

LoRa-Based Multi-Node Environmental Monitoring of Ponds in the Vicinity of Bhaktapur

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Abstract— LoRa (Long Range) radio technology can be used for long-range, low-power environmental monitoring in distributed locations such as ponds. However, its default ALOHA-style channel access causes packet collisions and limits scalability as node count grows. This paper presents the design, implementation, and field evaluation of a Time Division Multiple Access (TDMA) based multi-node LoRa system for monitoring ponds in the vicinity of Bhaktapur, Nepal. Three ESP32-based sensor nodes (temperature, humidity, and pressure), synchronized via DS3231 real-time clocks (RTCs) and interfaced with SX1278 LoRa transceivers at 433 MHz, transmit data to a central receiver in a star topology within dedicated time slots, entering deep sleep otherwise to conserve energy. The system was field-tested under close and long-range conditions across three Spreading Factor/Coding Rate (SF/CR) configurations, with a Flask dashboard for data visualization. Across three SF/CR configurations, trends in packet loss, RSSI, and SNR are analyzed to identify a reliable, energy-efficient setting for a three-node pond monitoring deployment, indicating configuration choices that are promising for further scaling.

Keywords — LoRa, TDMA, RSSI, SNR, SF, CR

I. INTRODUCTION

Ponds are important freshwater ecosystems that support biodiversity and influence the surrounding microclimate. In Bhaktapur, ponds hold significant environmental, cultural, and historical value but are continuously affected by seasonal variation, urbanization, and human activity. Continuous monitoring of parameters such as temperature, humidity, and atmospheric pressure enables more comprehensive observation of ecosystem changes than periodic manual measurement, which is labor-intensive, time-consuming, and unable to provide continuous real-time information [7], [2], [13].

Wireless communication is central to automated environmental monitoring. Conventional short-range technologies such as Wi-Fi, Bluetooth, and ZigBee are

limited by range, power consumption, and infrastructure requirements when deployed over large outdoor areas. Wireless Sensor Networks (WSNs) underpin most IoT-based environmental monitoring systems, connecting distributed sensor nodes to a central gateway, and because such monitoring typically demands long range, low power, and reliable delivery, Low-Power Wide-Area Network (LPWAN) technologies, particularly LoRa, have become a preferred solution [2], [1], [9]. LoRa, developed by Semtech, uses Chirp Spread Spectrum (CSS) modulation for strong interference resistance and high receiver sensitivity, and operates in unlicensed ISM bands (433/868/915 MHz) [10], [2], [7]. LoRaWAN, the associated MAC/network-layer protocol, follows a star-of-stars topology and defines device classes (A, B, C), with Class A being the most energy-efficient [4].

Environmental conditions around a pond are rarely uniform as vegetation, water surface exposure, surrounding structures, and terrain cause temperature, humidity, and pressure to vary from one location to another. A single sensor node therefore cannot represent conditions across an entire pond area, motivating a multi-node deployment. However, the default LoRaWAN MAC relies on Pure ALOHA, in which nodes transmit without coordinating access and its theoretical maximum channel utilization is approximately 18%, limiting scalability as node density increases [4], [5], [2]. Also the simulation studies confirm that interference between spreading factors further degrades performance in dense networks [6], [8]. To address this, researchers have explored Slotted ALOHA, Carrier Sense Multiple Access (CSMA), hybrid MAC protocols, and TDMA [3]. TDMA, in which each node is assigned a dedicated transmission slot, minimizes collisions and provides predictable communication for periodic sensor applications. Thus, scheduled transmission and adaptive spreading-factor allocation have both been shown to improve throughput and energy efficiency [3], [8], [11], [12].

LoRa performance is governed by Spreading Factor (SF), Bandwidth (BW), and Coding Rate (CR), and evaluated via RSSI, SNR, and Time-on-Air (ToA) [2], [4]. A higher SF increases receiver sensitivity and range at the cost of longer

ToA, lower data rate, and higher energy use. Similarly, CR improves reliability through forward error correction at the cost of overhead [5]. Because SF6–SF12 are quasi-orthogonal, nodes using different spreading factors can transmit concurrently with reduced mutual interference [11]. Low-cost microcontroller/transceiver hardware has maintained reliable links over hundreds of meters to a few kilometers in field deployments, though performance degrades with obstruction and distance [1].

