

Chapter 2

Literature Review

A review was done on the key technological foundations underlying this study, covering the evolution of the Internet of Things, a comparative analysis of wireless communication protocols with a focus on LoRa, and the detailed examination of its physical and MAC layers, all of which are critical to the design and implementation of a robust water quality monitoring system for shrimp farming.

2.1 Overview of Relevant Studies

In order to situate our system within the current state of the art, this section examines four representative IoT-based water-quality monitoring solutions published between 2021 and 2023. We compare each study's communication protocol, sensor suite, energy harvesting and storage, microcontroller platform, power consumption, sampling interval, and deployment environment. First, we provide a concise bullet-point summary of each work; then Table 2.1 presents a standardized, side-by-side comparison of their key design features.

- **Quevy et al. (2023)** [7]: Deploys a smart buoy for surface-water monitoring; measures temperature, pH, dissolved oxygen, conductivity and turbidity; uses an ESP32-WROOM over LoRaWAN; powered by four 1.5 V/250 mA solar cells charging a 3.7 V, 8000 mA h Li-Po; samples every 10 min with an average draw of 1.8 mA.
- **Kombo et al. (2021)** [8]: Groundwater-level WSN based on MS5803-14BA and MB280 sensors; employs a LoRa end-node that batches data using a micro-SD; built on an ATmega328P (Arduino Uno R3); harvests with a 6 V, 3 W panel into a 3.7 V, 5000 mA h Li-Po; duty-cycles at 6 h sampling and 12 h transmit, averaging 2.8 mW.
- **Mahmud et al. (2023)** [9]: Real-time shrimp-pond monitoring with temperature, dissolved oxygen, pH, salinity, turbidity and light sensors; runs on an Arduino Uno R3 + ESP8266 WiFi, pushing data to Firebase; supports an Android app for visualization and alerts.

- **Dalla Via (2021)** [10]: Prototyped a LoRaWAN buoy on The Things Network for lake water-quality monitoring; includes temperature, pressure, humidity, pH probe, light and INA219 power monitor on a Feather M0 + RFM95; powered by a 1.2 W panel and 3.6 V, 2000 mA h Li-ion; samples every 60 s at an average 2.8 mW.

Table 2.1: Comparison of four IoT-based water-quality systems

Parameter	Quevy et al. (2023)	Kombo et al. (2021)	Mahmud et al. (2023)	Dalla Via (2021)
Communication protocol	LoRaWAN	LoRa (single-channel)	WiFi	LoRaWAN
Sensor suite	Temp, pH, DO, EC, turbidity	Water-level (MS5803-14BA), ambient pressure/temperature/humidity (MB280)	Temp, DO, pH, salinity, turbidity, light	Water temp, pH, ambient temp, humidity, ambient pressure, light
Solar panel	4 × 1.5 V × 250 mA cells	6 V × 500 mA (3 W)	—	6 V × 180 mA
Battery	Li-Po, 3.7 V, 8000 mA h	Li-Po, 3.7 V, 5000 mA h	—	Li-ion, 3.6 V, 2000 mA h
Microcontroller	ESP32-WROOM	ATmega328P (Arduino Uno R3)	Arduino Uno R3 + ESP8266	Feather M0 (AT-SAMD21)
Avg. power consumption	1.8 mA (6.5 mW @ 3.6 V)	104 mW	—	2.8 mW (avg. cycle)
Record interval	10 min	6 h (sampling), 12 h (transmit)	—	1 min to 2 min (seasonal)
Environment	Surface water bodies	Groundwater wells	Shrimp aquaculture ponds	Freshwater lakes

2.2 Research Gap in Literature

While the existing literature provides valuable insights into the evolution of IoT technologies, LoRa communication, and water quality monitoring for aquaculture, several gaps and unresolved problems remain that warrant further investigation in this thesis:

1. **Continuous Real-Time Monitoring:** Although various studies have demonstrated the use of IoT systems for monitoring water quality parameters in shrimp farming, many rely on intermittent or manual data collection methods. There is a need for a system that provides continuous, real-time monitoring to detect rapid fluctuations in critical parameters (e.g., pH, dissolved oxygen, ORP, and salinity) that can significantly affect shrimp health.
2. **Reliability of LoRa Communication in Harsh Environments:** LoRa technology is widely recognized for its low power consumption and long-range capabilities. However, the performance of LoRa-based communication in the challenging environmental conditions of shrimp farms—such as high humidity, water interference, and temperature fluctuations—remains underexplored. Future research should systematically evaluate the robustness and reliability of LoRa networks under these specific conditions.
3. **Integration of Multi-Component Systems:** Existing research often addresses the individual components of water quality monitoring systems, such as sensor performance, wireless communication, or renewable energy integration, in isolation. There is a significant research gap in developing and validating a fully integrated system that combines IoT, LoRa communication, and renewable energy sources (solar panels) to achieve a reliable, energy-efficient solution for shrimp farming.

2.3 Theoretical Perspectives

2.3.1 The Internet of Things

The Internet of Things (IoT) represents a transformative technological advancement that connects physical objects to the internet, enabling data sharing and analysis at an unprecedented scale, thus enhancing human life. IoT consists of interconnected devices that collect and exchange data, improving efficiency and convenience in daily tasks [11]. By connecting various devices, IoT enables real-time data collection and analysis, leading to smarter operations in sectors such as healthcare, agriculture, and transportation [12]. A common IoT architecture includes:

1. **Device Layer:** Physical devices and sensors that collect data.
2. **Network Layer:** Facilitates communication between devices and the cloud.
3. **Cloud Layer:** Processes, stores, and analyzes data.
4. **Application Layer:** Provides user interfaces and applications for interaction.

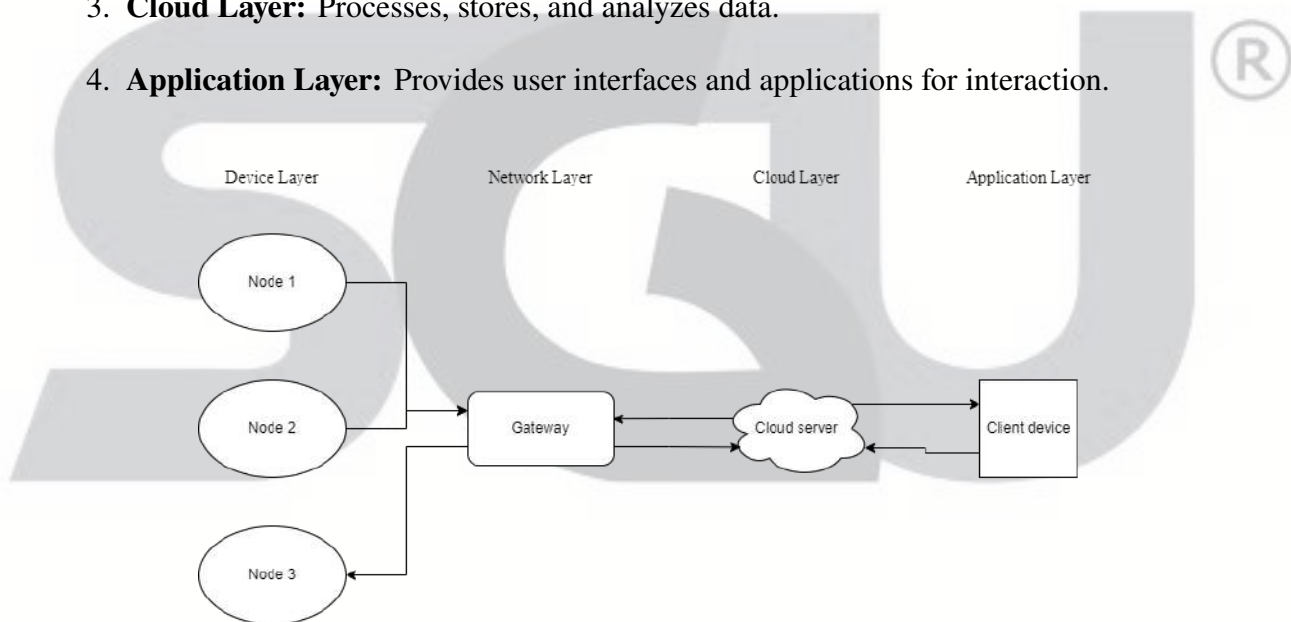


Figure 2.1: IoT Architecture

This is possible due to advances in several key technologies including:

1. **Wireless communication:** A growing number of different wireless technologies are developed (Such as: Zigbee, Z-Wave, NB-IOT, LoRaWAN, etc) [13] specifically targeting low power, low bandwidth applications ideal for IoT.
2. **Cloud Computing:** Robust and accessible cloud computing infrastructure necessary for data storage and processing.
3. **Big Data Analytics:** Helps in analyzing the vast amounts of data generated by IoT devices to derive meaningful insights.

4. **Artificial Intelligence:** AI algorithms can enhance decision-making processes by learning from data patterns. These technologies work together to create a robust IoT ecosystem that supports various applications and services (Ms., Bhoomi, et al., 2024)



2.3.2 Comparing LoRa to Alternative Wireless Communication

The system requirements for the wireless solution include:

- Data transmission over a distance of 1 km,
- Low power consumption,
- Operation in a license-free band,
- Support for private deployment,
- Relatively low data rate, and
- Low cost.

In the LPWAN space, technologies such as LoRa, SigFox, NB-IoT, and LTE-M are considered. Based on [14], the following table summarizes their key characteristics:

Characteristic	LoRa	SigFox	NB-IoT	LTE-M
Transmission Range (km)	5–20	10–40	1–10	5
Power Consumption	Very low	Low	Medium	Medium
Frequency Band	Sub GHz ISM	Sub GHz ISM	Licensed	Licensed
Modulation	CSS	DBPSK, GFSK	QPSK	QPSK, 16-QAM, 64-QAM
Data Rate (kbps)	50	0.1	200	1400
Cost	Low	Low	Medium	High
Bandwidth (kHz)	125	0.1–0.6	250	1000
Private Deployment	Yes (affordable)	Yes (expensive)	No	No

Table 2.2: Comparison of LPWAN Technologies

Both SigFox and LoRa are technically suitable for this application; however, due to the higher cost of SigFox gateways, LoRa was chosen.

2.3.3 The LoRa Physical Layer

The Chirp Spread Spectrum Modulation A chirp is a sine wave whose instantaneous frequency changes from an initial frequency to a final frequency over a time period. In LoRa, a linear frequency chirp is used. Mathematically, it is described as:

$$y(t) = A \sin(2\pi(f(t)t + \phi)),$$

where A is the amplitude, ϕ is the phase, and the frequency function is:

$$f(t) = c t + f_0,$$

with the chirp rate c defined by:

$$c = \frac{f_1 - f_0}{T}.$$

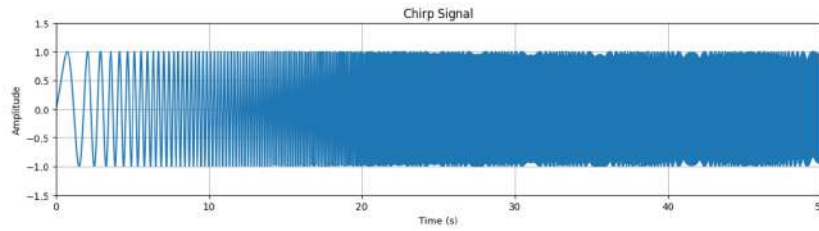


Figure 2.2: Chirp Signal

In LoRa, the Base Chirp starts at the minimum frequency $f_{\min} = -\frac{BW}{2}$ and ends at the maximum frequency $f_{\max} = +\frac{BW}{2}$. Shown in Figure 2.3. A Down Chirp is characterized by a chirp that starts with the maximum frequency $f_0 = f_{\max} = +\frac{BW}{2}$ and ends with the minimum frequency $f_1 = f_{\min} = -\frac{BW}{2}$; this chirp has the unique property of being practically the complex conjugate of the base chirp. Shown in Figure 2.4. In LoRa communication, digital signals are represented as symbols, which are simply a time-shifted base chirp. [15] Shown in Figure 2.5.

