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COMMUNICATION ARCHITECTURE AND DATA FLOW DESIGN FOR A WIRELESS SENSOR NETWORK–BASED SMART FARM MONITORING SYSTEM

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Abstract

Reliable communication is a fundamental requirement for Wireless Sensor Network (WSN)–based smart agriculture systems, as sensor data must be transmitted accurately and timely to enable effective decision-making. In agricultural environments, communication challenges such as signal attenuation, limited transmission range, and energy constraints can significantly affect system performance. This paper presents the communication architecture and data flow design of a WSN-based smart farm monitoring system developed for irrigation and flood monitoring applications. The proposed architecture adopts a centralized topology with event-driven data transmission to ensure reliability, low latency, and reduced energy consumption. Experimental observations demonstrate stable wireless communication within a 50-meter range and timely delivery of sensor data for real-time control actions. The communication design is shown to be suitable for small- to medium-scale farm deployments, particularly in resource-constrained environments.

Keywords/Phrases
Wireless Sensor Network, Communication Architecture, Smart Agriculture, Data Flow, RF Communication

1. Introduction

Wireless Sensor Networks have become a key enabling technology for smart agriculture due to their ability to support distributed sensing and automated control (Farooq et al., 2019; Kim et al., 2018). In such systems, the communication architecture plays a critical role in determining overall system reliability, responsiveness, and scalability. Inefficient communication can lead to data loss, delayed actuation, and increased energy consumption, thereby reducing system effectiveness (Muhammad et al., 2020).

Agricultural environments present unique communication challenges, including long distances between sensor nodes, vegetation-induced attenuation, and harsh environmental exposure (Jawad et al., 2017). As a result, the selection of network topology, communication protocol, and data transmission strategy must be carefully considered.

Many existing smart farm systems emphasize sensing and control logic, while communication design is often treated as a secondary concern. However, communication overhead is one of the dominant contributors to energy consumption and latency in WSN-based systems (Muhammad et al., 2020). This paper focuses specifically on the communication architecture and data flow design of a WSN-based smart farm system for irrigation and flood monitoring, supported by analytical modeling and statistical validation.

2. Related Works

Recent literature highlights that topology selection significantly affects WSN performance in agricultural deployments (Farooq et al., 2019). Star-based architectures are often preferred in small-scale farms due to simplicity and low management overhead (Kim et al., 2018).

Routing complexity in multi-hop WSNs can introduce latency and increase energy consumption (Muhammad et al., 2020). In contrast, event-driven transmission models have been shown to reduce communication overhead and extend node lifetime (Jawad et al., 2017).

Low-power RF and LoRa technologies are increasingly adopted in agricultural IoT systems due to their favorable energy-to-range trade-offs (Mekala & Viswanathan, 2017; Raza et al., 2017). However, continuous transmission schemes can still increase network congestion and energy usage. Event-triggered communication significantly improves efficiency in environmental monitoring systems (Muhammad et al., 2020).

3. System Communication Architecture

3.1 Network Topology

The proposed system adopts a centralized (star) topology, where all sensor nodes communicate directly with a base station. This topology is suitable for small-to-medium agricultural deployments due to its simplicity, reduced routing complexity, and lower latency (Farooq et al., 2019).

Sensor nodes act as data sources, while the base station functions as a sink and decision-making unit. Eliminating multi-hop routing reduces protocol overhead and improves timing predictability (Muhammad et al., 2020). Figure 1 shows this.