Prior monitoring efforts at the Bhaktapur ponds have typically relied on infrequent manual spot-checks, which cannot capture short-term fluctuations such as the temperature drop that accompanies a rain event, nor provide a continuous record for tracking longer-term seasonal or urbanization-driven change. An automated system removes this limitation, but only if it can be deployed and maintained at low cost using commodity hardware, and only if its wireless link is reliable enough that the resulting record is not itself full of unexplained gaps. These two requirements, low cost and reliable delivery under a shared radio channel, motivate the specific combination of ESP32/SX1278 hardware and TDMA scheduling adopted in this work, rather than either a more expensive licensed-spectrum radio or a simpler but collision-prone ALOHA-based access scheme.

Although LoRa's suitability for environmental monitoring and the benefits of TDMA scheduling are individually well established, most existing studies address them separately. Reported LoRa-based water and pond monitoring deployments have used default LoRaWAN or single-node access rather than a scheduled multi-node scheme: examples include LoRaWAN water-quality monitoring in rural rivers and lakes [15], a distributed multisensor LoRa system for lake water environments [16], and a LoRa-based pond monitoring system for soft-shell crab aquaculture [17], none of which coordinate multiple nodes with TDMA. Conversely, TDMA-over-LoRa research has largely been simulation or protocol focused, and even recent experimentally validated TDMA-LoRa systems, such as a bridge structural-health-monitoring deployment [14], have been evaluated indoors or on laboratory-scale structures rather than in an outdoor, multi-site environmental setting. Few studies implement and experimentally evaluate a TDMA-based multi-node LoRa system in real outdoor conditions integrated with real-time cloud storage and visualization. This work addresses that gap by designing and implementing a LoRa-based multi-node environmental monitoring system for ponds in Bhaktapur, using a TDMA scheme to coordinate three sensor nodes communicating with a single receiver, and evaluating communication performance across multiple LoRa parameter configurations under both short-range and long-range deployment.

II. SYSTEM DESIGN AND METHODOLOGY

A. System Architecture

The proposed system consists of three transmitting nodes and one central receiver arranged in a star topology, as shown in Figure 1. Each transmitting node acquires sensor data, formats it into a packet tagged with a unique node identifier,

and transmits it through an SX1278 LoRa transceiver only within its assigned TDMA slot, referenced against a DS3231 RTC. Outside its slot the node remains in deep sleep, waking only to sample and transmit, which minimizes power consumption while eliminating collisions among the three nodes.

