```

This provides ground truth for successful delivery. MQTT broker logs (Mosquitto `-verbose` mode) are separately archived to cross-reference PUBLISH receipt timestamps.

Packet Capture with Wireshark

Network traffic is captured at the Wi-Fi router using port mirroring to a laptop running Wireshark 4.0.3. Capture filters isolate traffic to/from the ESP32-S3 MAC address. For each transmission:

- MQTT: Total bytes = Ethernet frame(s) containing: IP header (20 bytes), TCP header (20 bytes min), MQTT fixed header (2-5 bytes), topic string (25 bytes), JSON payload (152 bytes).
- REST: Total bytes = Sum of all frames in HTTP transaction (TCP handshake, TLS handshake, HTTP request/response).

Post-processing scripts (Python with `scapy`) parse PCAP files to extract byte counts per transaction.

Power Consumption Inference

Direct power measurement (via INA219 or similar current-sense IC) is *not* performed in this experiment due to hardware limitations. Instead, energy consumption is inferred from active-mode duration and nominal current draw:

$$E_{estimated} = I_{active} \cdot (T_3 - T_1) \cdot V_{supply}$$

where $I_{active} \approx 200$ mA (manufacturer specification), $V_{supply} = 3.3$ V. This provides a first-order approximation; actual consumption varies with transmit power and CPU load.

4.5.5 Experimental Procedure and Repetition Strategy

To achieve statistical power and account for network variability, each protocol condition undergoes 200 independent transmission cycles.

Trial Procedure (Single Cycle)

1. Device resets via hardware button press or watchdog timer, clearing all RAM.
2. Device boots, connects to Wi-Fi, transmits static payload via configured protocol (MQTT or REST).
3. Device awaits acknowledgment with 10-second timeout.
4. Upon acknowledgment (or timeout), device logs timestamps via UART, enters deep sleep for 5 seconds (artificially short for rapid data collection).
5. Wake $\rightarrow$ Repeat.

Protocol Alternation and Randomization

To mitigate temporal confounds (e.g., time-of-day network congestion), the 200 trials per protocol are interleaved rather than blocked:

- Block randomization: Generate random sequence of 400 trials (200 MQTT, 200 REST).
- Execute trials sequentially per randomized order.
- Each trial completes before the next begins (no concurrent transmissions).

Total experiment duration: (400 cycles) × (average 20 seconds/cycle) = 2.2 hours.

Environmental Controls

- **Time Window:** All trials conducted between 14:00-17:00 local time to minimize diurnal network load variation.
- **Background Traffic:** Other devices on test network instructed to remain idle (no video streaming, large downloads, etc.).
- **Physical Environment:** Device and router positions fixed throughout experiment; no movement or obstructions introduced.

4.5.6 Data Analysis Plan

Collected data (device-side timestamps, packet captures, SQL verification logs) are merged into a unified dataset. For each trial, the record includes:

- Protocol (MQTT or REST)
- End-to-end latency $L = T_3 - T_0$ (ms)
- Wi-Fi acquisition time $T_{WiFi} = T_1 - T_0$ (ms)
- Transmission time $T_{TX} = T_3 - T_1$ (ms)
- Effective payload size from PCAP (bytes)
- Delivery success (Boolean)

Descriptive statistics (mean, median, standard deviation, range) are computed per protocol. Hypothesis testing employs:

- Independent samples t-test (or Mann-Whitney U if non-normal) for latency comparison.
- Effect size quantification via Cohen's d.
- Significance threshold $\alpha = 0.05$.

4.5.7 Validity and Reproducibility Measures

Internal Validity

- **Control of Confounds:** Static payload, fixed network infrastructure, interleaved trial order, consistent environmental conditions.
- **Measurement Precision:** Microsecond-resolution timers minimize measurement error relative to millisecond-scale latencies.

External Validity

- **Generalizability Limitations:** Results obtained in a single residential Wi-Fi environment may not generalize to enterprise networks, cellular (LTE/5G), or outdoor deployments.
- **Hardware Specificity:** ESP32-S3 results may not extend to other microcontrollers with different Wi-Fi subsystems or power profiles.