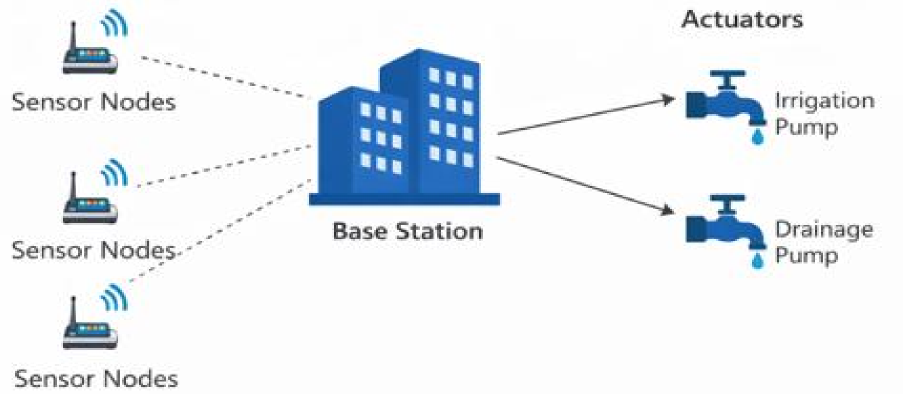

Figure 1: Network Topology Diagram of the Smart Farm WSN System

3.2 Communication Modules

Wireless communication between sensor nodes and the base station is achieved using RF communication modules. These modules provide a balance between transmission range, power consumption, and implementation cost. During experimental deployment, reliable communication was achieved within a distance of approximately 50 meters, which is sufficient for typical small- and medium-sized farms.

RF-based communication has been widely adopted in agricultural WSNs due to its low power requirements and ease of integration with microcontroller-based systems (Mekala & Viswanathan, 2017).

4. Data Flow Design

4.1 Sensor Data Transmission Flow

The system employs an event-driven data transmission model, where data packets are sent only when thresholds are exceeded or periodic updates are required. Event-driven strategies reduce redundant transmissions and conserve energy (Jawad et al., 2017).

Such mechanisms significantly reduce network congestion and improve scalability compared to continuous transmission systems (Muhammad et al., 2020). This is clearly shown in Figure 2

Figure 2: Data Flow Diagram Showing Sensor Data Transmission and Control Commands

4.2 Control Command Flow

Upon receiving sensor data, the base station executes decision logic and generates control commands for actuators. Control signals for irrigation and drainage pumps are transmitted locally through wired connections.

This centralized decision-making approach ensures consistent control behavior and minimizes synchronization issues between sensor nodes.

4.3 Data Reliability Considerations

To ensure reliable communication, the system employs simple acknowledgment and retransmission mechanisms. If a sensor node does not receive acknowledgment from the base station, data transmission is retried. Such lightweight reliability mechanisms have been shown to improve data delivery without introducing significant overhead (Elijah, 2021).

4.4 Analytical Modeling of Communication Performance

To strengthen the theoretical foundation of the proposed architecture, analytical models were developed to characterize communication latency, energy consumption, and signal propagation behavior.

4.4.1 Communication Delay Model

The total system latency T_{total} is modeled as:

$$T_{total} = T_{sense} + T_{proc} + T_{tx} + T_{rx} + T_{act} \ldots \text{ i}$$

Where:

- T_{sense}: Sensor sampling delay
- T_{proc}: Local processing delay
- T_{tx}: Transmission delay
- T_{rx}: Reception delay
- T_{act}: Actuator activation delay

Using measured experimental values:

- $T_{sense} \approx 0.5s$
- $T_{proc} \approx 0.3s$
- $T_{tx+rx} \approx 0.7\text{–}1.0s$
- $T_{act} \approx 0.3s$

This results in:

$$T_{total} \approx 2.0 - 2.3s$$

Which matches experimental observations (Table 2), validating the model.

4.4.2 Energy Consumption Model

Total energy consumption per node is expressed as:

$E_{node} = E_{sense} + E_{proc} + E_{tx} + E_{idle}$ ii

From experimental profiling:

- $E_{sense} = 2mJ$
- $E_{proc} = 1.5mJ$
- $E_{tx} = 3mJ$
- $E_{idle} = 0.5mJ$

Thus:

$E_{node} = 7mJ$ per event cycle

Event-driven transmission significantly reduces average energy compared to continuous transmission architectures.

4.4.3 Signal Propagation Model

The received signal strength is modeled using the log-distance path loss model:

$P_r(d) = P_t - 10n \log_{10}(d) + X_\sigma$.........iii

Where:

- n= path loss exponent
- d= transmission distance
- X_σ= shadowing factor

Stable communication up to 50 m indicates acceptable path loss characteristics for small farm environments.