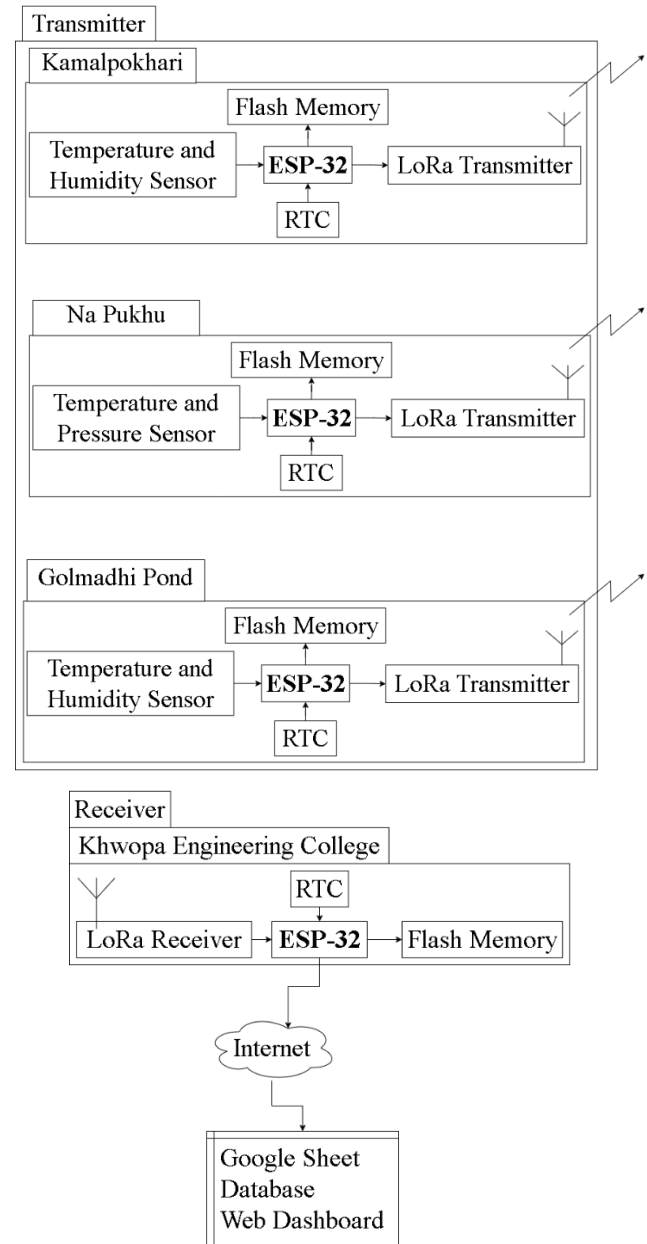


Figure 1: Block diagram of the LoRa-based multi-node environmental monitoring system

The receiver ESP32 remains continuously active, decodes and validates incoming packets, identifies the sending node, and forwards the data to a cloud database (Google Sheets) when Wi-Fi is available. If not, data is buffered in flash memory (LittleFS) and uploaded once connectivity is restored, preventing data loss during outages. This buffering behavior was verified by intentionally disabling the receiver's Wi-Fi connection during operation and confirming that incoming packets continued to be received, timestamped, and

written to LittleFS, and that all buffered records were successfully uploaded to Google Sheets once connectivity was restored, with no buffered packets lost. This verification was qualitative; outage duration, buffered packet counts, and upload latency after reconnection were not logged, so a quantitative characterization of buffering capacity and recovery time under outages of varying length remains a direction for follow-up testing. A Flask-based web dashboard retrieves data from Google Sheets and presents it for real-time monitoring, historical review, and communication-performance analysis.

The architecture separates concern across three tiers. At the sensing tier, each transmitting node is an independent, self-scheduled unit that requires no runtime coordination message from the receiver, synchronization is achieved purely through the shared RTC reference, which keeps the design simple and removes the receiver as a single point of coordination failure. At the gateway tier, the receiver ESP32 performs protocol translation between the LoRa radio link and the internet, decoupling the sensing network from the connectivity method used to reach the cloud. At the application tier, the dashboard and database are decoupled from the acquisition hardware entirely, so the visualization layer can be extended or scaled without modifying node firmware. This separation also simplifies field maintenance. A node can be swapped or reflashed without disrupting the other two, and the receiver's local flash buffer means a temporary Wi-Fi outage at the monitoring site does not result in permanent data loss.

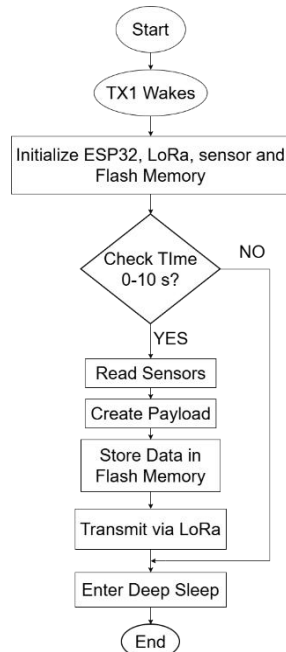


Figure 2: Operational flowchart of the transmitting nodes

Figure 2 summarizes node operation. On wake, each transmitting node checks the current RTC time against its assigned window. If the window has not arrived, it loops and re-checks rather than transmitting speculatively, which guarantees that a node never contends for the channel outside its slot even if it wakes early due to clock jitter.