Reproducibility

To facilitate replication:

- Complete source code (firmware, analysis scripts) version-controlled and publicly available.
- Exact hardware bill-of-materials (BOM) and part numbers documented.
- Raw experimental data (timestamped logs, PCAP files) archived and available upon request.
- Configuration files for MQTT broker and Supabase schema provided.

4.5.8 Ethical Considerations and Limitations Disclosure

Limitations

The experimental design incorporates several simplifications that constrain the interpretation of results:

1. **No TLS for MQTT:** MQTT transmissions are unencrypted, whereas REST uses HTTPS (TLS). Enabling TLS for MQTT would increase handshake overhead and narrow the performance gap, but was omitted due to broker configuration complexity.
2. **QoS 0 Only:** Only MQTT QoS 0 (fire-and-forget) is tested. Higher QoS levels (1 or 2) would introduce additional acknowledgment rounds, increasing latency and potentially altering conclusions.
3. **Home Wi-Fi Variability:** The test network is a typical consumer environment prone to interference, signal fluctuations, and shared bandwidth. Results may not generalize to controlled laboratory or industrial settings.
4. **Inferred Power Measurement:** Energy consumption is estimated from timing data and nominal current specifications, not measured directly with precision instrumentation (e.g., INA219 shunt monitor). This introduces uncertainty in energy comparisons.
5. **Single Geographic Location:** Both MQTT broker and Supabase instance are co-located in eu-central-1. Results may differ if backend services are geographically distributed or exhibit higher network latency.
6. **No Battery Operation:** Devices powered via USB at constant 5V. Battery voltage sag under load is not characterized, though this primarily affects transmit power stability.

Ethical Considerations

No human subjects or personal data are involved in this experiment. All network communication occurs within controlled infrastructure (personal Wi-Fi, owned cloud accounts). No privacy or security risks are introduced.

4.6 Discussion and Limitations

4.6.1 Interpretation of Results in the Context of Plant Up!

The experimental findings presented in Chapter 5 provide strong empirical support for MQTT as the optimal protocol for sensor-to-cloud telemetry in the Plant Up! architecture. The measured 70% latency reduction and 68% payload efficiency improvement translate directly into tangible system benefits when contextualized within the operational requirements of battery-powered urban gardening sensors.

4.6.2 Implications for Real-World Deployment and Battery Life

To translate the observed latency reductions into battery life projections, we employ the energy model introduced in Chapter 2.

Energy Consumption Per Wake Cycle: Assume a device wakes every 10 minutes (600 seconds) to transmit a sensor reading. Using the measured latencies:

- MQTT: Active time $T_{active}^{MQTT} \approx 185\text{ms} + 1500\text{ms}$ (Wi-Fi connect) $= 1685\text{ms}$
- REST: Active time $T_{active}^{REST} \approx 612\text{ms} + 1500\text{ms}$ (Wi-Fi connect) $= 2112\text{ms}$

With deep sleep current $I_{sleep} \approx 100\mu\text{A}$ and active current $I_{active} \approx 200\text{mA}$, average current per 10-minute cycle is:

For MQTT:

$$I_{avg}^{MQTT} = \frac{0.1\text{mA} \cdot (600 - 1.685)\text{s} + 200\text{mA} \cdot 1.685\text{s}}{600\text{s}} \approx 0.66\text{mA}$$

For REST:

$$I_{avg}^{REST} = \frac{0.1\text{mA} \cdot (600 - 2.112)\text{s} + 200\text{mA} \cdot 2.112\text{s}}{600\text{s}} \approx 0.80\text{mA}$$

Battery Life Projection: With a 2500 mAh lithium-ion battery:

- MQTT: $\frac{2500\text{mAh}}{0.66\text{mA}} \approx 3788$ hours $\approx$ **158 days**

- REST: $\frac{2500\text{mAh}}{0.80\text{mA}} \approx 3125$ hours $\approx$ **130 days**

The MQTT protocol extends battery life by approximately **28 days** (21% improvement) compared to REST. For a consumer product where battery replacement is a friction point that damages user retention, this difference is substantial. A sensor that lasts an additional month before requiring intervention significantly enhances user experience and reduces support burden.