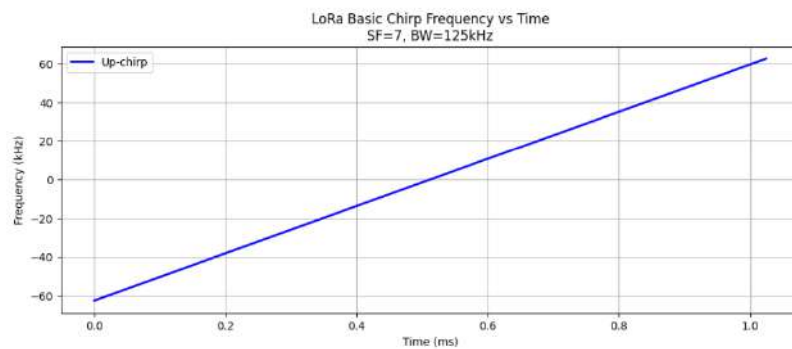


Figure 2.3: Base Chirp in frequency vs time graph

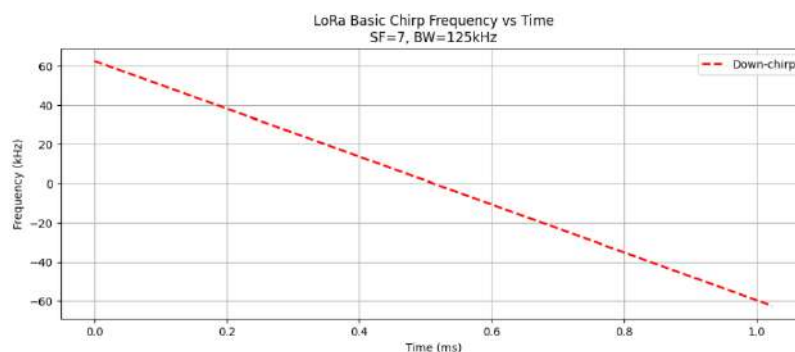


Figure 2.4: Down Chirp in frequency vs time graph

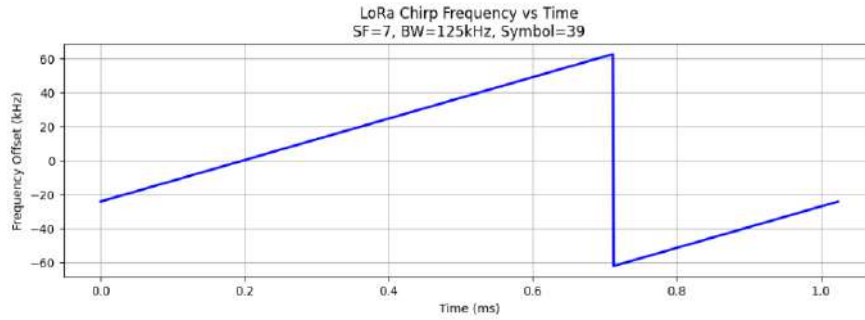


Figure 2.5: Symbol 39 in SF 7 CSS Modulation

The Communication Parameters The number of symbols in LoRa depends on the Spreading Factor (SF):

$$n = 2^{SF}.$$

For example, with $SF = 7$, there are 128 symbols, each representing 7 bits of data. To improve reliability, LoRa uses diagonal interleaving along with forward error correction (FEC) with code rates ranging from 4/5 to 4/8. The symbol rate is given by:

$$R_s = \frac{SF \times BW}{2^{SF}},$$

and the data rate (in bps) is:

$$R_b = \frac{SF \times BW}{2^{SF}} \times \frac{1000}{4 + CR},$$

where CR is the FEC code rate.[5]