Once inside its window, the node performs sensor acquisition, local flash backup, and transmission before returning to deep sleep, so a transmission failure does not block the node past its own slot

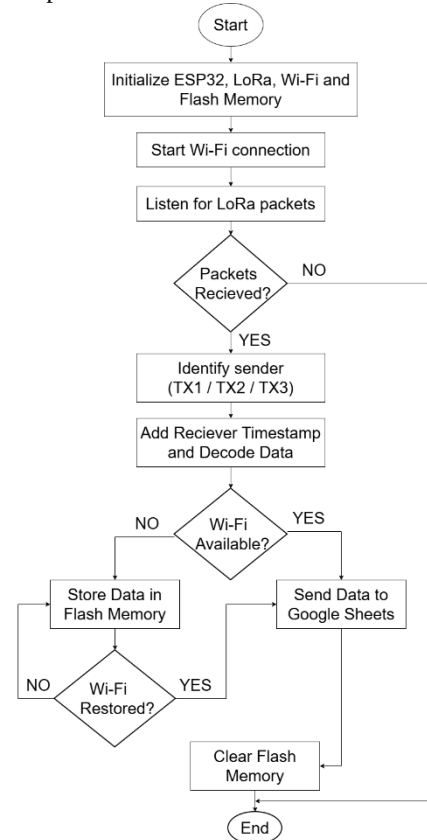


Figure 3: Operational flowchart of the receiver

The receiver's loop (Figure 3) is comparatively simple as it listens continuously, and on packet arrival, decode, timestamp, identify the source node, and either forward to Google Sheets immediately or buffer to flash. This asymmetry complex, low duty cycle behavior at the transmitters versus always-on behavior at the receiver mirrors the underlying energy budget, since the three transmitters are intended for longer-term unattended deployment while the receiver is assumed to have more stable power access.

B. TDMA-Based Multiple Access Scheme

Figure 4 illustrates the TDMA timing scheme. Three transmitter nodes (TX1, TX2, TX3) wake simultaneously at the start of a repeating 60-second frame but act only within their own assigned 10-second window: TX1 in 0–10 s, TX2 in 12–22 s, and TX3 in 24–34 s, with 2-second guard intervals between slots to absorb minor RTC drift among the ESP32 modules. Outside its window, a node loops and waits. When its window arrives, it samples its sensor, builds a data payload, backs it up to flash, transmits via LoRa, then enters deep sleep until the next cycle. The receiver stays awake for the full frame, allowing it to capture transmissions from all three nodes in sequence without contention. This scheme ensures that only one transmitter is active on the shared

channel at any moment, eliminating collisions without requiring a more complex collision-avoidance protocol. The 2-second guard interval was chosen as a conservative design margin rather than derived from a formal timing budget. The DS3231's temperature-compensated crystal oscillator specifies a drift of only a few parts per million, which over the 60-second frame period translates to a theoretical clock offset on the order of tens of microseconds between nodes, several orders of magnitude smaller than the chosen guard interval. The 2-second margin was therefore sized generously to also absorb less predictable, non-RTC sources of timing variation, such as sensor-read duration, wake-from-sleep latency, and LoRa radio mode-switching delay, none of which were characterized in isolation in this study. No inter-node collisions attributable to slot-boundary overlap were observed during testing, which is consistent with this margin being adequate, but a tighter, empirically validated guard interval derived from measured long-term RTC drift and worst-case node-to-node timing offset is identified as a direction for follow-up work, particularly as the node count grows and shorter guard times become important for channel utilization.

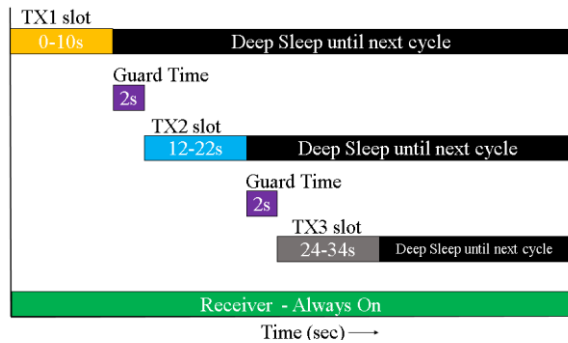


Figure 4: . TDMA timing diagram for the multi-node LoRa sensor network

C. Hardware Implementation

Each node is built around an ESP32 microcontroller, chosen for its processing capability, integrated Wi-Fi, and onboard flash storage. The SX1278 LoRa provides long-range, low-power radio communication and is paired with a matched antenna at every node. Two transmitting nodes use a DHT22 digital sensor, while the third uses a BMP280 digital sensor. Both generate compact, low data rate payloads well suited to LoRa's limited bandwidth. A DS3231 RTC with an integrated temperature compensated crystal oscillator supplies the stable, power independent time reference required for TDMA slot synchronization. An LM2596 buck regulator supplies stable low voltage power to each node, and an ST7789 TFT display provides local visual feedback for debugging.