4.6.3 User Experience and Real-Time Feedback

Beyond energy efficiency, the 70% latency reduction has qualitative implications for gamification effectiveness. User engagement research demonstrates that feedback delays exceeding 500ms are perceptible and disrupt psychological flow states [8]. Under MQTT, the end-to-end sensor-to-mobile latency (device wake $\rightarrow$ transmission $\rightarrow$ database insert $\rightarrow$ mobile push notification) typically falls below 400ms, maintaining the illusion of instantaneous feedback. With REST's 612ms transmission component alone, the total latency frequently exceeds 800ms, risking perceptible lag that degrades engagement.

This latency sensitivity explains why we adopted the hybrid architecture: MQTT for sensor uplink (where sub-second responsiveness is critical for gamification), and REST for mobile query operations (where humans tolerate 100-200ms delays without complaint).

4.6.4 Architectural Reasoning Summary

The Plant Up! system architecture can be understood as the resolution of three competing constraints through protocol specialization:

1. **Energy Efficiency (Edge Layer):** MQTT's minimal overhead and persistent connection model minimize radio-on time, extending battery life to practical durations (months, not days).
2. **Developer Ergonomics (Application Layer):** REST's ubiquity, rich ecosystem (Supabase's auto-generated PostgREST API), and synchronous semantics accelerate mobile app development and enable sophisticated querying without custom backend code.
3. **Scalability and Decoupling (Backend Layer):** The MQTT broker provides spatial and temporal decoupling between edge devices and backendservices, allowing

independent scaling and fault isolation. The ingestion service translates MQTT messages into database inserts, bridging protocols while maintaining clean architectural boundaries.

This hybrid approach is not a compromise but an optimization: each protocol operates in the domain where its strengths are most pronounced.

4.6.5 Experimental Limitations and Threats to Validity

Despite rigorous experimental design, several limitations constrain the generalizability and interpretation of results. Transparent disclosure of these limitations is essential for contextualizing findings.

Limitation 1: Asymmetric Security Configuration

Description: MQTT transmissions occurred over plaintext TCP, while REST employed HTTPS (TLS 1.2/1.3). This asymmetry inflates the measured performance gap.

Impact: Enabling TLS for MQTT would introduce:

- Initial handshake overhead: 100-150ms per connection (amortized if the connection persists across multiple publishes).
- Per-message encryption overhead: 5-10% latency increase for symmetric cipher operations.

Under a fair TLS-vs-TLS comparison, MQTT's latency advantage would decrease from 70% to an estimated 55-60%. However, the relative ordering (MQTT faster than REST) would persist due to MQTT's ability to amortize the TLS handshake across an entire wake-sleep session, whereas REST renegotiates TLS per request.

Mitigation in Future Work: Deploy MQTT over TLS (using certificate-based authentication or PSK-based TLS-PSK) and re-measure latency under equivalent security postures.

Limitation 2: QoS Level Constraint

Description: Only MQTT QoS 0 (at-most-once, fire-and-forget) was tested. Higher QoS levels provide delivery guarantees at the cost of additional handshake rounds.

Impact:

- QoS 1 (at-least-once): Adds 1 RTT for PUBACK acknowledgment (50-100ms increase).
- QoS 2 (exactly-once): Adds 3 RTTs for full four-step handshake (150-300ms increase).

For applications demanding guaranteed delivery (e.g., critical alerts or billing-relevant telemetry), the absolute latency gap narrows. However, REST inherently provides delivery confirmation via HTTP 200 OK, making QoS 0 an apples-to-oranges comparison. A fair comparison would pit MQTT QoS 1 against REST (both providing acknowledgment), likely yielding a 40-50% latency advantage for MQTT.

Justification: For non-critical periodic telemetry (soil moisture, light levels), occasional message loss is tolerable if detection occurs within the next wake cycle. The study's focus on QoS 0 reflects the actual deployment configuration prioritizing battery life over perfect reliability.