LoRa Package Structure The LoRa package structure begins with a preamble (used for synchronization), followed by an optional header (containing package length and code rate), and finally the data payload. LoRa operates in various Sub-GHz ISM bands (e.g., 433, 868, or 915 MHz).[5]

LoRa Mathematical Model for Communication Range The relationship between the transmitter (Tx) and receiver (Rx) power is:

$$P_{Rx} = P_{Tx} + G_{Tx} - L_{Tx} + G_{Rx} - L_{Rx},$$

and the receiver sensitivity is calculated as:

$$\text{Rx sens (dBm)} = -174 + 10 \log(BW) + \text{SNR Limit} + \text{Noise Figure}.$$

Signal to Noise Ratio (SNR) being correlated with the SF used in the following table

SF	SNR Limit (dB)
7	-7.5
8	-10
9	-12.5
10	-15
11	-17.5
12	-20

Table 2.3: SNR Limits for different Spreading Factors (SF)

For example, with $BW = 125$ kHz, an SNR limit of -20 dB (for SF12), and a noise figure of 6 dB, the sensitivity is approximately:

$$\text{Rx sens} \approx -137 \text{ dBm}.$$

If the transmit power P_{Tx} is 14 dBm, then the link budget is:

$$\text{Link Budget (dBm)} = 14 - (-137) = 151 \text{ dBm}.$$

The free space path loss (FSPL) is calculated by:

$$\text{FSPL (dBm)} = 20 \log(d) + 20 \log(f) - 147.55,$$

so for a distance $d = 1000$ m and frequency $f = 923$ MHz, we get:

$$\text{FSPL} \approx 91.75 \text{ dBm}.$$

Since the FSPL is lower than the link budget, the system meets the 1 km requirement.

The LoRaWAN MAC Layer The LoRaWAN MAC Layer works on top of the LoRa physical layer. It is responsible for managing the communication between end devices and network gateways.

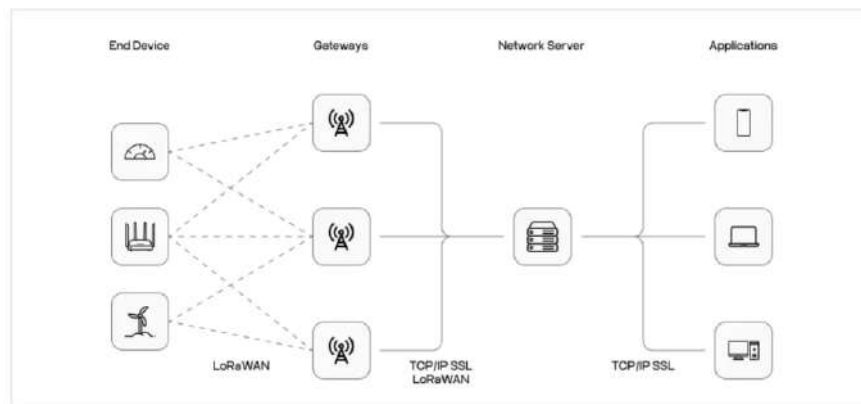


Figure 2.6: LoRaWAN Network Architecture [16]

The MAC layer serves several important functions:

- **Frame Management:** Formats data into frames for transmission and interprets received frames, ensuring proper structure for the PHY layer.
- **Channel Management:** Selects appropriate frequency channels and manages duty cycles to comply with regional regulations.
- **Adaptive Data Rate (ADR):** Dynamically adjusts the data rate based on network conditions, optimizing power consumption and communication range.
- **Security:** Manages encryption and decryption processes, ensuring secure communication through unique session keys.
- **Scheduling and Coordination:** Schedules transmissions to avoid collisions and coordinates timing between devices and gateways.

Importantly, the gateway in this architecture facilitates packet forwarding and timing control, but it is not responsible for initiating downlink messages [5], [17].