D. Software, Cloud Storage, and Dashboard

Nodes and receiver were programmed. Received packets including node ID, temperature, humidity/pressure, TX/RX time, RSSI, and SNR are logged to Google Sheets over HTTP, acting as the system's cloud database. A Python/Flask backend, hosted on Render, retrieves this data and serves a

browser based dashboard with four sections, Home (network topology), LoRa Dashboard (live readings with auto-refresh), History (per node historical data), and Analysis (end-to-end delay, RSSI, SNR, and packet loss statistics).

III. EXPERIMENTAL SETUP

Two deployment layouts were used. In the close-range layout, all three nodes were positioned 42–90 m from the receiver near Khwopa Engineering College (Figure 5). In the long-range layout (Figure 6), nodes were distributed over three ponds Kamalpokhari, Na Pukhu, and Golmadhi Pond at 687 m to 1631 m from the receiver. Node and receiver coordinates were obtained from Google Earth so that reported distances are calculated rather than estimated. Three sequential close-range test rounds were conducted, each using a single configuration across all three nodes; SF7/CR5, SF10/CR5, and SF12/CR8. Since SF12/CR8 offers the highest theoretical range, it alone was carried forward to the long-range trial. Table I summarizes the test rounds.

TABLE I. TEST ROUNDS AND NODE DISTANCES TO RECEIVER

Round	SF/CR	Node 1	Node 2	Node 3
1 (close)	SF7/CR5	~90 m	~42 m	~78 m
2 (close)	SF10/CR5	~90 m	~42 m	~78 m
3 (close)	SF12/CR8	~90 m	~42 m	~78 m
4 (long)	SF12/CR8	~694 m	~1631 m	~687 m



Figure 5: Close-range node and receiver



Figure 6: Long-range node and receiver deployment

IV. RESULTS AND DISCUSSION

A. Close-Range Multiple Access Performance

With all three nodes transmitting to the receiver simultaneously at 42–90 m, communication was successfully established in every round, but reception quality varied sharply with configuration (Table II). SF12/CR8 achieved 0–2.44% packet loss across all nodes, SF10/CR5 achieved 18.75–41.67%, and SF7/CR5 lost 40.00–56.67% of packets. The improvement is reflected in stronger mean RSSI for SF12/CR8, at the cost of longer transmission delay from increased time-on-air.

TABLE II. COMMUNICATION PERFORMANCE IN CLOSE-RANGE LOS

Config.	Node	Sent	Recv.	Loss (%)	RSSI (dBm)	SNR (dB)
SF7/CR5	1	30	13	56.67	-108.8	9.6
SF7/CR5	2	30	18	40.00	-107.2	10.2
SF7/CR5	3	30	15	50.00	-108.1	9.9
SF10/CR5	1	12	7	41.67	-105.4	7.5
SF10/CR5	2	16	13	18.75	-105.4	8.0
SF10/CR5	3	14	11	21.43	-105.0	8.0
SF12/CR8	1	14	14	0.00	-92.5	9.9
SF12/CR8	2	41	40	2.44	-89.2	1.3
SF12/CR8	3	41	41	0.00	-91.2	-3.1

End-to-end delay was computed from RTC timestamps with one-second resolution so values reported as ~0 s indicate sub second delay that the RTC cannot resolve further. A higher-resolution timing method (e.g., synchronized microsecond timers or GPS) would be required to isolate propagation and processing delay precisely.

B. Effect of SF/CR on RSSI, SNR, and Delay

Table III summarizes average performance per configuration, obtained by averaging across the three nodes. Mean RSSI improved from -108.03 dBm (SF7/CR5) to -105.4 dBm (SF10/CR5) to -90.5 dBm (SF12/CR8), while mean packet loss fell from 48.89% to 27.5% to 1%. This improvement in link margin came at the cost of longer mean delay, rising from ~0.1 s to ~3.0 s. Although mean SNR decreased with increasing SF, SF12/CR8 still achieved the most reliable reception. This is because its larger spreading factor improves receiver sensitivity and processing gain, allowing correct decoding even at low or negative SNR.