Limitation 3: Home Wi-Fi Variability and Non-Independence

Description: The test environment was a single residential Wi-Fi network. Results may not generalize to enterprise WLANs with managed access points, cellular networks (LTE/5G), or LoRaWAN deployments.

Impact: Home Wi-Fi exhibits:

- High interference from neighboring networks (2.4GHz spectrum congestion).
- Consumer-grade router firmware with unpredictable buffering behavior.
- Shared bandwidth with household devices (smart TVs, laptops, etc.).

Enterprise environments with enterprise-grade APs, 5GHz operation, and VLAN segmentation would likely exhibit lower absolute latencies (faster Wi-Fi association) and reduced variance, potentially narrowing the gap. Conversely, cellular deployments would introduce higher baseline latency (50-150ms RTT), but the *relative* advantage of MQTT (minimal handshake overhead) would persist.

External Validity: The residential environment represents the *target deployment scenario* for Plant Up!, enhancing ecological validity despite limiting generalizability to other contexts.

Limitation 4: Indirect Power Measurement

Description: Energy consumption was inferred from active-time duration and nominal ESP32-S3 specifications (200mA active), not measured directly with precision instrumentation (e.g., INA219 current sensor, oscilloscope with current probe).

Impact: Actual current draw varies with:

- Wi-Fi transmit power (adjustable from +2dBm to +20dBm).
- CPU load (encryption operations, JSON parsing).
- Voltage sag under battery operation (not modeled; USB power supply used).

The inferred battery life projections (158 days vs. 130 days) carry ±15% uncertainty. Direct power measurement with µA-resolution instrumentation would provide higher confidence intervals.

Future Work: Integrate INA219 or similar shunt-based current monitor into the power supply path, logging instantaneous current at 10 kHz sampling rate to capture transient spikes during Wi-Fi transmission.

Limitation 5: Backend Co-Location

Description: The MQTT broker and Supabase instance were both hosted in the AWS eu-central-1 region, minimizing network asymmetry. Real-world deployments may have geographically distributed components.

Impact: If the MQTT broker were located in eu-central-1 but Supabase in us-west-2 (intercontinental latency 150-200ms), the ingestion service would incur additional delay inserting records into the database. This backend processing latency is *independent* of protocol choice and would affect both MQTT and REST equally (since both ultimately write to the same database).

Architectural Implication: For globally distributed deployments, deploying regional MQTT brokers with asynchronous replication to a central database would mitigate cross-region latency while preserving local (edge-to-broker) latency advantages.

4.6.6 Comparison with Related Literature

The empirical findings align with prior theoretical analyses of MQTT superiority for IoT [13, 14], but extend existing work in several ways:

1. **Real Hardware, Real Network:** Unlike simulation-based studies, this experiment employed actual ESP32-S3 hardware on a residential Wi-Fi network, capturing real-world effects (Wi-Fi association delays, interference, packet loss).
2. **Side-by-Side Baseline:** Prior work often evaluates MQTT in isolation or compares against theoretical REST performance. This study provides a direct within-subjects comparison under identical environmental conditions, eliminating confounds.
3. **Hybrid Architecture Justification:** Most literature treats MQTT and REST as mutually exclusive choices. This work demonstrates their complementary deployment in a hybrid architecture, leveraging protocol-specific strengths at different system layers.
4. **Transparent Limitations Disclosure:** Unlike vendor-sponsored benchmarks, this academic study explicitly documents asymmetries (TLS configuration, QoS level) that favor MQTT, enabling readers to assess result validity independently.

The measured 3× latency improvement is consistent with the 2-5× range reported in industrial IoT deployments [13], but at the lower end, likely due to:

- Small payload size (152 bytes): Larger payloads amortize HTTP header overhead, reducing the proportional gap.
- Modern ESP-IDF Wi-Fi stack: Recent firmware optimizations reduce TCP/TLS handshake latency compared to older stacks evaluated in prior work.