LoRaWAN defines three classes of devices, each tailored to different application needs:

- **Class A:** Supports two-way communication with asynchronous uplink and downlink transmissions. This class is energy-efficient and ideal for sporadic communication.
- **Class B:** Builds on Class A by adding scheduled downlink opportunities, suitable for applications requiring timely data delivery.
- **Class C:** Enables nearly continuous listening for downlink messages, offering low-latency communication at the expense of higher power consumption [5].

2.3.4 Shrimp Farming and the Effect of Water Quality on Farm Productivity

Shrimp farming is the practice of cultivating shrimps in a controlled environment for human consumption. One of the most widely farmed species is *Litopenaeus vannamei*, commonly known as the Pacific white shrimp [18]. *L. vannamei* is favored in aquaculture due to its relatively high resistance to environmental disturbances and its strong export potential. Its adaptability allows for efficient cultivation in various systems, including super-intensive closed aquaculture setups, which maximize production output [19].

However, poor water quality significantly impacts the success of *L. vannamei* farming by causing fluctuations in dissolved oxygen (DO), temperature, pH, and salinity. These variations can reduce growth rates, increase stress levels, and raise mortality, thereby compromising shrimp health and the long-term sustainability of aquaculture operations [3].

Research has shown that periodic checks on these water quality parameters are insufficient. For example, a study by Raden, Iqlina, and Nursani [3] found that fluctuations in DO and temperature occur daily, making real-time, continuous monitoring essential for effective management. Another study by Ariadi, Fadjar, Mahmudi, *et al.* [20] analyzed the relationships between water quality parameters and shrimp growth in intensive ponds, revealing that DO negatively correlates with phosphate, nitrite, total ammonia nitrogen (TAN), total organic matter (TOM), total vibrio count (TVC), and total bacterial count (TBC). It also found a significant relationship between nitrite concentration and shrimp growth rate.

Additionally, a blog by Zulfikar [21] highlighted the utility of oxidation-reduction potential (ORP) as a single parameter that reflects various water quality conditions. ORP provides insights into pH, temperature, ammonia, oxygen demand, and nitrate levels. Recommended ORP values for shrimp farming range from 150–250 mV, while values at or below -100 mV are considered harmful.

The table below outlines key ideal ranges for water quality parameters in *L. vannamei* cultivation:

Table 2.4: Ideal Water Quality Parameters for *L. vannamei* Shrimp Farming

Parameter	Ideal Range
Dissolved Oxygen (DO)	4.4 to 8.6 mg/L
pH Level	7.5 to 8.5
Temperature	24°C to 31°C
Salinity	15 to 33 ppt
Oxidation-Reduction Potential (ORP)	150 to 250 mV

2.3.5 Solar Panels

Solar panels technology has come a long way since its inception back in 1839, when a French physicist, Alexandre Edmond Becquerel, discovered the photovoltaic effect. Photovoltaic (PV) is the principle that enables solar cells to convert sunlight into electricity [22]. Figure 2.7 provides a schematic view of a photovoltaic cell [23].

The movement of negatively charged electrons to the front of the PV cell creates an electrical charge imbalance between the front and back surfaces, generating a voltage potential similar to a battery's terminals. Conductors on the cell absorb these electrons, and when connected to an external load, such as a battery, electricity flows through the circuit.

PV cells are the basic units of a PV system, ranging from 0.5 to 4 inches in size and producing 1–2 Watts for small devices. Multiple cells form weather-resistant PV panels, which vary in size and power output based on the number of cells and the cell area. Panels can be combined into PV arrays, increasing the capacity to generate electricity. PV cells produce direct current (DC), which can either charge batteries directly or be converted to alternating current (AC) via inverters [23].

Some factors affect the efficiency of solar panels. For instance, as the temperature of a solar panel rises, a loss in efficiency is observed [24]. Additionally, in humid environments, corrosion and dew formation can reduce the output of the solar panel [25].