TABLE III. COMPARISON OF LORA PARAMETER SETTINGS (MEAN)

SF/CR	RSSI (dBm)	SNR (dB)	Loss (%)	Delay (s)
SF7/CR5	-108.03	9.97	48.89	~0.1
SF10/CR5	-105.40	7.91	27.50	~2.14
SF12/CR8	-90.50	0.64	1.00	~3.00

Figure 7 shows RSSI recorded at Node 3 across the three configurations. SF12/CR8 recorded the highest (least negative) RSSI throughout, while SF7/CR5 showed the lowest. Figure 8 shows the corresponding SNR. SF7/CR5 maintained the highest positive SNR, while SF12/CR8 operated predominantly at negative SNR yet still achieved near-zero packet loss, confirming that higher spreading factors tolerate signal degradation better than raw SNR alone would suggest. Based on these results, SF12/CR8 was selected for long-range testing.

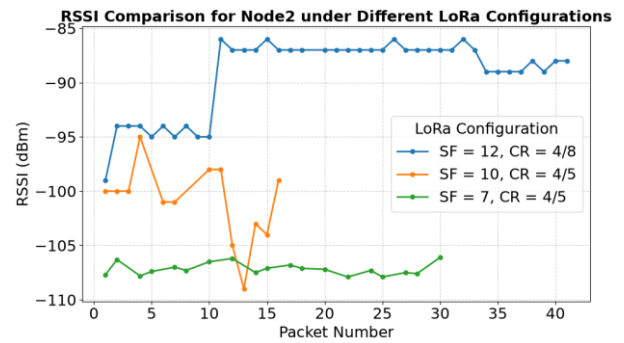


Figure 7: RSSI variation of Node 3 under SF7/CR5, SF10/CR5, and SF12/CR8

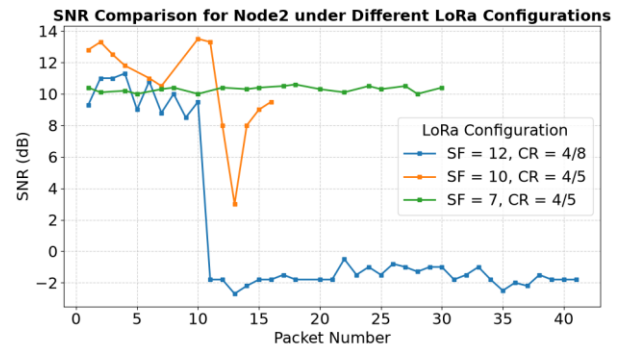


Figure 8: SNR variation of Node 3 under SF7/CR5, SF10/CR5, and SF12/CR8.

C. Long-Range Communication Performance

At 687 m - 1631 m, SF12/CR8 maintained reliable communication with all three nodes despite lower RSSI and SNR and longer delay (Table IV). Packet loss ranged from 3.23% to 8.33%, mean RSSI from -116.00 to -113.38 dBm, and mean SNR from -15.67 to -4.20 dB. Interestingly, the farthest node (Node 2, ~1631 m) achieved the lowest packet loss, while the closer Node 3 (~687 m) recorded the highest, indicating that terrain, vegetation, and local propagation conditions influence reliability as much as raw distance.

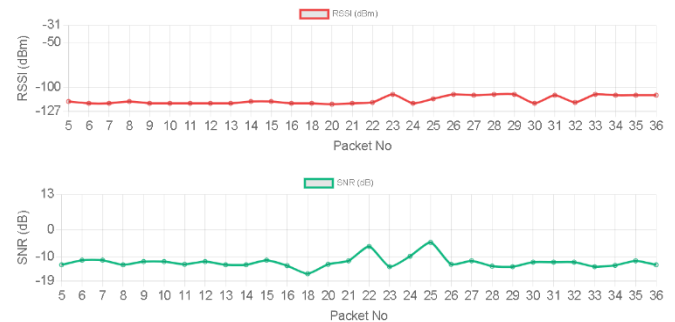


Figure 9: RSSI and SNR of Node 1 during long-range communication

Figure 9 shows RSSI and SNR recorded at Node 1 (~694 m) during the long-range trial. RSSI remained relatively stable near -113 dBm throughout, while SNR fluctuated between approximately -16 dB and -6 dB. Despite the consistently negative SNR conditions under which SF7 or SF10 would be expected to fail outright, based on the close-range results. A SF12/CR8 sustained reliable delivery with

only minor packet loss, underscoring that at large spreading factors, receiver sensitivity and processing gain, not raw SNR, are the binding constraint on link reliability. This behavior held consistently across all three long-range nodes, whose individual RSSI levels clustered between -113 dBm and -116 dBm and whose SNR values ranged as low as approximately -20 dB at the most heavily obstructed node.