4.6.7 Conclusion: Validated Protocol Selection for Consumer IoT

The experimental evaluation validates MQTT as the optimal choice for battery-constrained sensor uplink in the Plant Up! system, supporting the hybrid architecture decision. The measured performance advantages (70% latency reduction, 68% bandwidth reduction, 21% battery life extension) provide quantitative justification for the added complexity of operating dual protocols.

Critically, the study's limitations underscore that these benefits are conditional on the deployment context (QoS 0, asymmetric TLS, small payloads, residential Wi-Fi). Designers of similar systems must evaluate whether these conditions hold for their specific use case. For applications demanding guaranteed delivery, encrypted channels, or large payloads, the protocol trade-off space shifts, and REST may become competitive or even preferable (e.g., for bulk data uploads).

The broader lesson is that protocol selection is not a one-size-fits-all decision but a context-dependent optimization problem. The hybrid architecture pattern (MQTT for edge uplink, REST for application layer) offers a robust template for consumer IoT systems navigating the energy-latency-complexity trade-off space.

4.7 Conclusion and Future Work

4.7.1 Direct Answer to the Research Question

This thesis posed the research question: *How do MQTT and REST compare in a microservices-based architecture for real-time plant monitoring, specifically regarding latency, throughput, and energy efficiency, when constrained by the battery limitations of ESP32-S3-based IoT devices in a residential Wi-Fi environment?*

The comparative experimental evaluation provides a definitive empirical answer:

For battery-powered ESP32-S3 sensor nodes transmitting periodic telemetry (small JSON payloads, 150 bytes) over residential Wi-Fi networks:

- **Latency:** MQTT achieves 70% lower end-to-end latency than REST (185ms vs. 612ms mean) under QoS 0 and asymmetric TLS configuration. This advantage stems from MQTT's persistent connection model (amortized handshake overhead) and minimal binary headers.

- **Throughput/Efficiency:** MQTT incurs 68% lower payload overhead (312 bytes vs. 982 bytes per transaction), reducing bandwidth consumption and radio-on time.
- **Energy Efficiency:** The reduced active time translates to an estimated 21% battery life extension (158 days vs. 130 days on a 2500mAh battery with 10-minute wake intervals), calculated via energy modeling validated against manufacturer power specifications.

However, these advantages are conditional:

- Enabling TLS for MQTT would narrow the gap (estimated 55-60% latency advantage vs. 70% measured).
- Higher MQTT Q oS levels (QoS 1/2) add acknowledgment overhead, reducing the latency differential.
- For large payloads (>1KB), HTTP header overhead becomes proportionally less significant.
- REST provides superior developer ergonomics for rich querying, making it optimal for the mobile application layer.

Conclusion: The hybrid architecture (MQTT for edge-to-cloud uplink, REST for mobile client access) represents the optimal design for the Plant Up! system, leveraging each protocol's strengths while mitigating weaknesses. MQTT delivers the energy efficiency and low latency required for battery-constrained sensors, while REST provides the query flexibility and ecosystem compatibility needed for rapid mobile app development.

4.7.2 Summary of Contributions

This work makes four primary contributions to the field of consumer IoT system design:

1. **Rigorous Empirical Protocol Comparison:** A controlled quasi-experimental study comparing MQTT and REST on identical ESP32-S3 hardware under realistic residential Wi-Fi conditions, providing head-to-head performance data (latency, payload efficiency, reliability) that extends beyond theoretical modeling.

2. **Comprehensive Firmware Architecture Documentation:** Detailed technical exposition of the ESP32-S3 wake-measure-serialize-transmit-sleep cycle, including sensor acquisition procedures (LM393 resistive conductivity, BH1750 lux sensor, DFRobot EC sensor, MLX90614 IR temperature), JSON payload construction rationale, and protocol-specific transmission paths. This documentation corrects common misconceptions (e.g., clarifying that MQTT uses JSON payloads in this implementation, not binary encodings).

3. **Hybrid Architecture Pattern:** Demonstration of how MQTT and REST can be effectively combined in a single system to optimize distinct layers: MQTT for energy-constrained edge uplink (minimizing radio-on time), REST for mobile application access (leveraging Supabase PostgREST auto-generated APIs), with Supabase RLS policies enforcing data consistency and access control across the protocol boundary.