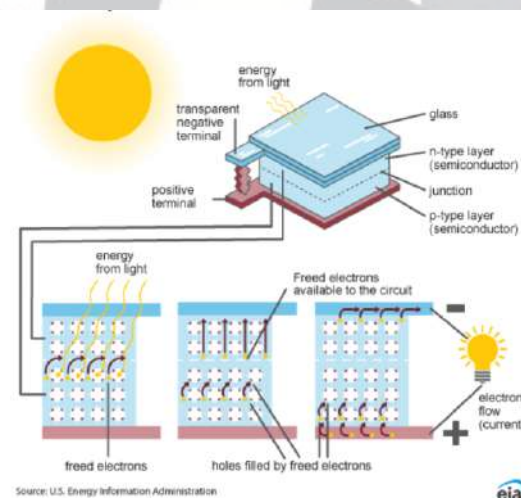


Figure 2.7: Inside a Photovoltaic Cell (U.S. Energy Information Administration, 2024)

Factors such as temperature and humidity can significantly impact solar panel efficiency, reducing the output power [24], [25].

2.3.6 Analog to Digital Converters

Analog-to-digital converters (ADCs) convert continuous analog signals into discrete digital values. There are different types of ADC architectures:

Sigma-Delta ($\Sigma - \Delta$) ADCs These ADCs operate by oversampling the input signal and using digital filtering to achieve high accuracy. Because of this technique, sigma-delta ADCs are relatively slow (approximately 1 MHz) [26], but they can provide high resolution (up to 32 bits). This architecture is often used for industrial measurements and audio applications [27].

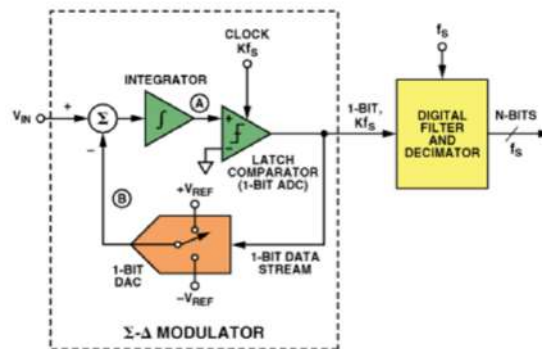


Figure 2.8: First Order Sigma-Delta ADC

Successive Approximation Register (SAR) ADCs SAR ADCs work by sampling the input signal and then converging on it through a series of comparisons. These ADCs are moderately fast (approximately 100 MHz) [28] and provide resolutions up to 20 bits. Their relative simplicity allows for easy integration into microcontrollers and other embedded systems [26], [29].

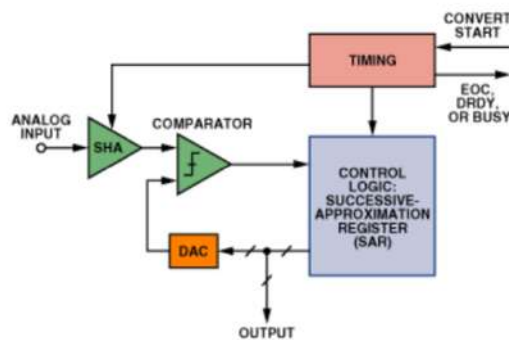


Figure 2.9: SAR ADC Block Diagram

Pipelined ADCs These converters are designed for high-speed applications where bandwidth is critical. They achieve fast conversion rates by processing multiple samples simultaneously through a series of stages, which can allow conversion speeds of approximately 1 GHz [26], albeit at the expense of modest resolution. Pipelined ADCs are essential for oscilloscopes and other high-bandwidth data acquisition systems.

Flash ADCs Flash ADCs are recognized for their extremely fast conversion times. They utilize a parallel architecture with an array of comparators, although they typically offer lower resolutions (up to 12 bits). These ADCs are best suited for rapid signal processing applications, such as RF measurements [26].

Dual-Slope ADCs Dual-slope ADCs excel in low-speed applications where high accuracy is required. They integrate the input signal over time, a method that lends itself well to digital voltmeters due to its simplicity and high resolution capabilities [30].