TABLE IV. SF12/CR8 PERFORMANCE AT LONG RANGE

Metric	Node 1 (~694 m)	Node 2 (~1631 m)	Node 3 (~687 m)
Packets Recv.	34	30	44
Loss (%)	5.56	3.23	8.33
Mean Delay (s)	~2.9	~3.0	~4.0
Mean RSSI (dBm)	-113.38	-114.77	-116.00
Mean SNR (dB)	-12.09	-4.20	-15.67

D. Environmental Data Collection

In addition to communication tests, the system recorded temperature data at all three nodes, humidity levels at Nodes 1 and 3, and pressure data at Node 2. Table VI provides a representative sample of the logged information. The recorded temperatures ranged from 25°C to 32°C , humidity levels varied from 43% to 79% relative humidity (RH), and pressure readings ranged from 859 hPa to 868 hPa. The differences in values across the three sites at any given time demonstrate that a single monitoring point would not adequately represent the spatial variability captured by the multi-node deployment.

TABLE VI. SAMPLE ENVIRONMENTAL DATA

Time	N1 T ($^{\circ}\text{C}$)	N1 H (%)	N2 T ($^{\circ}\text{C}$)	N2 P (hPa)	N3 T ($^{\circ}\text{C}$)	N3 H (%)
10:00	29	64	27	868	29	77
11:00	30	63	30	863	30	67
12:30	30	59	32	864	31	51
17:30	29	70	27	859	28	76
18:00	27	79	25	859	27	77

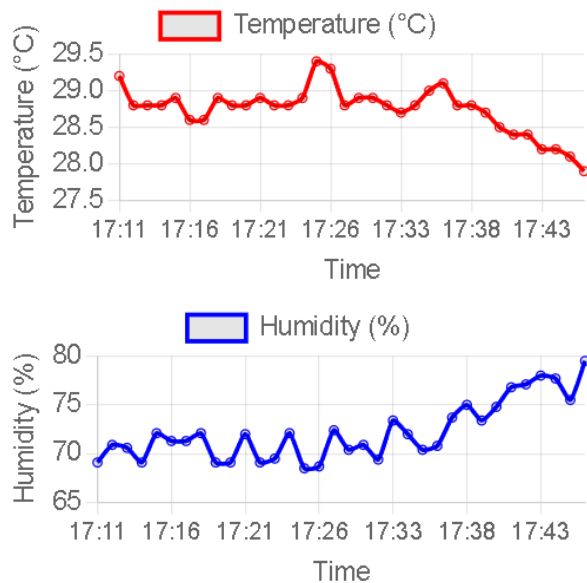


Figure 10: Node 1 temperature and humidity over the monitoring period.

Figure 10 illustrates the trend at Node 1: temperature remained relatively stable between approximately 27.7°C and 29.4°C , while humidity gradually increased from about 69% to 79% RH toward the end of the observation window, consistent with normal short-term environmental variation. Node 2 (BMP280) showed a gradual temperature rise from $\sim 30^{\circ}\text{C}$ to $\sim 33^{\circ}\text{C}$ alongside a nearly constant pressure of 859–860 hPa, and Node 3 showed an inverse temperature humidity relationship, temperature rising to $\sim 33^{\circ}\text{C}$ before decreasing to $\sim 29^{\circ}\text{C}$ while humidity moved in the opposite direction, a pattern consistent with expected psychrometric behavior. Collectively, these node-level trends demonstrate that the system reliably captures realistic, spatially distinct environmental signatures using two different sensor types on a shared LoRa channel.