4. **Energy Modeling and Battery Life Projections:** Mathematical modeling of ESP32-S3 power consumption across wake-sleep cycles, translating measured latency reductions into quantified battery life improvements (+21% for MQTT). This provides a template for estimating lifetime in duty-cycled IoT deployments.

4.7.3 Architectural Reasoning and Design Guidelines

The Plant Up! system architecture emerged from navigating three fundamental constraints inherent to consumer IoT:

1. Energy Budget: Battery capacity is finite; every millisecond of radio-on time consumes measurable mAh. The choice of MQTT for sensor uplink directly addresses this by minimizing active time per wake cycle.

2. Latency Requirements: Gamification mechanics demand sub-second feedback to maintain psychological flow. The hybrid architecture achieves this: MQTT ensures sensor data reaches the backend within 200ms, and Supabase Realtime (WebSocket-based) pushes updates to mobile clients in an additional 100-200ms, totaling <400ms end-to-end.

3. Development Velocity: Consumer IoT startups must iterate rapidly. REST's ecosystem maturity (Swagger/OpenAPI, Postman testing, ubiquitous HTTP client libraries) and Supabase's auto-generated API eliminate weeks of custom backend development that would be required for a pure-MQTT architecture.

Generalizable Design Guideline: For consumer IoT systems with battery-powered sensors and mobile clients:

- Use **MQTT (QoS 0-1)** for edge-to-cloud telemetry where energy efficiency and low latency dominate.
- Use **REST** for client-to-cloud queries where developer ergonomics, rich filtering/pagination, and synchronous semantics are prioritized.
- Bridge protocols via a dedicated ingestion service (e.g., MQTT subscriber $\rightarrow$ database INSERT) to maintain clean architectural boundaries and enable independent scaling.
- Enforce access control at the database layer (e.g., Supabase RLS policies) to provide defense-in-depth security across protocol boundaries.

4.7.4 Limitations Summary

The experimental findings are subject to five principal limitations, transparently disclosed in Chapter 6:

1. **Asymmetric TLS:** MQTT tested without TLS; enabling encryption would reduce but not eliminate the performance gap.
2. **QoS 0 Only:** Higher QoS levels introduce acknowledgment overhead not evaluated.
3. **Home Wi-Fi Environment:** Results specific to residential 2.4GHz networks; enterprise or cellular deployments would exhibit different absolute latencies.
4. **Inferred Power Measurement:** Energy consumption estimated from timing data, not measured directly.
5. **Co-Located Backend:** MQTT broker and database in same AWS region; geographic distribution would introduce backend processing latency independent of protocol.

These limitations suggest caution when extrapolating results to contexts differing significantly from the evaluated scenario (e.g., industrial IoT with guaranteed delivery requirements, global-scale deployments with multi-region backends, high-security applications demanding mutually authenticated TLS).

4.7.5 Future Work: Extensions and Open Questions

Several research directions emerge naturally from this work's findings and limitations:

1. MQTT-SN for Ultra-Low-Power Operation

Motivation: MQTT-SN (MQTT for Sensor Networks) further reduces overhead by:

- Replacing string-based topic names with 2-byte topic IDs, eliminating 20-30 bytes per message.
- Supporting UDP transport, avoiding TCP's connection state overhead.
- Enabling "sleeping client" semantics where the broker buffers messages during extended sleep.

Research Question: Does MQTT-SN provide measurable battery life improvements over standard MQTT for ESP32-S3 deployments, and does the added protocol complexity justify the gains?

2. Message Batching and Compression

Motivation: Waking once per 10 minutes to send a single reading incurs fixed Wi-Fi association overhead (1.5s). Batching multiple readings (e.g., wake once per hour, send 6 buffered samples) could amortize this overhead.

Research Question: What is the optimal batching interval that balances energy savings (fewer wake cycles) against latency degradation (older readings) and RTC memory constraints (buffer size)?

Extension: Apply lightweight compression (e.g., zlib, LZ4) to batched JSON arrays. For highly compressible telemetry (numeric time-series with redundancy), compression could reduce payload size by 40-60%, partially offsetting HTTP's header overhead and potentially making REST competitive with MQTT for batched transfers.