The choice of ADC architecture largely depends on the specific requirements of the application, such as resolution, sampling rate, power consumption, and cost considerations. For the system under consideration, a SAR ADC was selected for its low power consumption, cost-effectiveness, ease of integration, and adequate speed and resolution.

2.3.7 The Things Stack

The Things Stack is a robust, yet flexible LoRaWAN® Network Server that caters to the needs of demanding LoRaWAN deployments. It provides an infrastructure that enables easier deployment of LoRaWAN-based applications and follows an API-driven microservice architecture meant for high reliability and availability [31].

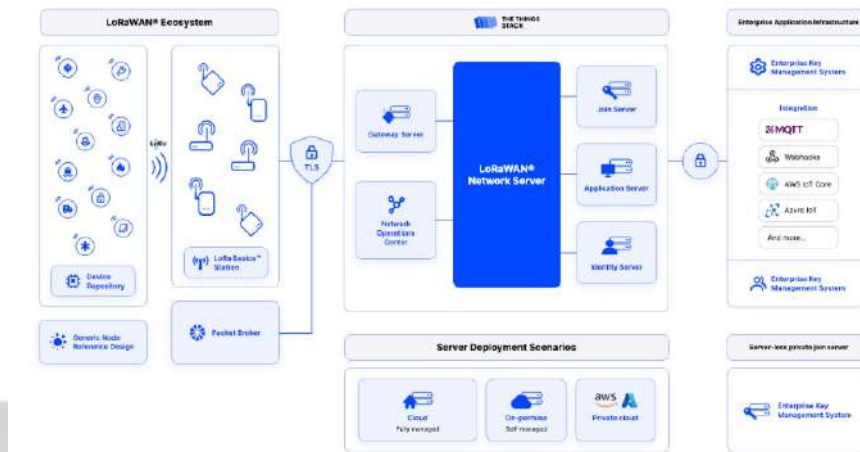


Figure 2.10: The Things Stack Architecture [31]

The architecture consists of several key components:

- **Gateway Server:** Manages communication with LoRaWAN gateways and forwards messages to the appropriate network server.
- **Network Server:** Handles data routing and device registrations.
- **Application Server:** Manages end device data and facilitates integration with various applications.
- **Join Server:** Manages device activation using methods such as ABP or OTAA.
- **Identity Server:** Manages user accounts and API keys.

Essentially, this architecture provides a secure framework for LoRa devices to send data seamlessly all the way to the application server [31].

2.3.8 Correlation between TDS, EC, and Salinity

Both total dissolved solids (TDS) and salinity of water are often estimated through the electrical conductivity (EC) of the water. Based on research by [32], to estimate TDS from EC, use the equation:

$$\text{TDS} = k \times \text{EC},$$

where k is a constant specific to the water type, with TDS given in mg/L and EC in $\mu\text{S/cm}$. The research also provides a rough range of k values for different water types at 25°C , as summarized in Table 2.5.

Table 2.5: Rough Range of k (TDS/EC Ratio) for Different Water Types at 25°C

Water Type	k
Natural water for irrigation	0.55–0.75
Natural water, EC = 500–3000 $\mu\text{S/cm}$	0.55–0.75
Distillate water, EC = 1–10 $\mu\text{S/cm}$	0.5
Freshwater, EC = 300–800 $\mu\text{S/cm}$	0.55
Seawater, EC = 45,000–60,000 $\mu\text{S/cm}$	0.7
Brine water, EC = 65,000–85,000 $\mu\text{S/cm}$	0.75

Salinity can also be inferred from TDS, but the relationship may not always be linear. Research by [33] finds that the chemical composition of water (specifically, the type and concentration of ions) plays an important role in the correlation between TDS and EC. Therefore, a specific correlation should ideally be generated for each water type. However, due to time constraints and a focus on the other aspects of the system, a linear model for salinity is preferred. Based on [34], salinity can be estimated using:

$$\text{Salinity} = k \times \text{EC},$$

where a k factor of approximately 0.5 is chosen as a starting point.