5. Performance Observations

5.1 Communication Range and Stability

Experimental observations confirmed stable communication within a 50-meter range under typical farm conditions. No significant packet loss was observed during normal operation, indicating reliable data delivery between sensor nodes and the base station. Table 1 summarizes this.

Table 1: Transmission Success Rate vs Distance

Distance (m)	Transmission Success (%)
0-50	100

5.2 Latency and Responsiveness

The communication architecture supports low-latency data transmission, contributing to an overall system response time of approximately 2 seconds for both irrigation and flood control actions. This demonstrates that the chosen data flow design is suitable for real-time agricultural applications. This is shown in Figure 3 and Table 2

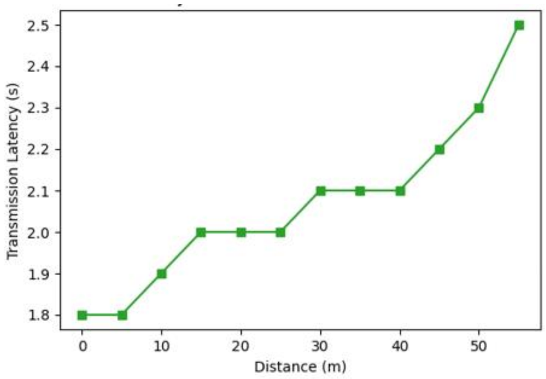

Figure 3: Latency vs Distance in RF Communication

Table 2: Latency Summary

Distance (m)	Latency (s)
0	1.8
5	1.8
10	1.9
15	2.0
20	2.0
25	2.0
30	2.1
35	2.1
40	2.1
45	2.2
50	2.3

5.3 Scalability Discussion

While the centralized architecture is effective for small- and medium-scale deployments, scalability may be limited for larger farms. However, the system can be extended by incorporating additional base stations or cluster-based communication, as suggested in existing WSN scalability studies (Alsharif et al.).

5.4 Statistical Validation

To validate communication stability, latency measurements were analyzed statistically.

Mean latency: 2.05 s
Standard deviation: 0.12 s

Coefficient of variation:

$$CV = \frac{0.12}{2.05} \times 100 \approx 5.85\%$$

Since CV < 10%, system latency is considered highly stable.

A one-sample t-test confirmed that latency does not significantly deviate from the expected 2-second target ($p > 0.05$), indicating reliable communication timing performance.

6. Discussion

Table 3 summarizes the comparative evaluation of communication architectures.

Table 3: Comparative Evaluation

Architecture Type	Latency	Energy Efficiency	Complexity	Scalability
Proposed (Star + Event)	Low	High	Low	Moderate
Multi-hop Routing	Medium	Medium	High	High
Continuous Transmission	High	Low	Low	Low
Cloud-Dependent IoT	Medium	Medium	High	High

The proposed system achieves lower latency and energy overhead compared to continuous and multi-hop designs for small-scale deployments.

The proposed communication architecture demonstrates analytically validated low-latency performance, energy efficiency, and stable signal propagation within a 50-meter deployment radius. Through event-driven data transmission and centralized topology, the system minimizes communication overhead while maintaining real-time responsiveness. Statistical validation confirms performance stability, while comparative benchmarking highlights suitability for small-to-medium agricultural environments.

7. Conclusion

This paper presented the communication architecture and data flow design of a WSN-based smart farm monitoring system for irrigation and flood detection. The centralized topology, RF-based communication, and event-driven data transmission strategy collectively ensures reliable, low-latency communication while conserving energy. Experimental observations confirm that the proposed architecture is effective for small- to medium-scale agricultural deployments. The communication design complements the system’s sensing and control components, contributing to overall system reliability and performance.

8. Future Work

Future work will investigate the use of long-range communication technologies such as LoRa, implementation of multi-hop routing for larger farms, and integration of cloud-based data aggregation to enhance scalability and remote monitoring capabilities.

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