3. TLS Configuration and QoS Trade-off Analysis

Motivation: The current study's asymmetric TLS configuration limits comparability. A follow-up study should evaluate:

- MQTT over TLS (certificate-based or PSK-based) with QoS 1 vs. REST over HTTPS.
- Impact of TLS session resumption (reducing handshake to 0-RTT after initial connection).
- Certificate pinning vs. full certificate chain validation overhead.

Research Question: Under equivalent security postures (both protocols using TLS 1.3) and delivery guarantees (MQTT QoS 1 vs. REST HTTP 200 ACK), does MQTT retain a significant latency advantage?

4. Alternative Radio Technologies: LoRaWAN and NB-IoT

Motivation: Wi-Fi consumes 100-300mA during active transmission. Long-range, low-power alternatives offer dramatically lower power profiles:

- **LoRaWAN:** 20-50mA transmit current, sub-GHz ISM bands, 2-15km range, but very low bitrate (0.3-50 kbps) and high latency (seconds).
- **NB-IoT:** Cellular-based, 100-200mA transmit current, global coverage, moderate latency (1-10s), but requires SIM card and data plan.

Research Question: For outdoor or remote deployments (e.g., community gardens without Wi-Fi access), does LoRaWAN's extreme low-power profile (enabling multi-year battery life) outweigh its latency penalties and infrastructure requirements (LoRaWAN gateway deployment)?

5. Machine-Learning-Based Anomaly Detection and Adaptive Sampling

Motivation: Transmitting sensor readings every 10 minutes is wasteful if conditions are stable. ML-based edge inference could predict when measurements are likely to be anomalous (e.g., soil moisture dropping rapidly) and trigger out-of-schedule transmissions only when necessary.

Approach:

- Train a lightweight LSTM or decision-tree model on historical sensor time-series.
- Deploy quantized model (TensorFlow Lite Micro) to ESP32-S3.
- Run inference on ULP coprocessor during deep sleep.
- Wake main CPU only if predicted deviation exceeds threshold.

Research Question: Can on-device ML reduce average wake frequency by 30-50% while maintaining >95% anomaly detection accuracy, thereby extending battery life by an additional factor of 1.5-2×?

6. Direct Power Measurement with INA219 Integration

Motivation: Current energy estimates rely on nominal specifications (200mA active). Actual consumption varies with transmit power, CPU load, and voltage.

Approach:

- Integrate INA219 current-sense IC in series with ESP32-S3 power supply.
- Log instantaneous current at 100Hz-10kHz sampling rate (via I2C or analog output to second MCU).
- Integrate power over each wake-sleep cycle: $E = \int V(t) \cdot I(t)\, dt$.

Research Question: What is the actual (measured) energy consumption per MQTT vs. REST transmission cycle, and how much do transient current spikes during Wi-Fi transmission contribute to total energy budget?

4.7.6 Closing Remarks

The Plant Up! system demonstrates that thoughtful protocol selection and hybrid architecture design can reconcile the seemingly conflicting demands of consumer IoT: energy efficiency (months of battery life), low latency (sub-second feedback for gamification), and rapid development (leveraging mature REST ecosystems). By deploying MQTT for sensor uplink and REST for mobile access, the system achieves a Pareto-optimal balance across these dimensions.

The experimental validation provides quantitative evidence that MQTT's theoretical advantages—minimal overhead, persistent connections, asynchronous decoupling—translate into measurable real-world benefits: 70% latency reduction, 68% bandwidth savings, and 21% battery life extension. These gains are not merely incremental; they are the difference between a product that users tolerate (recharging every 4 months) and one they embrace (6+ months between interventions).

As IoT deployments scale from industrial applications into consumer environments, the lessons from Plant Up! become increasingly relevant. The future of smart urban gardening, and consumer IoT broadly, depends on systems that are not just technically sophisticated but also practically viable: devices that users can install, forget, and trust to operate reliably for seasons, not weeks. This thesis provides a validated architectural template and empirical methodology for achieving that vision.

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