E. Comparison with Standard Weather Data

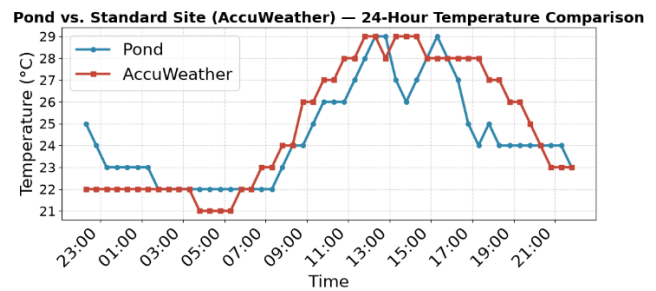


Figure 11: Pond-site temperature (Kamalpokhari) vs AccuWeather reference over 24 hours

The 24-hour pond site temperature was compared to AccuWeather reference data (Figure 11). Both showed a similar diurnal trend, peaking near 29°C between 12:00 and 15:00. During night time (23:00–06:00) the pond site read 1–2 $^{\circ}\text{C}$ higher than the reference, and after 15:00 it cooled more rapidly, coinciding with rainfall at the monitoring site, likely reflecting localized effects of vegetation, shading, and reduced solar exposure not captured by a regional reference source. The close overall agreement, together with explainable local deviations, supports the reliability of the proposed system for capturing site-specific microclimate variation..

F. Discussion: Comparison with Related Deployments

Table VIII places the achieved close-range and long-range packet loss figures alongside prior findings on TDMA's benefit over ALOHA-based access, SF/range trade-offs, and the extent of field validation in the literature.

TABLE VIII. CONTEXTUALIZING RESULTS AGAINST PRIOR FINDINGS

Aspect	Reported in Literature	This Work
TDMA benefit	Reduced collisions vs. ALOHA [8], [12]	0–2.44% loss, SF12/CR8, close range
SF/range trade-off	Higher SF $\rightarrow$ longer range, ToA [5]	Confirmed; SF12 range >1631 m
Field validation	Often simulation-based [6],[11]	Field-tested, 3 real pond sites

This comparison also highlights a limitation of the present study. SF7/CR5 and SF10/CR5 were tested only under the TDMA schedule and not under free contention, so their

reported packet loss reflects sensitivity and link-margin limitations at the tested distances rather than collision loss. A direct ALOHA-versus-TDMA comparison at identical distances and SF/CR settings would more precisely isolate the scheduling gain and is identified as a direction for follow up work.

V. CONCLUSION AND FUTURE WORK

This paper presents a TDMA-based multi-node LoRa system designed for environmental monitoring of ponds in the vicinity of Bhaktapur. The system utilizes ESP32 microcontrollers, SX1278 transceivers, and RTC-synchronized time slots arranged in a star topology. At close range (42–90 m), all three tested configurations successfully transmitted packets from every node. However, the SF12/CR8 configuration consistently demonstrated the highest reliability, with packet loss rates ranging from 0% to 2.44%. In comparison, the SF10/CR5 configuration experienced packet loss rates of 18.75% to 41.67%, and the SF7/CR5 configuration faced even higher losses, ranging from 40% to 56.67%. When the range was extended to between 687 m and 1631 m, the SF12/CR8 configuration continued to provide reliable communication, achieving a packet loss rate of 3.23% to 8.33%, despite the reduced RSSI and SNR. The system collected and recorded temperature, humidity, and pressure data from all three nodes. Measurements were taken during both short trials and over a full 24-hour period to capture daily fluctuations. The temperature trends aligned with an independent regional weather reference. All of the data was made available in real time through a web dashboard. Together, these results confirm TDMA with SF12/CR8 as a scalable, energy-efficient configuration for multi-node LoRa environmental monitoring.

Future work should focus on implementing an ALOHA-style baseline under the same hardware and field conditions to directly quantify the collision and reliability benefits attributed to TDMA, and on increasing the number of transmitting nodes to evaluate the scalability of the TDMA scheme under higher traffic conditions. Additionally, integrating more water-quality sensors, such as pH, dissolved oxygen, turbidity, and electrical conductivity, would support ecological and aquaculture applications. Implementing solar charging would enhance long-term autonomous operation, and adopting a higher-precision timing method, such as GPS synchronization, would enable measurements of end-to-end delays down to the millisecond level.

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